Hindawi Publishing Corporation
Advances in Mechanical Engineering
Volume 2014, Article ID 401587, 10 pages
http://dx.doi.org/10.1155/2014/401587

Review Article

Trends of Syngas as a Fuel in Internal Combustion Engines

Ftwi Yohaness Hagos,[1] A. Rashid A. Aziz,[1] and Shaharin Anwar Sulaiman[2]

[1] *Centre for Automotive Research and Electric Mobility (CAREM), Universiti Teknologi Petronas, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia*
[2] *Department of Mechanical Engineering, Universiti Teknologi Petronas, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia*

Correspondence should be addressed to Ftwi Yohaness Hagos; ftwi@yahoo.com

Received 16 September 2013; Accepted 17 November 2013; Published 30 January 2014

Academic Editor: Nadir Yılmaz

Syngas from biomass and solid waste is a carbon-neutral fuel believed to be a promising fuel for future engines. It was widely used for spark-ignition engines in the WWII era before being replaced with gasoline. In this paper, the technological development, success, and challenges for application of syngas in power generating plants, the trends of engine technologies, and the potential of this fuel in the current engine technology are highlighted. Products of gasification vary with the variation of input parameters. Therefore, three different syngases selected from the two major gasification product categories are used as case studies. Their fuel properties are compared to those of CNG and hydrogen and the effects on the performance and emissions are studied. Syngases have very low stoichiometric air-fuel ratio; as a result they are not suitable for stoichiometric application. Besides, syngases have higher laminar flame speed as compared to CNG. Therefore, stratification under lean operation should be used in order to keep their performance and emissions of NOx comparable to CNG counterpart. However, late injection stratification leads to injection duration limitation leading to restriction of output power and torque. Therefore, proper optimization of major engine variables should be done in the current engine technology.

1. Introduction

Scarcity of conventional petroleum resources and advancement in the solid-to-gas conversion technologies has revived interest in the use of solid fuels. Among the conversion technologies, gasification is the most reliable and energy efficient with advantages in both upstream and downstream flexibility [1]. It is a thermochemical conversion process that increases the hydrogen-to-carbon ratio of the feedstock by breaking carbon bonds and adding hydrogen to the gaseous products [2]. When high carbon solid fuel reacts with a controlled amount of gasifying agent at an elevated temperature of more than 600°C, carbon monoxide (CO) and hydrogen (H_2) are formed as depicted in (1). The process is called gasification and the produced gas is called syngas. This process consists of many reactions and details about the gasification process can be found elsewhere [2]. This conversion process is believed to be the major source of energy in the future, and instrumental in the move from carbon based to hydrogen based energy [1]:

$$\begin{aligned}&\text{Carbonaceous Fuel} + \text{Limited air}\\&\quad = O + H_2 + CH_4 + CO_2 + H_2O + N_2\end{aligned} \tag{1}$$

Syngas, an abbreviation for synthesis gas, is an end product of gasification. This is a name given for a mixture mainly comprised of CO and H_2 at varied proportions. It also consists of other gases like methane, nitrogen, and carbon dioxide apart from these major gases. It can be produced from different feedstock like coal, liquid hydrocarbons, biomass, and other waste products and the quality varies depending on the feedstock and the gasification process. The name "syngas" is a general term for any gasification product. However, different names were used for different products at different times in the past such as town gas, water gas, producer gas, and blast furnace gas [3].

The gasifying agent is the most significant parameter that affects the yield from the thermochemical conversion process [2]. The main gasifying agents used in the process are oxygen, steam, and air. Syngas produced using steam or oxygen as a gasifying agent is called medium calorific value syngas (simply syngas) with its heating value range of 10–28 MJ/Nm^3 [2]. On the other hand, syngas produced using air as a gasifying agent is called lower calorific value gas or "producer gas" and its heating value ranges from 4 to 7 MJ/Nm^3 [2]. Syngas can be used as a standalone fuel for power production or as an intermediate product in chemical industry for the production of synthetic natural gas, synthetic liquid petroleum, ammonia, and methanol [4].

A majority of research in the field of syngas utilization have been focused on its use as a direct fuel in integrated gasification combined cycle (IGCC) [4–10] and in the fuel and chemical production, where syngas is used as an intermediate product [4]. However, internal combustion engine (ICE) is the most vital technological advancement, playing a major role in the distributed energy power generation for a variable power output requirement. It has very flexible application in moving and stationary machineries. Compared to other types of combustion technologies, ICE is believed to have benefits like low capital cost, reliability, good part-load performance, high operating efficiency, and modularity and is quite safe to use. Because of this, utilization of syngas in these engines is noteworthy; yet research in this area has been very limited [4, 11]. The constituent of syngas that comes from gasification lacks consistency. Besides, there were misconceptions about syngas autoignition tendency at higher compression ratios and power derating which later were explained elsewhere [11, 12]. These were the two reasons for the lack of adequate research in the area.

2. Technological Development

The era of using oils (such as olive, sesame, nut fish, whale, and beeswax) for lighting was transformed into gas lighting at the end of 18th century. Initially streets used to get light from the hanging of door lamps facing the street. The idea of public street lighting was initiated after the discovery of flammable gas from coal by William Murdoch, who first used it to light his house in 1792. This was further strengthened by Frederick Albert Winsor, who got first patent in coal gas lighting in 1804 [17]. In 1799, a French engineer and chemist, Philippe Lebon patented his "thermolamp" which burned a distilled gas from wood [18]. This was the cornerstone for technological development of gasification and application of its products for lighting. This technology was later expanded to elsewhere to the Westminster Bridge (London) in 1813 and the city of Baltimore, MD, in the USA in 1816. It was further spread into major industries for lighting so that productivity could be stretched into the night shift [3].

The application of this gas in automotive technology was possible in the 1920s. In 1923, for instance, a French inventor Georges Imbert (1884–1950) developed a wood gas generator for mobile application [19]. Up to 9,000 vehicles were produced with Imbert technology until the end of 1930s [20]. In the later years, mass production of automobiles with this technology continued including companies like General Motors, Ford, and Mercedes-Benz.

World War II led to the shortage of gasoline and as a result development of wood gas vehicles expanded all over the world, which saw production of more than a million of such vehicles [20]. The number of cars running on producer gas at the time of WW II was estimated at 7 million [21]. Germany was leading with over 500,000 vehicles on the ground. Countries like Sweden, France, Denmark, Austria, Norway, and Switzerland were also on the list [20].

Petrol domination at the end of 1940s led to a quick exit of these Imbert-technology engines from the market. Since then, application of syngas shifted into integrated gasification combined cycle as a stationary power generation system. However, even at the moment, certain countries have not totally given up on the use of such fuel in mobile engine applications. USA is promoting the application of this technology as a backup energy supply source in the event the country faces petroleum crisis [22].

3. Syngas in Stationary Power Plant

Since the end of World War II, research and development on syngas application have shifted focus into stationary power generation. On top of this, coal, which is a prime fuel for steam and gas power plants, has been branded the most environmentally pollutant fuel. This has forced countries to draw stringent regulations on direct firing of coal and other solid fuels [2]. These two factors led to research into upgrading of solid fuels. Besides reducing pollutant emissions, the upgrading process of solid fuels through the gasification process has other advantages such as easy handling and flexibility of feedstock ranging from agricultural residue to municipal waste. The earlier versions of gas turbines were primarily fuelled on natural gas. However, since the oil crisis of 1970s there have been many commercial installations of syngas fuelled integrated gasification combined cycle and gasification cofiring plants globally. The feedstock for most of them was coal and petroleum coke. There are also some installations with biomass and solid waste as feedstock. General Electric (GE) has led in the technology development of syngas and other lower calorific value gas turbine technology in the last 20 years. Up to 2007, GE was operating gas turbines with a total capacity of more than 3 GW in 15 plants (25 turbines) installed in USA, Canada, Singapore, Germany, Italy, The Netherlands, and Czech Republic [23].

Gas turbine burners have been designed for monocomponent gaseous fuels (such as compressed natural gas (CNG)) and as a result fuelling of syngas in such burners would lead to problems. The problems are associated with varied composition of component gases, high hydrogen content, and high volume flow rate requirements to maintain comparable gas turbine efficiency [9, 24]. These issues, in turn, lead to flashback, flame oscillation under lean operation, autoignition of hydrogen at higher temperature and pressure, component overheating, handling problem of high flow rate fuel in the combustor, and compressor instability. Summary of these problems are explained elsewhere [24]. Besides, there is risk of high nitrogen oxides (NOx) emission consequent to high reactivity of hydrogen component of the fuel. Many research efforts have been undertaken globally to tackle the aforementioned problems [8, 9, 23, 25].

Direct coupling of gas production and power generation plants such as gas turbine or ICE have technical and economical drawbacks. The gasifier must be sized to fit the syngas end-use (gas turbine or ICE) [26]. Besides, such direct coupling lacks the flexibility to run the two plants separately. Therefore, introduction of syngas storage will enable utility stations to operate their power plant during peak demand while running the gas production syngas as per production schedule. There are few researches on the introduction of a syngas storage system in an integrated gasification combined cycle and small scale gasification plants, in which, gas production and power generation work separately and independently [26–28]. Yang et al. [29] reported that syngas can be stored with no effect on the chemical composition under temperature range of −15°C to 45°C and pressure up to 83 bar [29]. Introduction of storage has both technical and economic advantage according to a study by the National Energy Technology Laboratory (NETL) [26]. In comparison with other storage mechanisms, the study by the National Energy Technology Laboratory also emphasized that storage through compressed gas technology has some advantages such as its large-scale applicability and the fact that is less expensive than other methods.

4. Syngas in Internal Combustion Engine

Engines are divided into mobile and stationary types depending on their applications. The engines used in stationary applications are of both internal and external combustion types while mobile type engines are only of internal combustion types. ICE is the most vital technological advancement, playing a major role in distributed energy power generation especially when there is a need for a variable power output. They have very flexible application in moving and nonmoving machineries. ICE is believed to have benefits like low capital cost, reliability, good part-load performance, high operating efficiency, and modularity and are quite safe to use as compared to other types of combustion technologies [4].

The prospect of syngas as a fuel in ICE is believed to be very promising and cost competitive when compared with natural gas [4]. ICE is more tolerant towards contaminants as compared to gas turbines. Even though they are not significant in number like in the area of IGCC, there are some research works in the area of syngas utilization in ICE. These researches can be categorized into spark-ignition (SI) application specifically in the naturally aspirated carbureted and port injection type and dual-fuel compression ignition (CI) engines. Carbureted and port injection engines mix the fuel and air prior to the combustion chamber and the volumetric efficiency of the engine drops at the cost of the voluminous syngas displacing air. Furthermore, they have higher pumping and heat losses as compared to direct injection (DI) SI engines, resulting in high fuel consumption [30]. Consequently, the theoretical power output of syngas-fuelled carbureted and port-injection engines is lower than those of gasoline and CNG. In DI systems, fuel is mixed with air in the combustion chamber and there is no restriction to the amount of air aspirated into the chamber. Apart from other engine operating parameters, syngas-fuelled engine with a DI system is expected to have better engine power output. However, based on an extended literature survey on DI SI fueled with syngas has never been studied.

4.1. Syngas as a Dual Fuel in CI Engine. Stringent regulations towards the emissions from diesel engines are restricting development of the most efficient ICE. Application of syngas in diesel engines is considered to be a viable alternative both for the emissions and energy crises. However, syngas has high self-ignition temperature (typically above 500°C) and as a result, it cannot be ignited by compression ignition in a diesel engine. A possible way of utilizing syngas in the CI engine is through dual fuelling, where diesel is injected as a pilot fuel to initiate the ignition while syngas injected into the induction system. The main motivation in using syngas and other gaseous fuels in diesel engine is as a substitute to diesel as this can consequently reduce cost, minimize emissions (NOx and particulate matters), and increase the engine performance.

There are many reports on research regarding syngas dual fuelling in CI engine. Azimov et al. [31] investigated the effect of H_2 and CO_2 contents in syngas on the performance and emission of a four-stroke single cylinder engine [31]. Diesel was used to assist the autoignition of syngas in a pilot-fuel mode under lean condition for a wide range of equivalence ratio (ϕ). The engine was supercharged and operated in a premixed mixture ignition in the end-gas region (PREMIER). PREMIER combustion was observed for all syngas fuels, mainly when the pilot fuel used is very small. This combustion was observed enhancing the performance and increasing the efficiency of dual fuelling. Furthermore, they reported that an increase in hydrogen composition in syngas shortened the main combustion duration and thereby causing an increasing in the mean combustion temperature, indicated mean effective pressure (IMEP), and efficiency. However, neither diesel could be completely substituted nor could syngas stand alone as a fuel in a diesel engine in the study.

Sahoo et al. [32] investigated the second law analysis of a single cylinder DI CI engine fuelled with syngas under a dual fuel mode, in which diesel served as a pilot fuel [32]. The effect of H_2/CO ratio on the dual fuel engine performance and thermomechanical availability of the engine was studied. The imitation syngas was composed of H_2 and CO mixed in a gas mixer and was charged into the gas carburetor. The experiment was conducted at different load conditions ranging from 20 to 100% with a 20% interval. They reported that the syngas dual fuel had a better work availability at higher loads as compared to diesel fuelling. Besides, an increase in the content of hydrogen in syngas improved the work availability of the dual fuelling. In a separate study, the same researchers [14] investigated the effect of H_2/CO ratio on the performance of a dual fuel engine under the same test conditions. The performance parameters examined in the study [14] were brake thermal efficiency, diesel substitution, pressure profile, maximum cylinder pressure, and exhaust gas temperature. In addition, the resulting emissions like CO, NOx, and hydrocarbon (HC) were also investigated. The syngas H_2 and CO composition were 50 : 50, 75 : 25, and 100% in volume percentage. They observed that an increase in H_2 in the syngas results in an increase in the brake thermal efficiency. The highest diesel replacement with syngas and maximum in-cylinder pressure was observed at 80% load with 100% H_2. On emissions, NOx was observed to increase with H_2 content in syngas. As anticipated, the CO emission was directly related to the CO content in syngas. The HC emission was found to be minimum with 100% H_2 [14].

Wagemakers and Leermakers [33] reviewed the effect of dual fuelling of diesel and different gaseous fuels on performance and emission [33]. CNG, liquid petroleum gas (LPG), syngas, and hydrogen were some of the gaseous fuels considered in their review. They reported that all gaseous fuels, when applied in diesel fuel combustion as dual fuel, could decrease soot emissions except for syngas. Reduction in NOx was reported when both CNG and LPG were used as primary fuels. However, combustion of syngas and hydrogen increased the NOx level as compared to diesel. Unburned hydrocarbons and CO emissions increased with dual fuelling of all the gaseous fuels as compared to diesel alone. With regard to the effect of these fuels on efficiency, hydrogen and LPG affected positively while syngas and CNG affected negatively [33].

The performance of a dual fuel mode compression ignition engine fueled by syngas with a composition of 10% H_2, 25% CO, 4% CH_4, 12% CO_2, and 49% N_2 and diesel (as pilot fuel) was compared with that of methane under the same duel fuel arrangement [34]. For both two fuel mixtures, a shift from diffusion flame combustion to propagation flame combustion was reported with reduction of the pilot diesel fuel. Overall, methane was shown to perform better as compared to syngas in the duel fuelling mode for diesel substitution [34].

In summary, a complete replacement of diesel fuel with syngas could not be possible. Besides, the performance of such dual-fuelling of syngas and diesel was poorer as compared to dual-fuelling of CNG and diesel. Therefore, syngas cannot be a reliable substitute to diesel fuel in CI engines. However, it can be used as a supplementary fuel to reduce cost and emissions of NOx and particulate matter.

4.2. Syngas Combustion in Carbureted and Port Injection SI Engines. The research and development of wood gas automotive technology have taken place since the last 100 years. However, there are still key technoeconomic barriers that hinder its commercialization [35]. To date, research in this category has been more or less a continuation of the World War II wood gas engine development. There are many researches on both experimental and numerical investigations of fuelling syngas in naturally aspirated carbureted and port injection engines. The research works can be broadly classified into comparison of syngas and CNG [36] and comparison of syngas and diesel [21] more specifically to the study of overall energy balance of syngas fuelling, performance, and emission studies. The fuelling setup used was a direct coupling of gasification with a carburetion system of the engine with a subsequent cleaning and cooling system integrated. Most of the studies used the conventional carburetor. However, Sridhar et al. [12, 15, 21] used a locally manufactured carburetor in their investigation to address the high volume flow rate of gaseous fuel [12, 15, 21]. They modified a diesel engine into spark-ignition configuration to obtain a higher compression ratio SI engine suitable for syngas combustion. The latest research studies on utilization of syngas (including producer gas and medium calorific value syngas) in carbureted and port injection SI engine are summarized here.

Sridhar [15] studied utilization of biomass derived producer gas in a high compression SI engine experimentally and numerically/analytically [15]. In their experimental investigation, they optimized the compression ratio for maximum brake power and efficiency by varying the compression ratios to 11.5 : 1, 13.5 : 1, 14.5 : 1, and 17 : 1. Besides, they analyzed the overall energy balance and the emission levels of CO and NO. The syngas used in their study was a producer gas with gas composition of 19 ± 1% H_2, 19 ± 1% CO, 2% CH_4, 12 ± 1% CO_2, 2 ± 0.5% H_2O, and rest N_2 and calorific value of 4.65 ± 0.15 MJ/Nm^3, respectively. They observed a smooth combustion process with a very low cyclic pressure variation. The producer gas experienced a short combustion duration prompting a retardation of ignition timing. With respect to power and efficiency, it was compared with diesel and reported with a power drop of 16% and 32%, respectively. Furthermore, a higher overall heat loss was reported for producer gas. NO emission was dependent on the compression ratio and ignition timing. Maximum NO emission was observed at the highest compression ratio and advanced ignition timing. On the contrary, minimum CO emission was observed at the highest compression ratio. The main attribute of the emission results was high temperature due to high compression ratio. This experimental work was also reported elsewhere [12, 21]. Even though the study clarified the misconceptions about the autoignition of producer gas, it was restricted to naturally aspirated carburetor engines. The study was also limited only to lower calorific value syngas (producer gas) [12, 15, 21].

Ahrenfeldt [37] studied the fuelling of biomass producer gas on a combined heat and power (CHP) engine and its long-term effect [37]. Emission, performance, efficiency, and other operating parameters were investigated when producer gas produced from three different gasification plants with their lower heating values 5.5, 6, and 12.1 MJ/Nm^3 were engaged in the combined heat and power operations. Based on the performance study, it was reported that producer gas is an excellent fuel for lean burn application; its lean limit was close to an excess air ratio (λ) of 3.00. There was no effect of variation of ignition timing on the power and efficiency. However, ignition timing was observed to affect the emission level of NOx. The emission level of NOx was reported to be low. On the other hand, CO emission was observed to be very high due to the higher content of CO in the fuel. On the combustion study, the coefficient of variation (COV) of the IMEP and mass fraction burn (MFB) remained constant for the producer gas even when λ increased.

Mustafi et al. [38] investigated performance and emission of power gas in a variable compression ratio SI engine and further compared it with that of gasoline and CNG. The composition of power gas was mainly H_2, CO, and CO_2 similar to that of medium calorific value syngas produced from the gasification of solid fuels. However, the production of this fuel was through Aqua-fuel process. The molar ratio of the fuel investigated was 0.52, 0.44, and 0.04 for CO, H_2 and N_2, respectively. The lower heating value of the gas was 15.3 MJ/kg. The stoichiometric air-fuel ratio of the gas was observed to be 4.2 as compared to 14.6 and 15.5 for gasoline and CNG, respectively. A Ricardo single cylinder SI engine with a variable compression ratio was modified to accompany a gas mixer, gas regulator, and needle valve setting to accommodate the fuel-air blending before the cylinder. On their comparison of power output of this gas at different compression ratios, an improvement of 22% was reported by increasing the compression ratio from 8 : 1 to 11 : 1. The power output of this gas, gasoline and CNG was compared at constant speed of 1500 rev/min. It was reported that the brake torque of power gas was 30% and 23% lower than that of gasoline, and CNG, respectively. The fuel consumption was also compared and power gas was requiring 2.7 and 3.4 times more than that of gasoline and CNG, respectively. However, consumption was not affected with the change in compression ratio. Emissions of total hydrocarbon (THC) and CO of power gas were observed lower than for gasoline and CNG. However, CO_2 and NOx emissions were higher than all these fuels. These experimental results were compared with simulation model and were found to be consistent at all conditions [38].

Papagiannakis et al. [39] have numerically modeled the combustion process of a four-stroke, turbocharged, water-cooled, multicylinder SI GE Jenbacher 320 engine fuelled with syngas [39]. The fuel is a product of gasification of wood with a volume percentage composition of 19% H_2, 29% CO, 6% CH_4, 8% CO_2, and 38% N_2. The two-zone model predicted in-cylinder pressure profile, heat release rate, nitric oxide (NO), and CO concentrations. The model results were validated by the experimental results from the same engine operated at constant speed of 1500 rev/min at four conditions of 40, 65, 85, and 100% of full load. Their observation mainly focused on the validation of the numerical model. Moreover, they discussed the combustion, performance, and emission characteristics of syngas in comparison with CNG. However, the study was more focused on the numerical model validation than the effect of fuel property on the combustion, performance, and emissions. Similar reports on syngas with their main intention on predictive model validation could be found elsewhere [40–42].

A small-scale naturally aspirated single cylinder SI engine with compression ratio of 9.4 and 11.9 was used to test the performance of low-BTU gases produced from gasification and a two-step pyrolysis/reforming process. The gas produced from gasification was hydrogen rich with a lower calorific value (LCV) of 3.83 MJ/Nm^3 while from the two-step pyrolysis was methane rich with LCV of 4.2 MJ/Nm^3. The carburetor in the fuelling system was replaced with a gas mixer to adjust the air-fuel ratio. They reported that the two fuels had registered a similar thermal efficiency compared to CNG. Besides, the hydrogen-rich gas produced from gasification was reported with a wider stable engine operation λ up to 2.00. Compared to both CNG and the methane-rich pyrolysis gas, NOx and HC emissions were quite low with the hydrogen-rich gas. With the methane-rich gas, NOx was reported quite low too. There was no information about BSFC performance of the two fuels [43]. The study was limited to low-BTU gases only.

Shah et al. [44] have investigated the performance of a naturally aspirated, single-cylinder, four-stroke, SI engine with a capacity of 5.5 kW fuelled with syngas [44]. This fuel composition was 16.2–24.2% CO, 13–19.4% H_2, 1.2–6.4% CH_4, 9.3–13.8% CO_2, and balance N_2 with a lower heating value of 5.79 MJ/Nm^3. It was compressed to a pressure of 15 bar and stored in LPG tank before fueled in the engine. The performance parameters used in this study were power output, overall efficiency, and run duration of the engine by syngas. Emissions such as CO, CO_2, HC, and NOx were also investigated. The overall efficiency of both syngas and gasoline was reported to be similar at their respective maximum power output (1.392 kW for syngas and 2.451 kW for gasoline). On the exhaust emissions side, CO was observed to be 30–96% lower with syngas compared to gasoline at each operation. This was attributed to the higher carbon content and rich operation in gasoline. For syngas, the CO emission was observed to increase with an increase in flow rate. The CO_2 concentration was reported to be 33–167% higher with syngas compared to gasoline operation. This was attributed to the CO_2 presence in syngas and the conversion of CO content in the fuel upon combustion. The CO_2 concentration was observed to increase with an increase in flow rate of syngas. The hydrocarbon concentration of exhaust emission of syngas was less than 40 ppm in all operations. This negligible content was attributed to the limited presence of HC in syngas. NOx emission in syngas operation was reported to be 54–94% lower compared to gasoline operation. This was attributed to lower cylinder temperature as a result of lower heating value of syngas. The NOx concentration versus flow rate profile was similar to that of power output curve. In this study, comparison was made only to gasoline. CNG was not considered. However, comparison of gaseous fuel with liquid fuel in internal combustion has its own constraints as per Sridhar and Yarasu [45]. Combustion characteristics were not investigated in the study. Besides, effects of ignition timing and air-fuel ratio on the combustion, performance, and emissions were not properly addressed.

Bika [46] studied varied ratios of H_2/CO syngas in a port injection SI engine and variable compression (4 : 1–18 : 1) for their combustion characteristics and knock limit [46]. The fuel was injected at 4 cms from the intake port. The fuels investigated are pure H_2, 75% H_2/25% CO, and 50% H_2/50% CO. The study was limited to ϕ = 0.6–0.8 and compression ratios of 6 : 1 to 10 : 1. It was reported that an increase in percentage of CO increased the knock limit of syngas.

The study also indicated that the increase in CO percentage has advanced the ignition timing of MBT. Maximum heat release rate was observed with pure hydrogen. The peak pressure was, however, observed to be more influenced by the compression ratio rather than by the CO percentage. The MFB was also observed broader with an increase with CO percentage. The overall conclusion of the study was that there was an increase in combustion duration with an increase in CO percentage. A maximum indicated thermal efficiency of 32% was reported with 50% H_2/50% CO at $\phi = 0.6$ and compression ratio of 10 : 1. The study was limited to combustion only. Performance and emissions of these fuels were not investigated.

In summary, reduction of torque was reported in most of the researches with syngas as compared to their fossil-based counterparts. This was more pronounced with the lower colorific value syngases (producer gases) as it demands higher volume of gas to produce equal amount of power produced from higher calorific value gases such as CNG and gasoline. Besides other combustion parameters, the main attribute to such power reduction was the volumetric efficiency penalty. An appreciable amount of air gets displaced by the lower calorific value syngas.

5. Current Engine Technologies

Over the years, ICE has passed through a lot of technological advancements. The engine fuelling system was among other parts which had huge attention. Early engines were fueled with a surface carburetion system where air passes over a stored fuel picking some from the surface [47]. Through the inspiration of this technology, other carburetion systems came to light over the years. In 1875, Siegfried Marcus invented a rotary-brush atomizer that operates through dropping of fuel in the air suction as a result of brush rotation over the fuel storage surface. Even though this technology was better at atomizing the fuel, the fuel entered into the combustion chamber without evaporation. This shortcoming was addressed through the invention of wick carburetor by Frederick William Lanchester in 1896. A wick was extended from fuel storage chamber to the air passage chamber. As a result, fuel passed from the bottom of the wick into the upper chamber where it evaporated. The incoming air in the upper chamber mixed with the evaporated fuel and sucked into the combustion chamber [48]. The introduction of float type carburetors by Wilhelm Maybach and Gottlieb Daimler as cited in Barach [48].

The float type carburetor, also called simply carburetor, was dominant technology over 90 years up to 1980s with a continuous upgrading over the years. This technology became very complex as it had to include many circuits to accommodate the demands of high efficiency and low emissions. Even though it is still the cheapest fuelling technology, it has been phased out and replaced with other technologies due to its inefficiency and lack of attaining the current emission standards. However, it is still operational in countries where emission regulation is weak [49].

After the era of carburetor, fuel injection systems became the primary technology to deliver fuel into the chamber. In this technology, atomization of the fuel is done by forcing the fuel through a narrow nozzle with the help of high pumping pressure. The early fuel injection system was a throttle body fuel injection system where an electronically controlled injection system was added to the throttle body. This design was later modified into port injection system where every cylinder was equipped with fuel injectors that spray fuel near the inlet valve. Even though the multipoint/port injection is by far better technology than the carburetor in fuel metering, it still needs more time to completely mix fuel and air before entering the combustion chamber [50]. This further impinges negatively on the fuel efficiency of the engine. Such limitation has prompted for the adaptation of DI technology from diesel engines. In the DI SI engine, high-pressure fuel is delivered into a common rail, from where it is injected direct into the cylinder via fuel injectors. Due to the high pressure and injector nozzle interaction, the fuel is atomized in the cylinder with a varied degree of penetration depending on the angle of the injectors. This technology is fuel efficient, allowing precise control system that puts century-old ICE still in a better position compared to hybrid and electric vehicles.

With the emergence of DI application in SI engines, lean combustion strategy has become a means for the reduction of greenhouse gas emissions and an increase in thermal efficiency [30, 51–53]. This strategy is mainly accompanied with fuel stratification so that variable air-fuel ratio occurred around the combustion chamber. The stratification provides a relatively rich mixture near the igniter and a uniformly mixed ultralean mixture all over the cylinder [30]. Engine performance reduction due to volumetric efficiency drop can also be overcome by injecting the fuel very late after inlet valve closes (IVC). However, this may lead to insufficient time for fuel-air mixing and slow combustion rate. For the fast burning type fuels, this is the type of fuel injection strategy that has been adopted and it has attracted much attention these days.

CNG DI had been under intensified research and development since the 1970s. Previous research and development of natural gas vehicles (NGV) was focusing on modification of the existing petrol engines. However, currently there is an increasing trend on the application of original equipment manufacturer (OEM) vehicles for natural gas vehicle (NGV) with DI technology getting mature and the demand of NGV increasing [54]. Currently, the global NGV vehicle is estimated at 20.21 million with 21,400 refueling stations [55]. However, syngas-fuelled DI engine has not been investigated before.

6. Potential of Syngas in Current Engine Technologies

The success of syngas reported in old ICE needs to be investigated for the reinstatement of the fuel in the current engine technology. Syngas produced from gasification of biomass lacks consistency in the percentage composition of constituent gases [21]. There are many varieties of syngas

Table 1: Supplied syngas composition.

Component	Syn1 (V%)	Syn2 (V%)	Syn3 (V%)
Hydrogen	50	40	19.16
Carbon monoxide	50	40	29.60
Methane	0	20	5.27
Carbon dioxide	0	0	5.41
Nitrogen	0	0	40.56

products stated in the literature. The quality of syngas produced from gasification is mainly dependent on the gasifying agent used in the process. A low calorific value syngas (producer gas) of H_2, CO, CH_4, CO_2, and N_2 of varied proportion as constituent gases are generated if air is used as gasifying agent. If steam or oxygen is used instead of air, a medium calorific value syngas with H_2, CO, and CH_4 of varied proportions as constituent gases are produced [2]. In order to understand the suitability of syngas in the current engine technologies, representative of the abovementioned category of syngases, various compositions of syngases should be investigated for their combustion characteristics. Table 1 shows three different syngases selected from the lower and medium calorific value syngases for a case study.

Detailed knowledge of the properties of fuels helps selection of appropriate operating parameters for an internal combustion engines. In this section, properties of three different types of syngases were investigated for their properties. CNG and hydrogen two major gaseous fuels with their combustion and performance in the current engine technologies were widely investigated. Their potential and foreseeable challenges have been studied by different researchers [30, 56–60]. The combustion of CNG is less complete resulting in lower performance coupled with higher CO and THC emissions. They are attributed to the lower laminar flame velocity, narrow combustible range, high ignition energy requirement, and higher self-ignition temperature [30]. Even with such shortcomings, this fuel is currently serving its purpose as stated in Section 5. On the other hand, hydrogen has greater advantage with the greenhouse gas emission due to its clean combustion. However, usage of this fuel is hindered due to its high production cost, difficulty in its storage, high flame speed, and high flame temperature leading to unstable combustion and knock [58]. The properties of these syngases were compared with those of CNG and hydrogen to assess the suitability of this fuel in the current engine technologies. Table 2 shows the detailed comparison of properties of three syngases, CNG, and hydrogen.

The fuel properties for the three syngases listed in Table 2 are mostly calculated based on their species except for the laminar flame velocity and autoignition temperature. The hydrogen-to-carbon ratio (H/C) is the main factor in the production of the greenhouse gas emissions from the combustion of fuels [30]. An increase in H/C leads to reduced production of CO_2 and increased production of H_2O in the combustion products. To this end, hydrogen is free of greenhouse gas emissions. H/C of gasoline, CNG, Syn1, Syn2, and Syn3 are calculated to be 1.85, 4, 2, 2.67, and 1.45, respectively. Syn1 and Syn2 have better greenhouse gas emission performance as compared to gasoline. Besides, syngases are considered to be carbon neutral fuels especially if they are produced from biomass and solid waste gasification. Syngases are also oxygenated fuels resulting in a clean burning and an improved power and efficiency.

Syngases have lower calorific value compared to CNG. However, all syngases have better stoichiometric mixture energy density as compared to CNG in an air aspirating (direct-injection) engines as shown in Table 2. The energy obtained from the combustion chamber is more influenced by the mixture energy density than by the lower calorific value of the fuel [13]. Therefore, the performance of a direct-injection syngas powered engine is expected to be improved as compared to the naturally aspirated carbureted and port injection engines.

Syngases have also wider flammability range as compared to CNG. This property is responsible for COV of the IMEP of the combustion of the fuel. It is a measure of the extent of misfiring of the combustion. Therefore, syngases are expected to have lower COV. Additionally, syngases have higher autoignition temperature as compared to hydrogen and CNG. This will make them favorable for high compression engine application with no incident of knock. Similar observation was reported by Sridhar et al. [21]. The moderate laminar flame velocity of syngases improves the slow combustion reported with CNG and the unstable combustion reported with hydrogen.

Syngases, especially the medium calorific value syngases, have an adiabatic flame temperature close to that of hydrogen leading to higher NOx emissions. Moreover, syngases have extremely low stoichiometric air-fuel ratio as compared to CNG and H_2. This could result in high brake specific fuel consumption (BSFC). These fuels cannot be operated near stoichiometry as it is impossible to completely inject the amount of fuel that makes stoichiometric air-fuel ratio especially for fuels similar to Syn3. A lean charge direct-injection needs to be adapted to avoid the high NOx emissions and the higher BSFC of such fuels. However, the mixture energy density of a lean homogenous mixture of syngases will be very low leading to misfiring and demanding higher ignition energy. A charge stratification strategy can be followed to reduce the combustion misfiring. Such fuel stratification can only be attained through late injection of the charge after the inlet valve closes in the direct-injection spark-ignition engines. Nevertheless, late injection of syngases with low and medium calorific value leads to limitation of injection duration thereby limiting power output. Only the medium calorific value syngases (similar to Syn1 and Syn2) can deliver comparable power and torque output to their CNG counterparts. The lower calorific value syngases (similar to Syn3) may be feasible in older engines such as the naturally aspirated carbureted and port injection engines. However, their demand for longer injection duration in direct-injection engines and their associated lower mixture energy density at lean operation makes them less favorable in current engine technology.

Table 2: Properties of different syngases and their comparison to CNG and H_2.

Properties	Syngases Syn1	Syngases Syn2	Syngases Syn3	CNG	H_2
Composition, weight %					
Carbon	40.0	47.37	21.15	75.0	0.0
Hydrogen	6.67	10.53	2.56	25.0	100
Oxygen	53.3	42.1	28.3	0.0	0.0
Nitrogen	0.0	0.0	48.5	0.0	0.0
Molecular weight (g/mol)	15.0	15.2	23.2	16.04	2.02
Density at 0°C and 1 atm (kg/m^3)	0.67	0.68	1.04	0.75	0.09
Specific gravity at 0°C and 1 atm	0.52	0.53	0.8	0.58	0.07
Stoichiometric air-fuel ratio					
Molar basis	2.38	3.81	1.66	9.7	2.38
Mass basis	4.58	7.23	2.07	17.2	34.3
Stoichiometric volume occupation in cylinder, %	29.6	20.8	37.6	9.35	29.6
Lower calorific value					
MJ/Nm^3	11.65	16.48	7.67	38.0	10.7
MJ/kg	17.54	24.4	7.47	47.1	120.2
Stoichiometric Mixture Energy density (MJ/Nm^3)					
Mixture aspirated	3.3	3.25	2.73	2.9 [13]	3.2 [13]
Air Aspirated	4.45	3.92	4.19	3.60 [13]	4.54 [13]
Flammability limit, % vol. of fuel in air					
Lower	6.06	5.8	13.4	5.3	4.0
Higher	74.2	41.4	57.9	15.0	74.2
Laminar flame velocity (cm/s)	180 [14]	N/A	50 [15]	30	210
Adiabatic flame temperature, K	2385	2400	2200	2220	2383
Autoignition temperature, K	873–923	873–923	898	813 [16]	858 [16]

7. Conclusions

(i) The direct-injection fuelling system technology and high compression ratio of the latest spark-ignition engines, improvement in conversion efficiency, and advancement in the cleaning process of gasification, the introduction of syngas storage, and thereby separation of gas production and power generation are the motivating factors for syngas to be a fuel in current engine technologies.

(ii) Stratified lean charge combustion is an effective way of powering syngas in the current engine technology to address the problems of stoichiometric charge application caused due to very small stoichiometric air-fuel ratio. However, care should be taken to the limitation on the power caused due to limited injection duration. Further investigation of the optimization of injection timing, fuel composition, air-fuel ratio, and ignition advance needs to be done for better performance and emissions.

(iii) The problem associated with the higher BSFC of syngases need to be addressed mainly on the design of storage systems. The calorific value of CNG is three to ten times that of syngases. This has huge implication on the storage system in order to have the same driving range to CNG counterpart.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This work was supported by the Centre for Automotive Research and Electric Mobility (CAREM), Universiti Teknologi PETRONAS, and Educational Sponsorship Unit, PETRONAS Carigali Sdn Bhd.

References

[1] G. J. Stiegel and R. C. Maxwell, "Gasification technologies: the path to clean, affordable energy in the 21st century," *Fuel Processing Technology*, vol. 71, no. 1–3, pp. 79–97, 2001.

[2] P. Basu, *Biomass Gasification and Pyrolysis: Practical Design and Theory*, Elsevier, New York, NY, USA, 2010.

[3] G. A. Richards and K. H. Casleton, "Gasification technology to produce synthesis gas," in *Synthesis Gas Combustion Fundamentals and Applications*, T. Lieuwen, V. Yang, and R. Yetter, Eds., CRC Press, 2010.

[4] G. A. Richards, K. H. Casleton, and N. T. Weiland, "Syngas Utilization," in *Synthesis Gas Combustion Fundamentals and Application*, T. Lieuwen, V. Yang, and R. Yetter, Eds., pp. 197–222, Taylor and Francis, Boca Raton, Fla, USA, 2010.

[5] M. Baratieri, P. Baggio, B. Bosio, M. Grigiante, and G. A. Longo, "The use of biomass syngas in IC engines and CCGT plants: a comparative analysis," *Applied Thermal Engineering*, vol. 29, no. 16, pp. 3309–3318, 2009.

[6] H.-T. Kim and B.-C. Choi, "Stability of coal derived sysgas combustion for the application in IGCC system," in *Proceedings of the 224th ACS National Meeting*, pp. 593–595, August 2002.

[7] H. Boerrigter and R. Rauch, "Review of applications of gases from biomass gasification," in *Handbook Biomass Gasification*, H. A. M. Knoef, Ed., pp. 211–230, Biomass Technology Group (BTG), 2006.

[8] D. Sánchez, R. Chacartegui, J. M. Muñoz, A. Muñoz, and T. Sánchez, "Performance analysis of a heavy duty combined cycle power plant burning various syngas fuels," *International Journal of Hydrogen Energy*, vol. 35, no. 1, pp. 337–345, 2010.

[9] S. Daniele, P. Jansohn, and K. Boulouchos, "Experimental investigation of lean premixed syngas combustion at gas turbine relevant conditions: lean blow out limits, emissions and turbulent flame speed," in *Proceedings of 32nd Annual Meeting of the Italian Section on the Combustion Colloquia*, Napoli, Italy, 2009.

[10] K. Stahl, L. Waldheim, M. Morris, U. Johnsson, and L. Gardmark, "Biomass IGCC at varnamo at Sweden: past and future," in *Proceedings of the GCEP Energy Workshop*, Frances C. Arrillaga Alumni Center, Stanford University, Palo Alto, Calif, USA, 2004.

[11] S. Dasappa, P. J. Paul, H. S. Mukunda, N. K. S. Rajan, G. Sridhar, and H. V. Sridhar, "Biomass gasification technology: a route to meet energy needs," *Current Science*, vol. 87, no. 7, pp. 908–916, 2004.

[12] G. Sridhar, H. V. Sridhar, S. Dasappa, P. J. Paul, N. K. S. Rajan, and H. S. Mukunda, "Development of producer gas engines," *Proceedings of the Institution of Mechanical Engineers D*, vol. 219, no. 3, pp. 423–438, 2005.

[13] H. Eichlseder, T. Wallner, R. Freymann, and J. Ringler, "The Potential of Hydrogen Internal Combustion Engines in a Future Mobility Scenario," SAE Paper 2003-01-2267.

[14] B. B. Sahoo, N. Sahoo, and U. K. Saha, "Effect of H2:CO ratio in syngas on the performance of a dual fuel diesel engine operation," *Applied Thermal Engineering*, vol. 49, pp. 139–146, 2012.

[15] G. Sridhar, *Experiments and Modelling Studies of Producer Gas based Spark-Ignited Reciprocating Engines [Ph.D. thesis]*, Department of Aerospace Engineering, Faculty of Engineering, Indian Institute of Science, Bangalore, India, 2003.

[16] M. A. Escalante Soberanis and A. M. Fernandez, "A review on the technical adaptations for internal combustion engines to operate with gas/hydrogen mixtures," *International Journal of Hydrogen Energy*, vol. 35, no. 21, pp. 12134–12140, 2010.

[17] D. Redler, "History: 19th century-the gaslight era. Compulite-Danor Stage-Lighting-Museum," 2012, http://www.compulite.com/stagelight/html/history-4/history-4-text.html.

[18] P. D. Smith, "Bright Lights, Big City," 2012, http://www.peterdsmith.com/bright-lights-big-city/.

[19] S. E. ry, "Puukaasun historiaa," 2012, http://www.ekoautoilijat.fi/tekstit/historiaa.htm.

[20] K. D. Decker, "Wood gas vehicles: firewood in the fuel tank," 2010, http://www.lowtechmagazine.com/2010/01/wood-gas-cars.html.

[21] G. Sridhar, P. J. Paul, and H. S. Mukunda, "Biomass derived producer gas as a reciprocating engine fuel: an experimental analysis," *Biomass and Bioenergy*, vol. 21, no. 1, pp. 61–72, 2001.

[22] H. LaFontaine and G. P. Zimmerman, *Construction of a Simplified Wood Gas Generator for Fueling Internal Combustion Engines in a Petroleum Emergency*, Federal Emergency Management Agency, Federal Emergency Management Agency, Washington, DC, USA, 1989.

[23] K. Payrhuber, "Gas Turbine for Syngas," in *the Freiberg Gasification Conference*, Freiberg, Germany, 2007.

[24] T. B. Gibbons and I. G. Wright, "A review of Materials for gas turbines firing syngas fuels," U.S. Department of Energy, 2007.

[25] P. Kutne, R. Sadanandan, and W. Meier, "Experimental analysis of the combustion behaviour of syngas mixtures in a gas turbine model combustor under elevated pressure," in *Proceedings of the European Combustion Meeting*, Vienna, Austria, 2009.

[26] J. Apt, A. Newcomer, L. B. Lave, S. Douglas, and L. M. Dunn, *An Engineering-Economic Analysis of Syngas Storage*, National Energy Technology Laboratory, 2008.

[27] S. Hassan, Z. A. Zainal, and M. A. Miskam, "A preliminary investigation of compressed producer gas from downdraft biomass gasifier," *Journal of Applied Sciences*, vol. 10, no. 5, pp. 406–412, 2010.

[28] A. Newcomer and J. Apt, "Storing syngas lowers the carbon price for profitable coal gasification," *Environmental Science and Technology*, vol. 41, no. 23, pp. 7974–7979, 2007.

[29] P. Yang, E. P. Columbus, J. Wooten et al., "Evaluation of syngas storage under different pressures and temperatures," *Applied Engineering in Agriculture*, vol. 25, no. 1, pp. 121–128, 2009.

[30] H. M. Cho and B.-Q. He, "Spark ignition natural gas engines: a review," *Energy Conversion and Management*, vol. 48, no. 2, pp. 608–618, 2007.

[31] U. Azimov, E. Tomita, N. Kawahara, and Y. Harada, "Effect of syngas composition on combustion and exhaust emission characteristics in a pilot-ignited dual-fuel engine operated in PREMIER combustion mode," *International Journal of Hydrogen Energy*, vol. 36, no. 18, pp. 11985–11996, 2011.

[32] B. B. Sahoo, U. K. Saha, and N. Sahoo, "Theoretical performance limits of a syngas-diesel fueled compression ignition engine from second law analysis," *Energy*, vol. 36, no. 2, pp. 760–769, 2011.

[33] A. M. L. M. Wagemakers and C. A. J. Leermakers, "Review on the Effects of Dual-Fuel Operation, Using Diesel and Gaseous Fuels, on Emissions and Performance," SAE Paper 2012-01-0869.

[34] C. T. Spaeth, *Performance characteristics of a diesel fuel piloted syngas compression ignition engine [Master of Applied Science]*, Department of Mechanical and Materials Engineering, Queen's University, 2012.

[35] P. Hutton, "Powering an Engine Generator with a Biomass Gasifier. Biomass Magazine," 2011, http://biomassmagazine.com/articles/5301/powering-an-engine-generator-with-biomass-gasifier.

[36] P. P. Parke and S. J. Clark, "Biomass producer gas fueling of internal combustion engines naturally aspirated and supercharged mixtures," ASAE Paper 81-3593, 1981.

[37] J. Ahrenfeldt, *Characterization of biomass producer gas as fuel for stationary gas engines in combined heat and power production [Degree for Doctor of Philosophy]*, Department of Mechanical Engineering, Technical University of Denmark, 2007.

[38] N. N. Mustafi, Y. C. Miraglia, R. R. Raine, P. K. Bansal, and S. T. Elder, "Spark-ignition engine performance with "Powergas" fuel (mixture of CO/H_2): a comparison with gasoline and natural gas," *Fuel*, vol. 85, no. 12-13, pp. 1605–1612, 2006.

[39] R. G. Papagiannakis, C. D. Rakopoulos, D. T. Hountalas, and E. G. Giakoumis, "Study of the performance and exhaust emissions of a spark-ignited engine operating on syngas fuel," *International Journal of Alternative Propulsion*, vol. 1, pp. 190–215, 2007.

[40] B. Gamiño and J. Aguillón, "Numerical simulation of syngas combustion with a multi-spark ignition system in a diesel engine adapted to work at the Otto cycle," *Fuel*, vol. 89, no. 3, pp. 581–591, 2010.

[41] F. Centeno, K. Mahkamov, E. E. Silva Lora, and R. V. Andrade, "Theoretical and experimental investigations of a downdraft biomass gasifier-spark ignition engine power system," *Renewable Energy*, vol. 37, no. 1, pp. 97–108, 2012.

[42] F. O. C. Gonzalez, K. Mahkamov, E. E. S. Lora, R. V. Andrade, and R. L. Jaen, "Prediction by mathematical modeling of the behavior of an internal combustion engine to be fed with gas from biomass, in comparison to the same engine fueled with gasoline or methane," *Renewable Energy*, vol. 60, pp. 427–432, 2013.

[43] Y. Ando, K. Yoshikawa, M. Beck, and H. Endo, "Research and development of a low-BTU gas-driven engine for waste gasification and power generation," *Energy*, vol. 30, no. 11-12, pp. 2206–2218, 2005.

[44] A. Shah, R. Srinivasan, S. D. Filip To, and E. P. Columbus, "Performance and emissions of a spark-ignited engine driven generator on biomass based syngas," *Bioresource Technology*, vol. 101, no. 12, pp. 4656–4661, 2010.

[45] G. Sridhar and R. B. Yarasu, "Facts about producer gas engine," in *Paths to Sustainable Energy*, J. Nathwani and A. Ng, Eds., p. 664, InTech, 2010.

[46] A. S. Bika, *Synthesis Gas Use in Internal Combustion Engines [Ph.D. thesis]*, Faculty of Graduate School, University of Minnesota, St. Paul, Minn, USA, 2010.

[47] L. Mitchell, "Hubble, bubble... surface carburetors," 1999, http://earlymotor.com/leon/misc/html/surface.htm.

[48] J. Barach, "Fuel System. Automotive History," 2012, http://www.motorera.com/history/hist04.htm.

[49] R. Ilves and J. Olt, "Study of prior art of spark ignition engine fuel supply system," *Agronomy Researchm*, vol. 10, no. 1, pp. 55–74, 2012.

[50] B. B. Sahari, Y. Ali, F. l.R. Ahmadun et al., "Development of a prototype compressed natural gas direct injection vehicle: a Malaysian experience," in *Proceedings of the 12th IANGV Conference and Exhibition*, Rome, Italy, 2010.

[51] F. Y. Hagos, A. R. A. Aziz, S. A. Sulaiman, and Firmansyah, "Combustion characteristics of late injected CNG in a spark ignition engine under lean operating condition," *Journal of Applied Sciences*, vol. 12, pp. 2368–2375, 2012.

[52] R. L. Evans, "Extending the lean limit of natural-gas engines," *Journal of Engineering for Gas Turbines and Power*, vol. 131, no. 3, Article ID 032803, 2009.

[53] X. Mao, D. Wang, W. Xiao, Z. Liu, J. Wang, and H. Tang, "Lean limit and emissions improvement for a spark-ignited natural gas engine using a generalized predictive control (GPC)-based air/fuel ratio controller," *Energy and Fuels*, vol. 23, no. 12, pp. 6026–6032, 2009.

[54] M. Nijboar, *The Contribution of Natural Gas Vehicles to Sustainable Transport*, International Energy Agency, Paris, France, 2010.

[55] NGVJournal, "NFVs Worldwide. NGV Journal," 2013, http://www.ngvjournal.dreamhosters.com/statistics.

[56] S. E. Mohammed, M. B. Baharom, A. R. A. Aziz, and F. Firmansyah, "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 in CNG," *International Journal of Hydrogen Energy*, vol. 36, no. 18, pp. 11997–12006, 2011.

[57] Firmansyah, *Optimization of Injection Parameters in Compressed Natural Gas Direct Injection Spark Ignition Engine [Master of Science]*, Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 2007.

[58] C. M. White, R. R. Steeper, and A. E. Lutz, "The hydrogen-fueled internal combustion engine: a technical review," *International Journal of Hydrogen Energy*, vol. 31, no. 10, pp. 1292–1305, 2006.

[59] A. Mohammadi, M. Shioji, Y. Nakai, W. Ishikura, and E. Tabo, "Performance and combustion characteristics of a direct injection SI hydrogen engine," *International Journal of Hydrogen Energy*, vol. 32, no. 2, pp. 296–304, 2007.

[60] M. A. Abdullah, *Engine Performance and Combustion Characteristics of Hydrogen in A Direct Injection Engine [Master of Science]*, Mechanical Engineering, Universiti Teknologi PETRONAS, 2009.