Effect of CNG Engine Conversion on Performance Characteristic: A Review

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Abstract. The world has been experiencing a crisis of energy caused by the deterioration of scarce fossil fuel resources. The usage of fossil fuels, mainly liquid fuels is considered unsustainable due to resource depletion and the accumulation of pollutants. Natural gas has become a promising alternative fuel since it is highly abundant in the world, produces less emission, and gives similar engine performance compared to the existing liquid fuel, diesel, or gasoline. This paper presents various research regarding the engine performance characteristic of CNG. The studies reported that as compared to liquid-based fuel such as diesel oil or gasoline, CNG gives lower brake thermal efficiency (BTE) as compared to diesel fuel. However, the brake-specific fuel consumption (BSFC) of engine fueled with CNG is lower than diesel or gasoline fuel. In terms of exhaust gas temperature, CNG was always produced higher temperatures in comparison to gasoline. The maximum cylinder gas pressure of CNG was reported lower than diesel fuel operation. In general, the power produced by CNG combustion is a little bit lower than diesel fuel, this drawback of CNG fuel can be overcome by adding hydrogen fuel to CNG to increase produced power.

Keywords: CNG fuel, Engine Performance, Natural Gas

1. Introduction

Due to the dilution of finite fossil fuels, the world has been dealing with energy crisis problems. The usage of fossil fuels as a source of energy is now widely recognized as unsustainable due to resource depletion and the continuous accumulation of pollutants caused by engine combustion. It can be from ships, cars, and other vehicles also form industry [1]. Energy policy, regulation, and planning, as well as associated issues, have become a major public agenda item in most industrialized and developing countries in recent years, with governments supporting the use of alternative petroleum-based fuels in automobiles or even marine engines as a result. Where the purpose of all these regulations is to reduce the emissions. When comparing different alternative fuels, numerous factors must be considered such as availability of the resource, fuel supply sufficiency, production process efficiency, transportability and storage security, also fuel compatibility with the vehicle’s engine which mostly depends on the fuel properties [2]. One of the solutions to overcome this pollution issue is by utilizing natural gas as a fuel, replacing the diesel oil or gasoline. Natural gas is mostly structured or composed of methane (CH₄) and is produced by natural gas wells or in conjunction with the production of crude oil. Natural gas may be stored and compressed. To keep the equal amount (mass) of natural gas, CNG needs a
substantially greater volume and a very high pressure of roughly 200 bar [3]. CNG is attractive as a fuel because it burns cleanly, is plentiful, and has been proven to reduce particulate matter (PM) emissions. CNG is also less expensive in comparison to diesel fuel, emits fewer greenhouse gases, and produces less NOx and CO2, hence it has the potential to comply with strict emission rules [4], [5]. These advantages from CNG regarding the low emission produced made CNG or natural gas fuel known as environmentally friendly fuel. CNG-fueled engine research is also advancing around the world because it is promising as an alternative fuel for spark ignition engines. The different of chemical and physical properties between CNG and gasoline cause the difference in engine operation. Petroleum fuels are known to be liquid at normal temperature, however, CNG need to meet a condition at extremely low temperatures (-160°C) to become liquid [2]. The performance characteristic of a CNG-fueled engine has been investigated by several studies. CNG combustion has been shown to achieve efficiency comparable to diesel oil combustion. This is one of the reasons why CNG is feasible as a fuel. When compared to pure diesel, emissions such as unburned hydrocarbons (UHC) and carbon monoxide (CO) are often higher; however, soot emissions are much lower [4].

This paper aims to review the characteristic of the engine fueled using CNG effect on engine performance such as engine brake power, brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), engine exhaust gas temperature produced, and knocking. Most of the type of engine being discussed is converted diesel to CNG as its fuel. The diesel engine is converted into spark ignition so that it can perform a CNG combustion. Besides, there is also dual-fuel engine runs with CNG. In this paper also presents comparison analysis between CNG and other fuel such as hydrogen, biodiesel, diesel, gasoline, and even mixed fuel such as B20-CNG in terms of engine performance.

2. Characteristic of CNG as A Fuel

In terms of density, CNG is lighter than air, therefore if there is a leak, it will quickly evaporate upward. Petroleum fuels such as gasoline and diesel will remain on the ground, raising a risk of fire. In this case, CNG fuel is more safety compared to diesel fuel [3]. CNG has a lower density in comparison to gasoline, but CNG has higher-octane number or octane rating (ON = 130). It has a high compression ratio and a greater self-igniting temperature (about 723°C), making it a safe fuel in the event of a leak [6]. CNG fuel can be operated in conventional gasoline or diesel engines. As an alternative fuel, it is highly available in the world and environmentally friendly [7]. In order to overcome energy crisis and pollution problem, CNG can be used as a main fuel or can be mixed with other fuel, in other words the diesel fuel is still needed in a operation but in fewer amount. Thus, the use of diesel fuel can be reduced. Table 1 presents the properties of CNG fuel.

| CNG Properties                          | Value |
|----------------------------------------|-------|
| Density (kg/m³)                        | 0.72  |
| Limit of flammability (Volume % in air)| 4.3-15|
| Flammability (Ø)                       | 0.4-1.6|
| The temperature of autoignition (°C)   | 723   |
| The minimum energy of ignition (mJ)    | 0.28  |
| The velocity of the flame (m/s)        | 0.38  |
| Flame temperature at adiabatic (K)     | 2214  |
| Distance of quenching (mm)             | 2.1   |
| Fuel-air ratio at stoichiometric       | 0.069 |
| Volume fraction at stoichiometric %    | 9.48  |
| Lower heating value (MJ/kg)            | 45.8  |
| Combustion heat (MJ/kg air)            | 2.9   |
CNG is appealing and promising for several reasons, (1) In term of price, it's the only fuel that is less expensive than gasoline or diesel, (2) It emits fewer pollutants as a result of its design, (3) It emits fewer greenhouse gases, (4) Its use helps to extend petroleum supplies, and (5) vast amounts of the fuel are available around the world [3]. Natural gas is frequently kept in a compressed condition, or CNG, due to its low volumetric energy density (kJ/m$^3$). Table 2 presents the CNG fuel characteristic.

| Characteristic of CNG               | Value                      |
|------------------------------------|----------------------------|
| Vapour density                     | 0.68                       |
| Autoignition temperature           | 700˚C                      |
| Octane number                      | 130                        |
| Boiling point temperature (at Atm Pressure) | -162˚C                  |
| Air-Fuel Ratio (Weight)            | 17.24                      |
| Chemical reaction with the rubber  | No                         |
| The pressure of the storage tank   | 20.6 MPa                   |
| Quality of fuel-air mixture        | Good                       |
| The emission produced (CO-HC-NO$_x$) | Very Low                |
| Speed of flame (m/s)               | 0.63                       |
| Combustion ability with the air    | 4-14%                      |

In comparison to gasoline or diesel oil, CNG fuel has a lower density but higher-octane rating. Natural gas has an octane number of around 130, which means that engines may run at compression ratios up to 16:1 without knocking or detonating. Pre-ignition (the igniting of the mixture before the spark plug fires) or detonation (the spontaneous combustion of the remaining fuel/air combination in the chamber) are the causes of knocking. Other factor that can result in knocking are low octane rating fuel, carbon build-up in the engine combustion chamber, over advanced ignition timing, unsuitable spark plugs lean air-fuel mixture, and extreme combustion temperature. CNG, as a gaseous matter, necessitates a unique fuel induction strategy at all typical operation condition (pressure and temperature). As a result, there has been a surge in interest in using CNG as alternative fuel, and CNG is currently being utilized to power a wide range of vehicles, from ships, delivery trucks, cars, city buses and other applications [2], [3], [6]. Regarding emission production, natural gas combustion can reduce CO$_2$ up to 20-25 percent when compared to gasoline because natural gas (mainly composed with methane – CH$_4$) has a single carbon atom compared to diesel (C$_{15}$H$_{32}$) and gasoline (C$_8$H$_{18}$). CNG may be operated in spark-ignited engines with ease, less modification. Natural gas has the most efficiency when burned in a lean combination with Air =1.3 to 1.5, however, this results in a loss of power produced, which is maximum when the stoichiometric air/gas mixture is slightly rich. Furthermore, natural gas able to improve the efficiency of engine warm-up. When combined with diesel fuel, it able to enhance the engine thermal efficiency, thus it able to compensate the CNG penalty imposed by larger storage tanks [9].

### 3. Performance Characteristic

This chapter discusses the performance characteristic of engine fueled with CNG. Several studies have been tested the performance characteristic of an engine fueled with gaseous fuel (natural gas) or even mixed between natural gas and biodiesel, diesel, or other type of fuels. This chapter more likely to give a comparative explanation between CNG and other fuels concerning engine performance including the engine brake power, thermal efficiency (BTE), engine exhaust gas temperature, and brake specific fuel consumption (BSFC), also knocking characteristic.
3.1. Brake Thermal Efficiency (BTE)
BTE is described as the ratio of brake power produced by the engine to the heat energy generated from the fuel combustion [10], [15]. A study was performed by Das et al. [6] regarding a comparison of combustion characteristics and performance of hydrogen and CNG-fueled engines. It has been reported that as compared to hydrogen, CNG gives lower brake thermal efficiency in various engine speeds. The impact combination of quality of governing skills and lean operation is the cause for the increase in brake thermal efficiency for the hydrogen fueled engine [6]. Figure 1 shows the value of BTE of both fuels at different BMEP circumstances. From the figure 1, it shows that the higher BMEP results higher thermal efficiency. This can be applied both for hydrogen and CNG fuel. In comparison to hydrogen, CNG gives less brake thermal efficiency throughout various engine speeds. One of the reasons that contributes to this gained BTE is probably caused by different lower caloric value. Hydrogen has higher caloric value compared to CNG. Hydrogen has 119.93 MJ/kg and CNG 45.8 MJ/kg.

![Figure 1. Brake thermal efficiency (BTE) as a function of brake mean effective pressure (BMEP) at 2200 RPM for CNG and hydrogen [6].](image)

A study conducted by Zareei et al. [14] shows that mixing hydrogen with CNG increases the engine's overall performance. As compared to pure diesel oil and pure CNG, increasing the percentage of hydrogen in the HCNG (hydrogen compressed natural gas) mixture increased the amount of cylinder pressure due to combustion from HCNG starts early, which leads to a huge amount of fuel to be consumed in the combustion. The brake power of HCNG increases as the hydrogen concentration in the blend increases. As compared to pure diesel oil or pure CNG, HCNG provides higher engine brake power [14]. Due to a more homogeneous mixing of hydrogen and air, HCNG blends have a greater BTE than pure diesel and CNG. Another cause for increased BTE compared to fossil fuels is the greater compression ratio of hydrogen mixed fuel.

Mahla et al. [10] conducted research on the engine performance characteristic and emissions of a CNG-fueled engine utilizing Ricinus communis methyl ester as pilot fuel. It has been reported that CNG fuel has a lower BTE than diesel fuel throughout various engine speeds. In the dual-fuel mode with different pilot fuels, BTE was reported lower at lower engine load than in diesel mode. Because the pilot fuel quantity is low, the igniting source is likewise poor, and the total intake charge mixture is
At light load, natural gas share is high. This leads to poor ignition and combustion. As a result, combustion rates slow down, resulting in incomplete combustion and a reduction in thermal efficiency.

Figure 2. BTE as a function of engine load for various fuel mixture [10].

Based on figure 2, diesel fuel always has higher BTE compared to CNG fuel throughout various fuel mix. At maximum engine load, maximum BTE is achieved for all type of mix. In this case, diesel fuel gives highest BTE throughout various engine loads while B20-CNG gives the lowest BTE.

When compared to gasoline, throughout the various engine speeds for CNG operation, the engine's brake power form CNG was lower than gasoline. It is caused by the flame velocity of natural gas which is slower and by the air displacement by natural gas and [2]. The study conducted by Nwafor [11] shows a similar result, as compared to diesel fuel, dual fuel mode generated lower power.

(a)
When it comes to liquid fuels, the fuel was considered to not affect the volume of air suck into the engine cylinder. As a result, the peak or max power of a gasoline-fueled engine converted to run on CNG would be much lower [2]. According to a study conducted by [13] about the LNG-diesel marine engine's performance and emission characteristics, at low loads the overall efficiency of natural gas fuel is decreased around 1%, however, at high-medium load, the overall efficiency is increased up to 2%. From figure 3, it can be seen that CNG fuel generates lower brake power in comparison to gasoline throughout various engine speeds. As stated earlier, the main cause of this event is that gas fuel has slower flame velocity and air displacement.

From the several studies, it can be concluded that CNG produces lower brake thermal efficiency when compared to gasoline fuel or diesel fuel. In term of power produced, CNG gives less brake power in comparison to gasoline and diesel oil. This also happen when CNG is mixed with biodiesel or diesel.

3.2. Brake Specific Fuel Consumption (BSFC)

Specific fuel consumption is described as a fuel flow rate per unit measurement of generated power that is related to an engine's fuel efficiency. It is inversely proportional to the engine's efficiency, with lower specific fuel consumption favoring higher performance. The BSFC is affected by the compression and fuel equivalency ratios. Because more power can be produced from the burning fuel, a higher compression ratio will result in a lower BFSC [15].

The study conducted by Li et al. [12] shows that dual fuel has a lower BSFC than solely diesel. Under low engine load, the temperature inside the cylinder was too low to oxidize the gas. This leads in more natural gas consumption (see figure 4). As the higher engine load, the temperature of the cylinder rise and natural gas burnt more fully. Because the amount of natural gas used drops when the load is high or full, the BSFC from dual fuel operation increase dramatically. This means that in the higher engine speed, the dual-fuel operation is more cost-effective than the pure diesel operation. See figure 4.

![at 80% throttle condition](image-url)

**Figure 3.** Brake power in various engine speeds (RPM) at 50% throttle (a) and 80% throttle (b) [2].
The specific fuel consumption of the diesel and dual-fuel modes as a function of engine speed is shown in Figure 4. In can be seen that in term of brake specific fuel consumption, dual fuel operation gives lower BFSC throughout various engine speeds and engine loads. This lower BSFC means lesser fuel consumed during operation. Thus, dual fuel operation consumed lesser fuel as compared to conventional diesel mode in same load.

The BSFC from the dual fuel operation is reported higher than that of the solely diesel mode at low speeds, see figure 4a. The main cause for this outcome is that natural gas is harder to get ignited under low engine loads as compared to diesel fuel. At state where the engine speed was 600 rpm, the BFSC was reported lower, after the engine reached 700 rpm and higher, the BSFC of dual fuel operation was always lower than diesel operation [12]. In figure 4b, throughout engine loads, the BSFC of dual-fuel operation was always lower.

Another comparative research about CNG and gasoline by [2] shows that BSFC of CNG fuel was reported lower than gasoline, this is since CNG has a higher heating value (47.669 MJ/kg) than gasoline (44 MJ/kg). The rapid escalation in friction at low engine throttle but high rpm results the increase of BSFC.
Figure 5. BSFC for each engine speed for: 50% throttle (a), 80% throttle (b) [2].

From figure 5, it can be seen that throughout various engine speed and loads, CNG gives lower SFC. This means that CNG consumes less fuel mass to produce a certain amount of power. In the other words, CNG is more economic than gasoline in term of fuel consumption. In figure 5a, trendline shows that the SFC of CNG gradually increase as the engine speed increases. However, in figure 5b, at 80% throttle condition, the SFC of CNG seems like to constant at 5000 rpm to 5500 rpm. When compared to another alternative fuel, such as hydrogen, the BFSC of CNG is higher than that of hydrogen. The BFSC decrease as the power output increase. The condition at which the BSFC reaches the lowest value is known to as the “best economical mixture” [6]. For example, in figure 5b, at engine speed 4000 rpm, that is the point where gasoline operation is most economical in term of fuel consumption. Another study regarding hydrogen and CNG fuel has been performed, according to...
Zareei et al. [14], it has been reported that when compared to diesel fuel and pure CNG, adding hydrogen reduces the value of BSFC. Because hydrogen has a larger caloric value, the more hydrogen content is increased, the less fuel is consumed. Higher caloric value means higher energy content per unit mass. Hydrogen lower caloric value is 119.93 MJ/kg and CNG 45.8 MJ/kg [6].

Several studies conducted by Semin shows that engine injector in CNG engine can give huge impact on engine performance. By modifying its holes number, holes diameter can improve engine performance such as engine brake power, indicated torque and indicated specific fuel consumption [16-21]. Compression ratio improvement also enhance engine performance in terms of torque and engine power [22-26].

3.3 Exhaust Gas Temperature and Peak Cylinder Pressure

Jahirul et al. [2] reported that the exhaust gas generated from CNG combustion was always higher in comparison to gasoline throughout various engine speeds. CNG has a higher heating value (45.8 MJ/kg) than gasoline (43 MJ/kg) and igniting temperature of CNG is higher, which causes this to happen. In internal combustion engine, fuel burning could continue until the end of stroke expansion. Since CNG has a slower flame propagation speed than gasoline, it is increasing the exhaust gas temperature. This is another cause of higher exhaust gas temperature.

![Figure 6](image_url)

**Figure 6.** Engine exhaust gas temperature in relation with engine rpm for: 50% throttle (a), 80% throttle (b) [2].
Form figure 6, it shows that exhaust gas temperature increased as the engine RPM increased. The temperature different between CNG and gasoline is not much at 50% engine throttle (figure 6a), however at 80% throttle, the temperature different is quite significant (figure 6b). The heat remained trapped at high speeds because the amount of heat transferred from the cylinder to the jacket water was reduced, as was the amount of lubricating oil. The average exhaust gas temperature for gasoline was 602.36°C and for CNG was 747.05°C at 80 percent throttle condition. At 5000 RPM, the highest exhaust temperature for gasoline and CNG were found to be 747.05°C and 893.1°C, respectively [2]. In contrast to pure diesel fuel operation, the ignition delay of a dual fuel engine increases as engine speed decreases. Dual-fuel modes have a slower burning rates and longer ignition delay. When compared to diesel fuel mode, the initial rate of pressure rise is low and the maximum engine cylinder pressure is decreased [10]-[11]. When comparing dual fuel mode to diesel mode, the peak cylinder gas pressure for both pilot fuels is found to be lower because a reduction of gaseous fuel-air mixture combustion rate during the premixed controlled combustion stage and later ignition under dual-fuel operation. It has been reported that at full load, CNG gives a higher gross heat release rate (HRR) in comparison to that diesel mode. This is most likely richer natural gas-air mixture that able to burn faster. In the early phase of pre-ignition and combustion, the HRR in the premixed combustion phase is greatly impacted by the time of ignition delay, mixture generation, and combustion rate. Higher NO\textsubscript{x} production is likewise linked to a high value of HRR [10].

3.4 Knocking

Pre-ignition (the igniting of the mixture before the spark plug fires) or detonation (the spontaneous combustion of the remaining fuel/air combination in the chamber) are the causes of knocking. Knocking occurs in compressed ignition engines because of the combustion of premixed fuel, and the knock degree is determined by the period of ignition delay. In general, there are three types of knocks have been found in dual-fuel engines, according to a study conducted by Nwafor [11]. The premixed pilot fuel combustion causes diesel knock, end gas auto-ignition causes spark knock, and unpredictable knock is caused by alternative fuel secondary ignition. The key causes that impact the incidence of these knocks are the amount of pilot fuel, engine rpm, engine gas flow rate, ignition delay period, secondary ignition time interval, and engine load. Increase the pilot fuel quantity while reducing the main fuel in dual-fuel engines able to reduce knocking.

4. Conclusion

CNG is a promising alternative fuel due to its availability, clean emission, and the performance produced by CNG is comparable to that of another fossil fuel or in other words, the combustion from CNG can achieve efficiencies like petroleum liquid-based fuel. As compared to liquid-based fuel such as diesel oil or gasoline, CNG gives lower BTE in comparison to diesel. However, CNG gives lower BSFC in comparison to diesel or gasoline fuel. In terms of exhaust gas temperature, CNG combustion was always gives higher temperatures than gasoline. The peak cylinder gas pressure of CNG was found to be lower than diesel operation. In general, the power produced by CNG combustion is slightly lower in comparison to diesel, this can be overcome by adding hydrogen to CNG to increase produced power.

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