Chapter

Alternative Fuels for Internal Combustion Engines

Mehmet Ilhan Ilhak, Selim Tangoz, Selahaddin Orhan Akansu and Nafiz Kahraman

Abstract

Researchers have studied on alternative fuels that can be used with gasoline and diesel fuels. Alternative fuels such as hydrogen, acetylene, natural gas, ethanol and biofuels also uses in internal combustion engines. Hydrogen in the gas phase is about 14 times lighter than the air. Moreover, it is the cleanest fuel in the world. On the other hand because of its high ignition limit (4–75%), low ignition energy, needs special design to use as pure hydrogen in internal combustion engines. It is proved that hydrogen improves the combustion, emissions and performance, when is added as 20% to fuels. Natural gas is generally consisting of methane (85–96%) and it can be used in both petrol and diesel engines. Ethanol can be used as pure fuel or mixed with different fuels in internal combustion engines. In this section, the effects of natural gas, hydrogen, natural gas + hydrogen (HCNG), ethanol, ethanol + gasoline, ethanol + hydrogen, acetylene, acetylene + gasoline mixtures on engine performance and emissions have been examined.

Keywords: internal combustion engines, hydrogen, acetylene, natural gas, ethanol

1. Introduction

Oil is the undisputed largest source of energy for internal combustion engines (ICE). However, rapid depletion of the oil due to the increasing number of vehicles, the pollutant emissions within its combustion products that threaten the ecological system and the concerns about the security of supply due to the oil reserves unevenly distributed over the globe, of which about 50% is located in the Middle East, encourages the exploration of fuel sources that are more environmentally friendly and have widespread reserves in the world [1].

Gasoline and diesel fuels that are produced from crude oil can also be produced synthetically from CO and H\(_2\) gases with the method found by the German chemists Franz Fischer and Hans Tropsch in 1923. Fischer-Tropsch synthesis, a patented method since 1926, provides obtaining synthetic liquid fuel from many different kinds of carbon and hydrogen-derived raw materials. Generally, coal, natural gas and methane are used to obtain large amounts of CO and H\(_2\) gases that are necessary for synthesis reactions. Today, Germany, India, China and South Africa that have major coal reserves produce commercially synthetic fuels with Fischer-Tropsch synthesis [2–4]. However, because the
compositions of the synthetic gasoline and diesel fuels are similar to the natural gasoline and diesel fuels, their effects on the pollutant emissions resulting from vehicles are also similar.

In this chapter, for the purpose of reducing pollutant emissions resulting from internal combustion engines, the characteristics of hydrogen, natural gas, acetylene and ethanol, which are alternative fuels and can be used without requiring a structural change in SI and CI engines, and their effects on engine performance

| Properties            | Acetylene | Hydrogen | CNG   | Ethanol | Gasoline | Diesel |
|-----------------------|-----------|----------|-------|---------|----------|--------|
| Formula               | C₂H₂      | H₂       | CH₄   | C₂H₅OH  | C₄–C₁₂   | C₆–C₂₀ |
| Density (1 atm, 20°C (kg/m³)) | 1.092     | 0.08     | 0.65  | 809.9   | 720–780  | 820–860 |
| Auto ignition temperature (°C) | 305       | 572      | 540   | 363     | 257      | 254    |
| Stoichiometric ratio (kg/kg) | 13.2      | 34.3     | 17.2  | 9       | 14.7     | 14.5   |
| Motor octane number   | 45–50     | 130      | 105   | 89.7    | 95–97    | –      |
| Flammability limits in air (%Vol.) | 2.5–81    | 4–74.5   | 5.3–15| 3–19    | 1.4–76   | 0.6–5.5 |
| Adiabatic flame temperature (K) | 2500       | 2400     | 2320  | 2193    | 2300     | 2200   |
| Min. quenching diameter (mm) | 0.85      | 0.9      | 3.5   | 2.97    | 2.97     | –      |
| Min. ignition energy (MJ) | 0.019     | 0.02     | 0.29  | 0.23    | 0.23     | –      |
| Maximum flame speed (m/s) | 1.5       | 3.5      | 0.42  | 0.61    | 0.5      | 0.3    |
| Lower heating value (kJ/kg) | 48.225    | 120.000  | 49.990| 26.700  | 43.000   | 42.500 |

Table 1. Physical and combustion properties of fuels [146–153].

| Fuels          | Resource | Expended energy [MJ/MJ fuel] | Greenhouse emissions [g CO₂/MJ] |
|----------------|----------|------------------------------|--------------------------------|
| Gasoline       | Crude oil| 0.18                         | 13.8                           |
| Diesel         | Crude oil| 0.20                         | 15.4                           |
| Natural gas    | EU-mix NG| 0.17                         | 13.0                           |
|                | Import. NG 7000 km | 0.29               | 22.6                           |
|                | Import. NG 4000 km | 0.21               | 16.1                           |
|                | LNG†       | 0.28                         | 19.9                           |
|                | Shale gas  | 0.10                         | 7.8                            |
|                | Synthetic from wind electricity | 1.05 | 3.3 |
| Ethanol        | Sugar†     | 1.20                         | 28.4                           |
|                | Wheat†     | 1.31                         | 55.6                           |
|                | Other†     | 1.66                         | 41.4                           |
| Hydrogen       | Natural Gas† | 1.10     | 118                           |
|                | Coal†      | 1.45                         | 237                            |
|                | Biomass†   | 1.05                         | 14.6                           |
|                | Electricity† | 3.11                      | 190                            |

†Average value.

Table 2. Energy and greenhouse gas balance in WTT analyses for EU (2010–2020+) [154].
and exhaust emissions are mentioned. The physical and chemical characteristics of gasoline, diesel fuel and alternative fuels that are mentioned in this chapter are shown in Table 1.

Fuels used in ICE are generally produced from primary resources. To convert a source to a fuel and bring this fuel to a vehicle, well to tank (WTT) analyzes are made in terms of energy consumption and greenhouse gas emissions. The energy and greenhouse gas balances obtained from WTT analyses based 2010–2020+ years for the alternative fuels in EU are shown in Table 2. When Table 2 is investigated according to fuel types, the maximum energy is consumed for the production of hydrogen gas and the minimum energy is expended for gasoline fuel. On the other hand when Table 2 has been compared in terms of resources, the highest energy consumption is obtained as 3.11 MJ/MJ by the using of electrolysis in hydrogen production, while the lowest energy consumption occurs as 0.1 MJ/MJ in the producing of shall gas removed from EU geography. It is seen from Table 2 that the highest CO₂ value is produced in the obtaining of hydrogen gas and the least emission value is emitted for gasoline fuel. In terms of resources, while the highest greenhouse emissions value is obtained as 237 g CO₂/MJ in hydrogen production from coal, the lowest greenhouse gas produce is 3.3 g CO₂/MJ in the producing of synthetic natural gas from wind electricity.

2. Acetylene

Acetylene was used as fuel in internal combustion engines in the early 1900s. Gustave Whitehead used a 15 kW engine powered by acetylene on his flying machine in 1901. Towards the year 1940s, acetylene began to be used in automobiles. In those years, about 4000 licenses for the conversion of vehicles to alternate fuels had been issued, and more than half of them were for conversion to acetylene [5]. Nowadays acetylene is only used in metal and chemical industries and it is not used in vehicles. Nevertheless, experimental studies on the use of acetylene in ICE have gained momentum in recent years due to high flame speed and energy density.

Acetylene was first discovered by Edmund Davy in 1836. But thereafter it was forgotten. Marcellin Berthelot rediscovered this hydrocarbon compound in 1860. He coined the name “acetylene” to this compound [6].

Acetylene, the first member of the alkynes (CₙH₂n−2), is a colorless and odorless gas but with an odor similar to garlic if produced from calcium carbide. Acetylene gas does not occur in quantities in nature but it is commonly obtained from the reaction of calcium carbide with water [7]. Calcium carbide (CaC₂) is produced by heating the mixture of quicklime and coke in electric arc furnaces to 2000–2100°C. Quicklime (CaO) is produced by heating calcium carbonate (CaCO₃) about at 900°C. Figure 1 shows a schematic representation of an integrated facility for the production of calcium carbide [8]. Moreover, the processes are seen in Eqs. (1) and (2) [8–10].

\[
\text{CaCO}_3 + \text{heat} \rightarrow \text{CaO} + \text{CO}_2 \quad (1)
\]

\[
\text{CaO} + 3\text{C} \rightarrow \text{CaC}_2 + \text{CO} \quad (2)
\]

Acetylene has higher flame speed and energy density than gasoline and diesel [11] hence acetylene engines could more approach thermodynamically ideal engine cycle efficiency. But the octane number of acetylene is lower than other fuels which use in internal combustion engines [12]. Therefore the maximum amount
of acetylene consumption is limited to the onset of knock. Lower ignition energy, high flame speed, wide flammability limits and lower octane number leads to premature ignition and undesirable combustion phenomenon called knock [13, 14]. These are the main problems encountered in using acetylene as a fuel in internal combustion engines.

In SI engines, acetylene and gasoline are either injected into the intake manifold or directly into the cylinder and the mixture is ignited by spark plug at the

![Diagram of calcium carbide production facility](image)

**Figure 1.**
Integrated calcium carbide production facility [8].

| Load (%) | Gasoline (g/h) | Acetylene (g/h) | Acetylene (%) | Peak Pressure (bar) | Spark Advance (CA BTDC) |
|----------|----------------|-----------------|---------------|---------------------|------------------------|
| 25       | 1877           | 0               | 0             | 16.6               | 21                     |
|          | 1320           | 500             | 27.5          | 16.5               | 13                     |
|          | 840            | 1000            | 54.3          | 15.6               | 2                      |
| 50       | 2805           | 0               | 0             | 25.4               | 18                     |
|          | 2145           | 500             | 18.9          | 26.5               | 11                     |
|          | 1800           | 1000            | 35.7          | 20.9               | 1                      |
| 75       | 3730           | 0               | 0             | 31.5               | 15                     |
|          | 3250           | 500             | 13.3          | 24.6               | 3                      |
|          | 2750           | 1000            | 26.7          | 23.8               | 0                      |
| 100      | 4265           | 0               | 0             | 40.6               | 11                     |
|          | 3890           | 500             | 11.6          | 30.9               | 1                      |
|          | 3390           | 1000            | 22.8          | 29.0               | -2*                    |

*2 CA After Top Dead Center

**Table 3.**
Mass flows of fuels, peak pressure and spark advance [18].
end of the compression stroke. In diesel engines, acetylene is either inducted along with intake air or injected directly into the cylinder and compressed. However, the mixture of acetylene-air does not auto-ignite due to its very high self-ignition temperature. A small amount of diesel fuel called pilot fuel is injected into the mixture towards the end of the compression stroke. The pilot diesel fuel auto-ignites first and ignites the acetylene-air mixture such as spark plug. So, dual fuel diesel engines combine the features of both SI and CI engines [15–17].

The main advantages of using acetylene as gasoline-acetylene mixtures in SI engines [5, 18–21]:

- Acetylene-gasoline mixtures can be used in SI engines at every load from low load to full load. However, it can be also used as a single fuel at partial loads.
If acetylene is mixed with gasoline under stoichiometric conditions, it causes a decrease in gasoline consumption at constant output power as seen in Table 3. At the same time, as can be seen Figure 2, hydrocarbon emissions were significantly reduced at all loads and as can be seen Figure 3, NO emissions were reduced at full loads according to working with gasoline [18]. Experimental studies [18] were realized at 1500 rpm and stoichiometric ratio under 25, 50, 75% and full load conditions. The acetylene was injected into the intake manifold of test engine through the gas injector 500 and 1000 g/h gas flow rates.

• Acetylene increases the poor combustion limit in partial loads in SI engines. The engine can be operated in leaner conditions with gasoline-acetylene mixtures. As seen in Figures 4 and 5 the brake thermal efficiency of the engine increases and the specific fuel consumption decreases. Further, at high equivalence ratios, the fairly reduced exhaust emissions are observed. NO emissions are almost non-existent as in-cylinder temperatures decrease in lean fuel-air

![Figure 4](image)

**Figure 4.**
The variation of BTE with excess air ratio (1500 rpm, 25% load) [19].

![Figure 5](image)

**Figure 5.**
The variation of BSFC with excess air ratio (1500 rpm, 25% load) [19].
mixtures and unburned hydrocarbon emissions are quite reduced when compared gasoline operation in SI engines as can be seen Figures 6 and 7. With the use of acetylene as an alternative fuel in SI engines, air pollution from SI engine vehicles in large cities can be significantly reduced [19].

- Acetylene operates in diesel engines with dual fuel mode by a little engine modification and while reduces NOx, HC, CO and CO2 emissions, contributing to a significant reduction in diesel fuel consumption [16]. Acetylene cannot be used as a single fuel in diesel engines due to the high compression ratio. In that study, the tests were conducted on a four-stroke diesel engine with a rated power output of 4.4 kW at 1500 rpm, with slight modification in intake manifold for holding the gas injector. The gas flow rates of 110, 180 and 240 g/h and optimized injection timings were arranged by ECU’s. Table 4 gives energy share ratio of diesel and acetylene at 240 g/h flow rate [16].

- In countries with large coal reserves and little or no oil reserves acetylene can be used in automobiles that form the largest part of vehicle traffic. Thus the country’s need for oil can be reduced.

The main disadvantages of acetylene as alternative motor fuel [22–26]:

- Acetylene is a very explosive gas which sensitive to pressure and temperature. For this reason, in vehicles that use acetylene as fuel should be security precautions taken seriously and should not be parked in closed areas.

- Acetylene is a fuel with very low ignition energy and may cause backfire in intake manifold.

- As the knock resistance of acetylene is low, the air-fuel ratio must be precisely adjusted to avoid knock.

- Acetylene can be used as the only fuel in SI engines only under very lean air-fuel mixture conditions. In very lean conditions, we cannot get maximum power out of the engine.

![Figure 6. The variation of NO with excess air ratio (1500 rpm, 25% load) [19].](image)
Storage of acetylene in vehicles is an unsolved problem yet. As acetylene is decomposed at a pressure of 2.5 bar, it cannot be stored as compressed gas like other gases. Acetylene is stored dissolved in acetone contained in a metal cylinder with a porous filling material under 18 bar pressure. When acetylene cylinders are empty, on-site filling is not possible. Therefore, disassembly and montage of the cylinder is a major disadvantage. Although manufactured in different sizes, cylinders that can be stored 8.7 m$^3$ acetylene have a volume of about 60 liters and average weighs (full) 70 kg\cite{27}. This situation causes great difficulties in practice.

Another method is to produce acetylene from carbide as in the 1940s and to use it without storage. This method requires a complex system as shown in Figure 1. Disposal of the residue called calcium hydroxide is another important problem of an on-board fuel generating system.

3. Natural gas

Natural gas is a fossil fuel found in nature reserves, associated or not with petroleum\cite{28}. The cost of obtaining from nature is lower than other fossil fuels. Natural gas consists of about 90% methane, 3% ethane, 3% nitrogen, 2% propane and other trace gases. Methane which is the always dominant component of natural gas is the

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Load (%) & Energy equivalent of diesel fuel (kW) & Energy equivalent of acetylene fuel (kW) & Energy share of gas (%) & Energy share of diesel (%) \\
\hline
0 & 4.01 & 3.21 & 44 & 56 \\
\hline
25 & 5.31 & 3.21 & 38 & 62 \\
\hline
50 & 7.79 & 3.21 & 29 & 71 \\
\hline
75 & 9.33 & 3.21 & 26 & 74 \\
\hline
100 & 10.39 & 3.21 & 24 & 76 \\
\hline
\end{tabular}
\caption{Energy share ratio of diesel and acetylene at 240 g/h\cite{16}.}
\end{table}
first member of alkane’s family. Since it has a high H/C ratio, natural gas is known as the cleanest fuel in fossil fuels. Due to its ecological benefits, city buses operate with natural gas engines in many countries. CO$_2$ gas, which should normally be between 180 and 280 ppm in the atmosphere, reached 405 ppm as of September 2018 due to overuse of fossil fuels [29]. Therefore, many countries encourage the use of natural gas instead of petrol and diesel fuel in vehicles. Because, natural gas mixes perfectly with air, it is easy to ignite, provides clean combustion and gives high heat. The thermal efficiency of natural gas engines is higher than that of gasoline engines due to these engines have a higher compression ratio than gasoline engines [28–35].

Unlike gasoline and diesel engines, natural gas-powered internal combustion engines do not require fuel enrichment in cold start, and exhaust emissions are not affected by low temperatures. Natural gas vehicles (NGV) produce emission values lower than the EURO 6 standard according to vehicles using petroleum-derived fuel [30].

According to NGV Global’s report, the number of NGV and filling stations in the world is increasing rapidly (Figures 8 and 9). China ranks first in the NGV Park with 6,080,000 vehicles and 8400 filling stations, according to 2018 data. In the number of NGV, Iran, India and Pakistan are the countries that come after China. The total number of NGVs reached to 26,130,000 as of June 2018 [31].

The biggest disadvantage for the NGV transportation sector comes from the storage challenge of natural gas. Natural gas is a lighter gas than air. While the density of air at sea level at 15°C is 1.225 kg/m$^3$, although the density of natural gas varies according to its composition, it is about 0.71 kg/m$^3$. As natural gas is a light gas the energy density per unit volume is low and in order to ensure a reasonable driving distance the storage volume should be chosen large. Fortunately, technology has developed and the natural gas has been begun to storage in steel or carbon tubes at a pressure of 200 bar with high pressure compressors. Parking of natural gas vehicles in enclosed spaces is dangerous for safety reasons. Nowadays, cars with natural gas engines have a range of more than 300 miles with a single filling. Also, natural gas is not a renewable energy source, like other fossil fuels [35–37].

High knock resistance of natural gas allows it to be used in engines with higher compression ratios as compared to gasoline engines. Operation of natural gas vehicles at higher compression ratios than gasoline vehicles increases the thermal

---

**Figure 8.**
Number of natural gas vehicles worldwide by years [31].
efficiency. As seen in Figure 10, in the tests carried out at different compression ratios with natural gas and natural gas-hydrogen mixtures (HCNG), the minimum fuel consumption for the compression ratio of 12.5 was obtained. Figure 11 shows that, THC emissions are lower than the Euro VI standards in all compression ratios [30]. The experiments have been carried out using a modified diesel engine having 9.6, 12.5 and 15 different compression ratios at 1500 rpm under full load conditions fueled by hydrogen enriched compression natural gas blends (100% CNG, 95% CNG + 5% H₂, 90% CNG + 10% H₂ and 80% CNG + 20% H₂). Engine performances
and emissions parameters have been realized at 10°CA BTDC ignition timing and different excess air ratios ($\lambda = 0.9–1.3$).

$NO_X$ values for $\lambda = 1.0$ and $\lambda = 1.15$ show in Table 5. As seen in the table, increasing of compression ratio and hydrogen fraction values lead to an increase in $NO_X$ values.

### 4. Ethanol

Ethanol is generally produced from renewable sources such as biomass and agricultural feedstock [38, 39]. So, ethanol has been used widely as alternative fuel in internal combustion engines. The octane number of ethanol is higher than the octane number of the gasoline. The high octane number of ethanol allows the use of ethanol as fuel in an SI engine with a higher compression ratio [40]. The latent vaporization heat of ethanol increases cooling effect in the cylinder, this situation leads to an increase in volumetric efficiency [41]. Ethanol burns cleaner than gasoline and diesel fuels and it produce less CO, CO$_2$, and NO$_X$. It has low diffusivity and ignition difficulty at low temperature, therefore combustion is not completed at low temperature and HC increases compared to gasoline in ethanol use. Ethanol chemical formulation is C$_2$H$_5$OH. Hydrogen percentage of ethanol is higher than gasoline.

Recently environmental authorities in large urban centers have expressed their concerns on the true effect of using ethanol blends of up to 20% in-use vehicles without any modification in the setup of the engine control unit (ECU), and on the variations of these effects along the years of operation of these vehicles [40].

Pure ethanol can be used internal combustion engines but there are some problems [42–45]. These problems are:

1. Ethanol has a low flame speed. So it has a bad cold-starting function. The using as fuel is hard in the winter months.

2. There is no passenger car designed for 100% ethanol. The use of pure ethanol can damage engines. Even engines that can work with gasoline-ethanol mixtures can reach up to 85% ethanol.
3. Ethanol is a corrosive fuel. So, the materials and surfaces of parts of combustion chamber, all plastic materials having contact with fuel and fuel injection system must be improved.

5. Hydrogen

Although hydrogen is the most common element in the world and it does not exist in nature in its pure state, so it has to be produced from sources like water and natural gas. The environmental impact and energy efficiency of hydrogen depends on how it is produced [46, 47].

Hydrogen has been studied as an alternative gas fuel for a long time. Hydrogen has not some problems associated with liquid fuels, such as vapor lock, cold wall quenching, inadequate vaporization and lean mixing. Hydrogen has clean burning behaviors. As hydrogen is burned, it produces mainly water. The combustion of hydrogen does not bring out toxic products such as hydrocarbons, carbon monoxide and carbon dioxide [48]. The most important advantage of hydrogen is that it does not produce CO₂ gas, which is one of the most important sources of global warming. In addition, hydrogen has a wider limit of flammability than gasoline, diesel and natural gas [49, 50]. Moreover, hydrogen has high flame speed and it has high self-ignition temperature [51]. Also, hydrogen can easily burn in ultra-lean mixtures [52]. The energy required to ignite the hydrogen-air mixture is only 0.02 MJ. Therefore, it is ideal for poor mixed burns [50]. Finally, hydrogen can be used at wide compression rates in internal combustion engines as the self-ignition temperature of hydrogen is too high [53]. Due to these properties, many studies have been carried out on the use of hydrogen in internal combustion engines [54–56].

Due to the low energy required for the ignition of hydrogen, the mixture immediately ignites when it comes into contact with a hot spot in the cylinder. As a result, knock may occur [56, 57]. As can be seen from Figure 12, another disadvantage of hydrogen is its low energy density [58]. In addition, the formations of NO₅ emissions are increased by hydrogen combustion due to high flame temperature [59, 60]. The increasing of NO₅ with hydrogen can be seen from Figure 13.

![Figure 12. The energy density of some fuels [145].](image-url)
The experiments in the study fueled by pure hydrogen and gasoline [61], in which Figure 13 was taken, carried out on a four-cylinder, four stroke, SI engine with carburetor, having 8.8:1 compression ratio. The ignition timing was set to 10° before top dead center (BTDC). The engine was run between 2600 and 3800 rpm engine speeds. In the experimental study [62], the tests were carried out at 1400 rpm engine speed, 61.5 kPa manifold air pressure, MBT spark timing and different excess air ratios (1.0–2.6). In this study, to simulate the hydroxygen, the hydrogen-to-oxygen mole ratio was fixed at 2:1 through adjusting the injection durations of hydrogen and oxygen. Moreover, three standard hydroxygen volume fractions in the total intake gas of 0, 2 and 4% were adopted in the tests.

6. Hydrogen mixture

Because of hydrogen has some negative effects on internal combustion engine, it is used as a mixture rather than pure. The most widely mixture of hydrogen is
HCNG. The mixture has been formed by the blending of natural gas. Natural gas-hydrogen mixtures (HCNG), which are considered as alternative fuels for conventional engines, are mixtures formed to combine the superior properties of natural gas and hydrogen. There are many studies [63–70] using HCNG as an alternative fuel.

As can be seen in Figure 14, the hydrogen adding causes an increase in thermal efficiency and causes an expansion of the flammability limits. In addition, when the figures are examined, it is seen that the addition of hydrogen increases the stability of combustion and the value of brake power and reduces the specific fuel consumption.

Figure 14. BTE, COV, power and BSFC values versus equivalence ratio at 2200 rpm, 50% WOT with MBT timing and different hydrogen percent [69].

Figure 15. Emission values versus equivalence ratio at 2000 rpm (a), 2400 rpm (b) and 2800 rpm (c) and different hydrogen rates [70].
Moreover, as can be seen in Figure 15, the addition of hydrogen to natural gas leads to a decrease in CO and HC emissions and an increase in NO\textsubscript{X} values. In the experimental study, in which Figure 15 was taken, the experiments were performed at 2000, 2400 and 2800 rpm with wide open throttle and varying the equivalence ratio. The engine with single-cylinder having 7.25:1 compression ratio was fueled by compressed natural gas, and mixtures of hydrogen in CNG as 5, 10, 15 and 20% by energy.

Another mixture made using hydrogen is the ethanol-hydrogen mixture. In the literature, it can be found many studies on the use of hydrogen and ethanol in internal combustion engines [71–85].

In the experimental study [85], in which Figure 16 was taken, the experiments were carried out on a compression ignition engine modified to run on spark ignition mode fueled with hydrogen-ethanol dual fuel combination with different percentage of hydrogen (0–80%) under compression ratio conditions of 7:1, 9:1 and 11:1 by varying the spark ignition timing at a constant speed of 1500 rpm.

In a study conducted with a mixture of hydrogen-acetylene, Sampath Kumar et al. [86] have been investigated the performance and the emission behaviors of SI

![Figure 16](image_url)

*Figure 16. The BSFC variations versus ignition timings at 7:1 and 11:1 compression ratios for different ethanol-hydrogen blend [85].*

![Figure 17](image_url)

*Figure 17. SFC and BTE values versus different fractions of hydrogen [87].*
engine fueled by hydrogen-acetylene fuel. The results indicated that brake thermal efficiency raised and emissions values descended when compared to gasoline.

In the another study, Tangöz et al. [87] have been analyzed the performance and emission values of an SI engine fueled by acetylene-hydrogen at a fixed BMEP value of 2.095 bar, a load of 30 Nm and an engine speed of 1500 rpm under lean mixture conditions ($\lambda = 1.3–2.8$). As can be seen from Figures 17 and 18, the experimental results showed that the values of specific fuel consumption are declined between 18.5 and 20.1% by hydrogen addition in the blend. The values of brake thermal efficiency are declined between 6.2 and 3.3% with the addition of hydrogen in the blend. The curves of cylinder pressure and heat release rate are advanced to top dead center by the adding of hydrogen to acetylene. The adding of hydrogen in acetylene leads to a decrease in CO and HC emissions and an increase in NO\textsubscript{X} values for fixed lambda.

7. Alternative fuels for new ICE applications

Today, one of the most important problems in the use of internal combustion engines is the production of harmful emission gases. For this reason, many studies have been carried out to reduce the emissions while maintaining engine performance, with new ICE applications such as HCCI, RCCI, PCCI and PPC. Moreover, for the purpose of reducing emissions, some of these studies focused on the use of alternative fuels. In these new engine applications have a process in which a homogeneous mixture of air and fuel is compressed under the conditions in which auto-ignition occurs close to the end of the compression stroke, followed by combustion, which is significantly faster than conventional diesel or Otto combustion. The auto-ignition and combustion phasing in cylinder are controlled by mixture stratification and fuel injection timing [88–93]. These engine applications compared to conventional engines allows to reduce nitrogen oxide and soot emissions and to achieve higher thermal efficiency [94–98]. However, it is very difficult to control the auto ignition in these engines. Many studies were carried out to control the auto ignition process in the engines by using alternative fuels having high auto ignition temperature or low reactivity or high octane number.

One of the most important new ICE applications is homogeneous charge compression ignition (HCCI). To control the auto ignition process in HCCI engine, some fuels having high auto ignition temperature use as alternative fuel. When these studies are examined, it is seen that the studies focused on the natural
gas [99–104], ethanol [105–108], acetylene [109–114] and hydrogen [115–122]. Reactivity controlled compression ignition (RCCI), premixed charge compression ignition (PCCI) and partially premixed combustion (PPC) are other new ICE applications. In the engine applications, the low reactivity fuel is introduced from port injection to form a homogeneous mixture in the cylinder, and the high cetane number fuel is injected directly into the cylinder to control the combustion phasing and duration. High octane fuels or low reactivity with resistance to spontaneous ignition are more favorable for RCCI, PCCI and PPC combustion. For this reason, most of the studies carried out on RCCI, PCCI and PPC engines are focused on natural gas [89, 123–133] and ethanol [134–144] as an alternative fuel.

As a result, the operation parameters such as fuel type, fuel composition, air fuel ratio and inlet temperature were observed to significantly affect working regime of the new ICE applications. However, it is considered that a complete framework for each ICE application modes has not been provided. Moreover, in spite of significant reduction in NO\textsubscript{X} and soot emissions is observed in the applications fueled by the alternative fuels, significant amounts of HC and CO emissions forming still remain problematic.

8. Conclusion

Acetylene has some suitable properties such as high energy density, high flame temperature, high flame speed and low emission production. For this reason, it is considered to be used as an important contribution fuel or alternative fuel in the future for internal combustion engine. It increases brake thermal efficiency while contribute to decrease fuel consumption and all emission values. However, some studies should be carried out to increase the knock resistance of acetylene. Moreover, efficient production methods and new storage methods need to be developed in order to use acetylene as an alternative fuel in vehicles. Finally, in order to determine whether acetylene is economical or not, well to tank analysis should be performed.

Looking at today’s applications, it is seen that natural gas fuel is a suitable fuel especially for SI engines having high compression ratio due to high knock resistance. Operation of natural gas vehicles at high compression ratios than gasoline vehicles decreases the BSFC. On the other hand, natural gas, the cleanest fossil fuel due to having high H/C ratio, provides more reduction in THC emission values than Euro VI standard when suitable compression ratio is met. However, the storage problem must be eliminated in order to be used in all engines. Moreover, studies should also be done to increase the energy density.

Ethanol has high octane number. However, it is expensive than fossil fuels and it has corrosive property. In addition, even engines that can work with gasoline-ethanol mixtures can reach up to 85% ethanol. Ethanol can be blended to other alternative fuel to improve the energy density. Ethanol burns cleaner than gasoline and diesel fuels and produces less CO, CO\textsubscript{2} and NO\textsubscript{X} but HC increases due to it has low diffusivity and ignition difficulty at low temperature.

Hydrogen is a clean fuel and the mass energy density is very high. Fast burning characteristics of hydrogen permits high speed engine operation and less heat loss occurs for hydrogen than gasoline. NO\textsubscript{X} emission of hydrogen fuelled engine is about 10 times lower than gasoline fuelled engine if it works lean conditions. Because of hydrogen has some disadvantages such as very low ignition energy and volume energy density, it is mixed with other fuels especially natural gas to use in SI engines. Intensive studies such as the use of hydrogen in a liquid state should be done to solve the storage problems in order to achieve the desired level of use in internal combustion engines. Also, the methods or mixtures that reduce NO\textsubscript{X} formation should be studied.
In spite of significant reduction in NO\textsubscript{X} and soot emissions is observed in the new ICE applications such as HCCI, RCCI, PCCI and PPC fueled by the alternative fuels, significant amounts of HC and CO emissions forming still remain problematic.

Consequently, each fuel has positive and negative properties for use in internal combustion engines. There are differences in the effects of each alternative fuel on emissions and engine performance. The future studies could be carried out to obtain an appropriate hybrid fuel by making a comparison between these alternative fuels to reduce all emissions and to improve engine performance.

**Abbreviations**

- BMEP: brake mean effective pressure
- BSFC: brake specific fuel consumption
- BTE: brake thermal efficiency
- CA BTDC: crank angle before top dead center
- CI: compression ignition engine
- COV: coefficient of variation
- CR: compression ratio
- EU: European Union
- HCNG: natural gas-hydrogen mixtures
- ICE: internal combustion engine
- MBT: maximum brake torque
- NGV: natural gas vehicles
- SI: spark ignition
- WOT: wide open throttle
- WTT: well to tank

**Author details**

Mehmet Ilhan Ilhak\textsuperscript{1}, Selim Tangoz\textsuperscript{2}, Selahaddin Orhan Orhan Akansu\textsuperscript{*}, and Nafiz Kahraman\textsuperscript{3}

1 Department of Mechanical Engineering, Faculty of Engineering, Erciyes University, Kayseri, Turkey

2 Department of Airframes and Powerplants, Faculty of Aeronautics and Astronautics, Erciyes University, Kayseri, Turkey

3 Department of Astronautical Engineering, Faculty of Aeronautics and Astronautics, Erciyes University, Kayseri, Turkey

*Address all correspondence to: akansu@erciyes.edu.tr

**IntechOpen**

© 2019 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
References

[1] Türkiye Petrolleri. 2017 Yılı Ham Petrol ve Doğalgaz Sektör Raporu. 2018. 50 s

[2] Schulz H. Short history and present trends of Fischer-Tropsch synthesis. Applied Catalysis A: General. 1999;186(1-2):3-12

[3] Dry ME. High quality diesel via Fischer-Tropsch process—A review. Journal of Chemical Technology and Biotechnology. 2001;77:43-50

[4] Dry ME. The Fischer Tropsch process 1950-2000. Catalysis Today. 2002;71:227-241

[5] http://www.douglas-self.com/MUSEUM/POWER/acetylene-eng/acetyleneeng.htm [Accessed: 2018]

[6] https://todayinsci.com/D/Davy_Edmund/DavyEdmundBio.htm [Accessed: 2018]

[7] Odell WW. Facts relating to the production and substitution of manufactured for natural gas/ acetylene (C₂H₂). Bulletin, 300-308. U.S. Government Printing Office. 1829. p. 64

[8] https://www3.epa.gov/ttn/chief/ap42/ch11/bgdocs/b11s04.pdf [Accessed: 2018]

[9] Kannan P, Viswabharathy P, Kumar PD. Experimental study of carbide as an alternate fuel using in internal combustion engine. International Journal of Emerging Technologies in Engineering Research. 2017;5(5):92-104

[10] Oršula I, Lehecký M, Steltenpohl P. Simulation of calcium acetylide and acetylene production. Acta Chimica Slovaca. 2015;8(2):91-96

[11] Behera P, Jha AK, Murugan S. Dual fuel operation of used transformer oil with acetylene in a di diesel engine. International Journal on Theoretical and Applied Research in Mechanical Engineering. 2013;2(2):126-132

[12] Kumar P, Reddy SJ, Bodukuri K. Internal combustion engine using acetylene as an alternative fuel. International Journal of Engineering Research and Development. 2018;14(5):56-61

[13] Lakshmanan T, Nagarajan G. Performance and emission of acetylene-aspirated diesel engine. Jordan Journal of Mechanical and Industrial Engineering. 2009;3(2):125-130

[14] Sudheer. Experimental performance analysis of acetylene aspirated diesel engine. International Journal for Scientific Research & Development. 2016;4(06):2321-0613

[15] Lakshmanan T, Nagarajan G. Experimental investigation on dual fuel operation of acetylene in a DI diesel engine. Fuel Processing Technology. 2010;91:496-503

[16] Lakshmanan T, Nagarajan G. Experimental investigation of timed manifold injection of acetylene in direct injection diesel engine in dual fuel mode. Energy. 2010;35:3172-3178

[17] Lakshmanan T, Nagarajan G. Experimental investigation of port injection of acetylene in DI diesel engine in dual fuel mode. Fuel. 2011;90:2571-2577

[18] Ilhak Mİ, Akansu SO, Kahraman N, Unalan S. Experimental study on an SI engine fuelled by gasoline-acetylene mixtures. Energy. 2018;151:707-714

[19] Ilhak Mİ. Investigation of the effect of acetylene gas on the engine performance and emissions in an SI engine [PhD thesis]. 2018. p. 156
[20] Hilden DL, Stebar RF. Evaluation of acetylene as a spark ignition engine fuel. International Journal of Energy Research. 1979;3:59-71

[21] Gupta K, Suthar K, Jain SK, Agarwal GD, Nayyar A. Design and experimental investigations on six-stroke SI engine using acetylene with water injection. Environmental Science and Pollution Research. 2018;25:23033-23044

[22] Shaik Khader Basha SK, Rao PS, Rajagopal K. Experimental investigation of performance of acetylene fuel based diesel engine. International Journal of Advancements in Technology. 2016;7(1):3-7

[23] Pravinkumar SC, Bhavsar AA. Experimental investigation of diesel engine operating parameters for a mixture of acetylene and turpentine oil with diesel by design of experiment. International Journal for Innovative Research in Science & Technology. 2017;3(2):11-16

[24] Sahu GK, Kumar S. Performance analysis of four stroke diesel engine working with acetylene and diesel. International Journal for Research in Applied Science & Engineering Technology. 2017;5(8):2038-2043

[25] Mahla SK, Kumar S, Shergill H, Kumar A. Study the performance characteristics of acetylene gas in dual fuel engine with diethyl ether blends. International Journal on Emerging Technologies. 2012;3(1):80-83

[26] Nataraja M, Kiran Kumar M, Manjunath K, Madhukumar K. Acetylene as an alternate fuel in modified 4-stroke spark ignition engine. International Journal of Innovative Research in Science, Engineering and Technology. 2018;7(7):351-360

[27] https://www.supagas.net.au/acetylene-8-7m3-cylinder.html#.W8QPAmszbIU [Accessed: 2018]

[28] Neiva L, Gama L. The Importance of Natural Gas Reforming, Natural Gas. InTech; 2010. ISBN: 978-953-307-112-1. Available from: http://www.intechopen.com/books/natural-gas/the-importance-of-natural-gas-reforming [Accessed: 2018]

[29] https://www.esrl.noaa.gov/gmd/ccgg/trends/monthly.html [Accessed: 2018]

[30] Tangöz S, Akansu SO, Kahraman N, Malkoç Y. Effects of compression ratio on performance and emissions of a modified diesel engine fueled by HCNG. International Journal of Hydrogen Energy. 2015;40:15374-15380

[31] http://www.iangv.org/current-ngv-stats/ [Accessed: 2018]

[32] Demirbas A. Chapter 2: Methane gas hydrate. In: Natural Gas. London, England: Springer; 2010. pp. 57-76

[33] Aljamali S, Mahmood WMFW, Abdullah S, Ali Y. Comparison of performance and emission of a gasoline engine fuelled by gasoline and CNG under various throttle positions. Journal of Applied Sciences. 2014;14:386-390

[34] Tabar AR, Hamidi A, Ghadamian H. Experimental investigation of CNG and gasoline fuels combination on a 1.7 L bi-fuel turbocharged engine. International Journal of Energy and Environmental Engineering. 2017;8:37-45

[35] Baranes E, Jacqmin J, Poudou JC. Non-renewable and intermittent renewable energy sources: Friends and foes? Energy Policy. 2017;111:58-67

[36] Kato K, Igarashi K, Masuda M, Otsubo K, Yasuda A, Takeda K. Development of engine for natural gas vehicle. 1999. SAE Paper No. 1999-01-0574.1-11

[37] Dubois LH. Adsorbed Natural Gas On-Board Storage for
Light-Duty Vehicles. California Energy Commission. 2017. Publication Number: CEC-500-2017-038

[38] Fulton L, Howes T, Hardy J. Biofuels for Transport—An International Perspective. Paris: International Energy Agency; 2004

[39] Zvirin Y, Gutman M, Tartakovsky L. Fuel effects on emissions. In: Sher E, editor. Chapter 16 in the Handbook of Air Pollution from Internal Combustion Engines, Pollutant Formation and Control. San Diego, USA: Academic Press; 1998. pp. 548-651

[40] Tibaquirá JE, Huertas JI, Ospina S, Quirama LF, Niño JE. The effect of using ethanol-gasoline blends on the mechanical, energy and environmental performance of in-use vehicles. Energies. 2018;11(221):1-17

[41] Foong TM, Morganti KJ, Brear MJ, da Silva G, Yang Y, Dryer FL. The octane numbers of ethanol blended with gasoline and its surrogates. Fuel. 2014;115:727-739

[42] Luo M, El-Faroug MO, Yan F, Wang Y. Particulate matter and gaseous emission of hydrous ethanol gasoline blends fuel in a port injection gasoline engine. Energies. 2017;10:1-16

[43] https://www.arndoldclark.com/newsroom/347-can-cars-run-on-alcohol [Accessed: 2018]

[44] Liao SY, Jiang DM, Cheng Q, Huang ZH, Wei Q. Investigation of the cold-start combustion characteristics of ethanol-gasoline blends in a constant-volume chamber. Energy & Fuels. 2005;19:813-819

[45] Yahuza I, Dandakouta H. A performance review of ethanol-diesel blended fuel samples in compression-ignition engine. Journal of Chemical Engineering & Process Technology. 2015;6(5):1-6

[46] Bossel U, Eliasson B. Energy and the Hydrogen Economy. 2003. Available from: https://afdc.energy.gov/files/pdfs/hyd_economy_bossel_eliaasson.pdf [Accessed: 2018]

[47] Azzeh SE, Marjan S, Fayaz R. Hydrogen economy and the built environment. In: Conference: World Renewable Energy Congress—Sweden, 8-13 May 2011; Linköping, Sweden. 2011

[48] Rao S, Dipak A. Review of hydrogen as a fuel in IC engines. International Journal of Science and Research. 2017;7:914-922

[49] Satheesh kumar C, Mohammed Shekoor T. Evaluation of emission characteristics of hydrogen as a boosting fuel in a four stroke single cylinder gasoline engine. International Journal of Engineeering Research & Technology (IJERT). 2014;3(10):151-154

[50] Gandhi R. Use of hydrogen in internal combustion engine. International Journal of Engineering and Technical Research (IJETR). 2015;3(2):207-216

[51] Yousufuddin S, Mehdi SN, Masood M. Performance and combustion characteristics of a hydrogen-ethanol fuelled engine. Energy & Fuels. 2008;22:3355-3362

[52] Petkov T, Veziroglu TN, Sheffield JW. An outlook of hydrogen as an automotive fuel. International Journal of Hydrogen Energy. 1989;14:449-474

[53] Lee JT, Kim YY. The development of a dual injection hydrogen fueled engine with high power and high efficiency. In: Proceedings of the 2002 Fall Technical Conference of the ASME Internal Combustion Engine Division, ICEF2002-514, 8-11 September, New Orleans, Louisiana, USA. 2002. pp. 323-333
[54] Ma F, He Y, Deng J, Jiang L, Naeve N, Wang M, et al. Idle characteristics of a hydrogen fueled SI engine. International Journal of Hydrogen Energy. 2011;36(7):4454-4460

[55] Yamin Jehan AA, Gupta HN, Bansal BB, Srivastava ON. Effect of combustion duration on the performance and emission characteristics of a spark ignition engine using hydrogen as a fuel. International Journal of Hydrogen Energy. 2000;25(6):581-590

[56] De Boer PCT, McLean WJ, Homan HS. Performance and emissions of hydrogen fueled internal combustion engines. International Journal of Hydrogen Energy. 1976;1(2):153-172

[57] Jie M, Yongkang S, Yucheng Z, Zhongil Z. Simulation and prediction on the performance of a vehicle’s hydrogen engine. International Journal of Hydrogen Energy. 2003;28(1):77-83

[58] Ciniviz M, Köse H. Hydrogen use in internal combustion engine. International Journal of Automotive Engineering and Technologies. 2012;1(1):1-15

[59] Wang S, Ji C, Zhang B, Zhou X. Analysis on combustion of a hydrogen-blended gasoline engine at high loads and lean conditions. Energy Procedia. 2014;61:323-326

[60] D’Andrea T, Henshaw PF, K Ting DS. The addition of hydrogen to a gasoline-fuelled SI engine. International Journal of Hydrogen Energy. 2004;29(14):1541-1552

[61] Kahraman E, Cihangir Ozcanlı S, Özerdem B. An experimental study on performance and emission characteristics of a hydrogen fuelled spark ignition engine. International Journal of Hydrogen Energy. 2007;32(12):2066-2072

[62] Wang S, Ji C, Zhang J, Zhang B. Improving the performance of a gasoline engine with the addition of hydrogen-oxygen mixtures. International Journal of Hydrogen Energy. 2011;36(17):11164-11173

[63] Turns SR. An Introduction to Combustion Concepts and Applications. New Delhi: McGraw-Hill; 2000. 676 p

[64] Huang Z, Wang J, Liu B, Zeng K, Yu J, Jiang D. Combustion characteristics of a direct-injection engine fueled with natural gas—Hydrogen blends under different ignition timings. Fuel. 2007;86(3):381-387

[65] Akansu SO, Dulger A, Kahraman N, Veziroglu TN. Internal combustion engines fueled by natural gas—Hydrogen mixtures. International Journal of Hydrogen Energy. 2004;29(14):1527-1539

[66] Collier K, Mulligan N, Shin D, Brandon S. Emission results from the new development of a dedicated hydrogen-enriched natural gas heavy duty engine. 2005. SAE Paper No. 2005-01-0235

[67] Nanthagopal K, Subbarao R, Elango T, Baskar P, Annamalai K. Hydrogen enriched compressed natural gas (HCNG)—A futuristic fuel for internal combustion engines. Thermal Science. 2011;15(4):1145-1154

[68] Bell SR, Gupta M. Extension of a lean operating limit for natural gas fuelling of a spark ignition engine using hydrogen blending. Combustion Science and Technology. 1997;123(1-6):23-48

[69] Munshi SR, Nedelcu C, Harris J. Hydrogen blended natural gas of a operation of a heavy duty turbocharged lean burn spark ignition engine. 2004. SAE Paper No. 2004-01-2956

[70] Sandhu SS, Babu MKG, Das LM. Investigations of emission characteristics and thermal efficiency
in a spark-ignition engine fuelled with natural gas—Hydrogen blends. International Journal of Low Carbon Technologies. 2013;8(1):7-13

[71] Thring RH. Alternative fuels for spark-ignition engines. 1983. SAE Paper No. 831685

[72] Desoky AA, El-Emam SH. A study on the combustion of alternative fuels in spark-ignited engines. International Journal of Hydrogen Energy. 1985;10:497-504

[73] Cooney AP, Yeliana JJ, Worm JD, Naber JD. Combustion characterization in an internal combustion engine with ethanol gasoline blended fuels varying compression ratios and ignition timing. Energy & Fuels. 2009;23:2319-2324

[74] Al-Baghdadi MAS, Al-Janabi HAS. Improvement of performance and reduction of pollutant emission of a four stroke spark ignition engine fueled with hydrogen-gasoline fuel mixture. Energy Conversion and Management. 2000;41:77-91

[75] Zhang B, Ji C, Wang S. Performance of a hydrogen-enriched ethanol engine at unthrottled and lean conditions. Energy Conversion and Management. 2016;114:68-74

[76] Norman DB. Ethanol fuelled single-cylinder engine study of efficiency and exhaust emissions. 1982. SAE Paper No. 810345.1410-24

[77] Akansu SO, Tangöz S, Kahraman N, Ilhak MI, Açıkgöz S. Experimental study of gasoline-ethanol-hydrogen blends combustion in an SI engine. International Journal of Hydrogen Energy. 2017;42(40):25781-25790

[78] Shuofeng W, Changwei J, Zhang B. Effect of hydrogen addition on combustion and emissions performance of a spark-ignited ethanol engine at idle and stoichiometric conditions. International Journal of Hydrogen Energy. 2010;35:9205-9213

[79] Park C, Choi Y, Kim C, Oh S, Lim G, Moriyoshi Y. Performance and exhaust emission characteristics of a spark ignition engine using ethanol and ethanol-reformed gas. Fuel. 2010;89:2118-2125

[80] Al-Hamamre Z, Yamin J. The effect of hydrogen addition on premixed laminar acetylene-hydrogen-air and ethanol-hydrogen-air flames. International Journal of Hydrogen Energy. 2013;38:7499-7509

[81] Al-Baghdadi M. Hydrogen-ethanol blending as an alternative fuel for spark ignition engines. Renewable Energy. 2003;28:1471-1478

[82] Schefer RW. Hydrogen enrichment for improved lean flame stability. International Journal of Hydrogen Energy. 2003;28:1131-1141

[83] Wang J, Huang Z, Tang C, Zheng J. Effect of hydrogen addition on early flame growth of lean burn natural gas-air mixtures. International Journal of Hydrogen Energy. 2010;35:7246-7252

[84] Ceper B, Aydin K, Akansu SO, Kahraman N. Numerical simulation and experimental studies of a biogas fueled spark ignition engine. Energy Education Science and Technology Part A: Energy Science and Research. 2012;28(2):599-610

[85] Yousufuddin S, Masood M. Effect of ignition timing and compression ratio on the performance of a hydrogen-ethanol fuelled engine. International Journal of Hydrogen Energy. 2009;34(16):6945-6950

[86] Kumar NS, Prabhu BG, Selvan KK, Kumar RM, Kumar KM. Emission and performance characteristics of hydrogen-acetylene fuel in IC engine.
Internal Combustion Engines

[87] Tangöz S, İlhak Mİ, Akansu SO, Kahraman N. Experimental investigation of performance and emissions of an SI engine fueled by acetylene-methane and acetylene-hydrogen blends. Fresenius Environmental Bulletin. 2018;27:4174-4185

[88] Aziz Hairuddin A, Wandel AP, Yusaf TF. Hydrogen and natural gas comparison in diesel HCCI engines—A review. Southern Region Engineering Conference. 11-12 November 2010. Toowoomba, Australia. 2010

[89] Liu J, Wang J, Zhao H. Optimization of the injection parameters and combustion chamber geometries of a diesel/natural gas RCCI engine. Energy. 2018;164:837-852

[90] Jia M, Xie M, Wang T, Peng Z. The effect of injection timing and intake valve close timing on performance and emissions of diesel PCCI engine with a full engine cycle CFD simulation. Applied Energy. 2011;88(9):2967-2975

[91] Zheng Z, Yao M. Charge stratification to control HCCI: Experiments and CFD modeling with n-heptane as fuel. Fuel. 2009;88:354-365

[92] Singh AP, Agarwal AK. Low-Temperature Combustion: An Advanced Technology for Internal Combustion Engines. Singapore: Springer Nature Singapore Pte Ltd; 2018. pp. 9-41

[93] Noehre C, Andersson M, Johansson B, Hultqvist A. Characterization of partially premixed combustion. 2006. SAE Technical Paper 2006-10-16

[94] Fiveland SB, Assanis DN. A four-stroke homogeneous charge compression ignition engine simulation for combustion and performance studies. 2000. SAE Paper No. 2000-01-0332

[95] Rattanapaibule K, Aung K. Performance predictions of a hydrogen-enhanced natural gas HCCI engine. In: International Mechanical Engineering Congress and Exposition (IMECE2005), Florida. 2005. pp. 289-294

[96] Caton J. Thermodynamic advantages of low temperature combustion (LTC) engines using low heat rejection (LHR) concepts. 2011. SAE Technical Paper 2011-01-0312

[97] Asad U, Divekar P, Zheng M, Tjong J. Low temperature combustion strategies for compression ignition engines: Operability limits and challenges. 2013. SAE Technical Paper. 2013-01-0283

[98] Okude K, Mori K, Shiino S, Moriya T. Premixed compression ignition (PCI) combustion for simultaneous reduction of NOx and soot in diesel engine. 2004. SAE Technical Paper Series. 2004-01-1907

[99] Fiveland SB, Agama R, Christensen M, Johansson B, Hiltner L, Maus F, et al. Experimental and simulated results detailing the sensitivity of natural gas hcci engines to fuel composition. 2001. SAE Technical Paper 2001-01-3609

[100] Jamsran N, Putrasari N, Lim O. A computational study on the autoignition characteristics of an HCCI engine fueled with natural gas. Journal of Natural Gas Science and Engineering. 2016;29:469-478

[101] Morsy MH. Ignition control of methane fueled homogeneous charge compression ignition engines using additives. Fuel. 2007;86:533-540

[102] Yousefzadeh A, Jahanian O. Using detailed chemical kinetics 3D-CFD
model to investigate combustion phase of a CNG-HCCI engine according to control strategy requirements. Energy Conversion and Management. 2017;133:524-534

[103] Zheng J, Caton JA. Effects of operating parameters on nitrogen oxides emissions for a natural gas fueled homogeneous charged compression ignition engine (HCCI): Results from a thermodynamic model with detailed chemistry. Applied Energy. 2012;92:386-394

[104] Christensen M, Johansson B, Einewall P. Homogeneous charge compression ignition (HCCI) using iso-octane, ethanol and natural gas: A comparison with spark ignition operation. 1997. SAE Technical Paper 972874

[105] Maurya RK, Agarwal AK. Experimental investigations of performance, combustion and emission characteristics of ethanol and methanol fueled HCCI engine. Fuel Processing Technology. 2014;126:30-48

[106] Bahri B, Aziz AA, Shahbakhti M, Said MFM. Understanding and detecting misfire in an HCCI engine fuelled with ethanol. Applied Energy. 2013;108:24-33

[107] Maurya RK, Agarwal AK. Experimental study of combustion and emission characteristics of ethanol fuelled port injected homogeneous charge compression ignition (HCCI) combustion engine. Applied Energy. 2012;88:1169-1180

[108] Viggiano A, Magi V. A comprehensive investigation on the emissions of ethanol HCCI engines. Applied Energy. 2012;93:277-287

[109] Sudheesh K, Mallikarjuna JM. Development of an exhaust gas recirculation strategy for an acetylene-fuelled homogeneous charge compression ignition engine. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 2010;224:941-952

[110] Puranam S, Steeper R. The effect of acetylene on iso-octane combustion in an HCCI engine with NVO. SAE International Journal of Engines. 2012;5(4):1551-1560

[111] Nathan SS, Mallikarjuna J, Ramesh A. HCCI engine operation with acetylene the fuel. 2008. SAE Technical Paper 2008-28-0032

[112] Nathan SS, Mallikarjuna JM, Ramesh A. Effects of charge temperature and exhaust gas re-circulation on combustion and emission characteristics of an acetylene fuelled HCCI engine. Fuel. 2010;89:515-521

[113] Aithal SM. Prediction of voltage signature in a homogeneous charge compression ignition (HCCI) engine fueled with propane and acetylene. Combustion Science and Technology. 2013;185:1184-1201

[114] Sudheesh K, Mallikarjuna JM. Diethyl ether as an ignition improver for acetylene-fuelled homogeneous charge compression ignition operation: An experimental investigation. International Journal of Sustainable Energy. 2015;34(9):561-577

[115] Guo H, Hosseini V, Neill WS, Chippior WL, Dumitrescu CE. An experimental study on the effect of hydrogen enrichment on diesel fueled HCCI combustion. International Journal of Hydrogen Energy. 2011;36(21):13820-13830

[116] Guo H, Neill WS. The effect of hydrogen addition on combustion and emission characteristics of an n-heptane fuelled HCCI engine. International
[117] Antunes JMG, Mikalsen R, Roskilly AP. An investigation of hydrogen-fuelled HCCI engine performance and operation. International Journal of Hydrogen Energy. 2008;33(20):5823-5828

[118] Ibrahim MM, Ramesh AA. Investigations on the effects of intake temperature and charge dilution in a hydrogen fueled HCCI engine. International Journal of Hydrogen Energy. 2014;39(26):14097-14108

[119] Gowda BD, Echekki T. Complex injection strategies for hydrogen-fueled HCCI engines. Fuel. 2012;97:418-427

[120] Maurya RK, Saxena MR. Characterization of ringing intensity in a hydrogen-fueled HCCI engine. International Journal of Hydrogen Energy. 2018;43(19):9423-9437

[121] Shudo T, Yamada H. Hydrogen as an ignition-controlling agent for HCCI combustion engine by suppressing the low-temperature oxidation. International Journal of Hydrogen Energy. 2007;32(14):3066-3072

[122] Kozlov VE, Chechet IV, Matveey AG, Titova NS, Starik AM. Modeling study of combustion and pollutant formation in HCCI engine operating on hydrogen rich fuel blends. International Journal of Hydrogen Energy. 2016;41(5):3689-3700

[123] Poorghasemi K, Saray RK, Ansari E, Irdmousa BK, Shahbakhti M, Naber ND. Effect of diesel injection strategies on natural gas/diesel RCCI combustion characteristics in a light duty diesel engine. Applied Energy. 2017;199:430-446

[124] Kakae AH, Rahnama P, Paykani A. Influence of fuel composition on combustion and emissions of natural gas/diesel RCCI engine. Journal of Natural Gas Science and Engineering. 2015;25:58-65

[125] Gharehghani A, Hosseini R, Mirsalim M, Jazayeri A, Yusaf T. An experimental study on reactivity controlled compression ignition engine fueled with biodiesel/natural gas. Energy. 2015;89:558-567

[126] Ansari E, Shahbakhti M, Naber J. Optimization of performance and operational cost for a dual mode diesel-natural gas RCCI and diesel combustion engine. Applied Energy. 2018;231:549-561

[127] Walker NR, Wissink ML, DelVescovo DA, Reitz RD. Natural gas for high load dual-fuel reactivity controlled compression ignition (RCCI) in heavy-duty engines. In: Proceedings of the ASME Internal Combustion Engine Division, Fall Technical Conference; Vol. 1. ASME, V001T03A016. 2014

[128] Olmeda P, García A, Monsalve-Serrano J, Sari RL. Experimental investigation on RCCI heat transfer in a light-duty diesel engine with different fuels: Comparison versus conventional diesel combustion. Applied Thermal Engineering. 2018;144:424-436

[129] Khatamnejad H, Khalilarya SH, Jafarmadar S, Mirsalim M. The effect of high-reactivity fuel injection parameters on combustion features and exhaust emission characteristics in a natural gas–diesel RCCI engine at part load condition. International Journal of Green Energy. 2018;15(13):874-888

[130] Jia Z, Denbratt I. Experimental investigation of natural gas-diesel dual-fuel RCCI in a heavy-duty engine. SAE International Journal of Engines. 2015;8(2):797-807

[131] Shim E, Park H, Bae C. Intake air strategy for low HC and CO emissions
in dual-fuel (CNG-diesel) premixed charge compression ignition engine. Applied Energy. 2018;225:1068-1077

[132] Park H, Shim E, Bae C. Improvement of combustion and emissions with exhaust gas recirculation in a natural gas-diesel dual-fuel premixed charge compression ignition engine at low load operations. Fuel. 2019;235:763-774

[133] Esfahanian V, Salahi MM, Gharehghani A, Mirmay M. Extending the lean operating range of a premixed charged compression ignition natural gas engine using a pre-chamber. Energy. 2017;119:1181-1194

[134] Dempsey AB, Das Adhikary B, Viswanathan S, Reitz RD. Reactivity controlled compression ignition (RCCI) using premixed hydrated ethanol and direct injection diesel. In: Proceedings of the ASME Internal Combustion Engine Division Fall Technical Conference (ICEF). 2011. pp. 963-975

[135] Qian Y, Wang X, Zhu L, Lu X. Experimental studies on combustion and emissions of RCCI (reactivity controlled compression ignition) with gasoline/n-heptane and ethanol/n-heptane as fuels. Energy. 2015;88:584-594

[136] Loaiza JCV, Sanchez FZ, Braga SL. Combustion study of reactivity-controlled compression ignition (RCCI) for the mixture of diesel fuel and ethanol in a rapid compression machine. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2016;38(4):1073-1085

[137] Liu H, Ma G, Hu B, Zheng Z, Yao M. Effects of port injection of hydrous ethanol on combustion and emission characteristics in dual-fuel reactivity controlled compression ignition (RCCI) mode. Energy. 2016;145:592-602

[138] Park SH, Shin D, Park J. Effect of ethanol fraction on the combustion and emission characteristics of a dimethyl ether-ethanol dual-fuel reactivity controlled compression ignition engine. Applied Energy. 2016;182:243-252

[139] Elzahaby AM, Elkelawy M, Bastawissi HAE, El-Malla SM, Naceb AMM. Kinetic modeling and experimental study on the combustion, performance and emission characteristics of a PCCI engine fueled with ethanol-diesel blends. Egyptian Journal of Petroleum. 2018;27(4):927-937

[140] Natarajan S, Shankar SA, Sundareswaran M. Early injected PCCI engine fuelled with bio ethanol and diesel blends: An experimental investigation. Energy Procedia. 2017;105:358-366

[141] Saravanan S, Pitchandi K, Suresh G. An experimental study on premixed charge compression ignition-direct ignition engine fueled with ethanol and gasohol. Alexandria Engineering Journal. 2015;54(4):897-904

[142] Mancaruso E, Vaglieco BM. Spectroscopic analysis of the phases of premixed combustion in a compression ignition engine fuelled with diesel and ethanol. Applied Energy. 2015;143:164-175

[143] Kokjohn S, Splitter DA, Reitz RD, Manente V, Johansson B. Modeling charge preparation and combustion in diesel fuel, ethanol, and dual-fuel PCCI engines. Atomization and Sprays. 2011;21:107-119

[144] Noh HK, No SY. Effect of bioethanol on combustion and emissions in advanced CI engines: HCCI, PPC and GCI mode: A review. Applied Energy. 2017;208:782-802

[145] Sartbaeva A, Kuznetsov VL, Wells S, Edwards P. Hydrogen nexus in a sustainable energy future. Energy & Environmental Science. 2008;1(1):79-85
[146] Lovel WG. Knocking characteristics of hydrocarbons. Journal of Industrial and Engineering Chemistry. 1948;40(12):2388-2438

[147] Hoseinpour M, Sadrnia H, Tabasizadeh M, Ghabadian B. Energy and exergy analyses of a diesel engine fueled with diesel, biodiesel-diesel blend and gasoline fumigation. Energy. 2017;141:2408-2420

[148] Ji C, Shi L, Wang S, Cong X, Su T, Yu M. Investigation on performance of a spark-ignition engine fueled with dimethyl ether and gasoline mixtures under idle and stoichiometric conditions. Energy. 2017;126:335-342

[149] Özcan H. Hydrogen enrichment effects on the second law analysis of a lean burn natural gas engine. International Journal of Hydrogen Energy. 2010;35(3):1443-1452

[150] Papagiannakis RG, Rakopoulos CD, Hountalas DT, Rakopoulos DC. Emission characteristics of high speed, dual fuel, compression ignition engine operating in a wide range of natural gas/diesel fuel proportions. 7th International Symposium on Alcohol Fuels. 2010;89(7):1397-1406

[151] Greenwood JB, Erickson PA, Hwang J, Jordan EA. Experimental results of hydrogen enrichment of ethanol in an ultra-lean internal combustion engine. International Journal of Hydrogen Energy. 2014;39:12980-12990

[152] Catapano F, Di Iorio S, Magno A, Sementa P, Vaglieco BM. A comprehensive analysis of the effect of ethanol, methane and methane-hydrogen blend on the combustion process in a PFI (port fuel injection) engine. Energy. 2015;88:101-110

[153] Pulkrabek WW. Engineering Fundamentals of the Internal Combustion Engine. 2nd ed. New Jersey: Prentice Hall; 2003

[154] Edwards R, Larivé JF, Rickeard D, Weindorf W. Well-to-Wheels analysis of future automotive fuels and powertrains in the European context well-to-tank (WTT) report version 4.a, Joint Research Centre of the European Commission, Luxembourg: Publications Office of the European Union, 2014