A Comparative Study on Influence of Natural Gas Composition on the Performance of a CNG Engine

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Abstract

Natural gas is the cleanest fossil fuel and it has high energy conversion efficiencies for power generation in internal combustion engines. Natural gases have varying composition depending on the place where they are produced. This paper studies the effects of natural gas composition on the combustion and emissions characteristics of CNG engines and presents the overall combustion characteristics obtained from running a 1.65 L, 4-cylinder EF 7 CNG engine. Engine power, Torque, BMEP and BSFC were measured under steady state operation conditions at full load conditions. The obtained simulation results were compared with experimental ones in the literature and showed that the CNG composition had a considerable influence on engine performance and fuel economy. A correlation has been proposed to help gain insight into the relationship between the Methane Number (MN) and engine power, and it provides a practical method for estimating the engine power when the composition of natural gases varies.

1. Introduction

Environmental regulations, tightening legislations, growing concerns about shortage of crude oil resources and the high price of conventional fuels have led to the creation of incentives to promote and further evaluate alternative fuel sources for conventional internal combustion engines. Natural gas is one such fuel available in large quantities in many parts of world at attractive prices. It is a clean burning fuel as compared to the conventional liquid fuels like diesel or gasoline [1]. Natural gas has been investigated extensively for use in spark-ignition (SI) and compression-ignition (CI) engines. It is predominantly constituted from methane (CH4), and also contains heavier hydrocarbons and inert diluents. The levels of these species vary substantially with geographical source, time of year, and treatments applied during production or transportation. Natural gas has a high octane number and therefore it is suitable for engines with relatively high compression ratio. Its self-ignition temperature is 730°C and it requires intense source of energy to enable combustion i.e. glow plug, spark plug or pilot liquid fuel. The CNG engine also yields very low levels of PM emissions when compared with other conventional engines. Natural gas combustion is clean and emits less CO2 compared to other fossil fuels, which makes it favorable for utilization in internal combustion engines [2-5]. In light of these advantages, the number of CNG vehicles is continuously growing, and old vehicles are being converted into CNG vehicles through engine modifications [6-8].

When considering the use of natural gas, it is vital to understand the effects of fuel composition on the combustion system. Natural gas is a mixture of various hydrocarbon molecules. Commercial-grade natural-gas compositions vary from 70% to 95% CH4, with the balance composed of heavier hydrocarbons (primarily ethane, C2H6, and propane, C3H8) as well as diluents such as molecular nitrogen (N2) and CO2. There are also trace levels of sulfur compounds, often added as odorants, and other hydrocarbon species. The effect of fuel composition on the combustion process and on the emissions from natural-gas fuelled engines has been ad-dressed in both fundamental and applied studies. The majority of research has focused on spark-ignition engines, which are currently the predominant form of natural-gas engines.

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Kubesh et al. [9] emphasized that a change in octane number resulting from a change in fuel composition had a critical influence on vehicle driving conditions near knock-limited power, and they developed a correlation between the octane number and gas composition. Naber et al. [10] studied the effects of variations in natural gas composition on auto-ignition of natural gas under direct-injection (DI) diesel engine conditions experimentally in a constant-volume combustion vessel and computationally using a chemical kinetic model. Thigagaran et al. [11] investigated varying gas composition effects on the performance and emissions of a spark-ignited engine. Ly [12] examined the variations of natural gas composition variations on the operation, performance and exhaust emissions of natural gas-powered vehicles. Min et al. [13] investigated the effects of the difference in gas composition on the engine performance and emission characteristics of a Compressed Natural Gas Engine. The TLHV (Total Lower Heating Value of Intake) was proposed as a potential index for compatibility of gas fuels in a CNG engine. McTaggart-Cowan et al. [2] studied the implications of natural-gas composition on the combustion in a heavy-duty natural-gas engine and on the associated pollutant emissions. They reported the effects of adding ethane, propane, hydrogen, and nitrogen to the fuel. They indicated that these additives had no significant effect on the engine’s power or fuel consumption. Kim et al. [14] numerically and experimentally evaluated the influence of fuel composition on the combustion and emissions characteristics of CNG engines. In their research work, a correlation was proposed to help gain insight into the relationship between the Wobbe Index (WI) and engine power. The performance and emission characteristics of a CNG engine were experimentally investigated under different natural gas compositions by Ha et al. [15]. They showed that the emissions of CO2, CO, and NOx were decreased as the HHV of the fuel gas was lowered. On the other hand, the emissions of THC were not consistent, and the extent of change in their emissions was small. Karavalakis et al. [16] investigated the implications of natural gas composition on the gaseous pollutants, fuel economy, and the engine power output of two light-duty vehicles operated over different driving cycles. The results of their study showed that for modern light-duty NGVs, fuel properties have a clear and direct impact on fuel economy and some emissions components, such as CO2 and NMHC, but not for other emission components, such as THC, NOx, and CO. Jahanian and Jazayeri [17] studied the influence of natural gas composition on engine operation in HCCI mode. Six different compositions of natural gas have been considered to study the engine performance via a thermo-kinetic zero-dimensional model. Results indicated that the peak value of pressure/temperature of in-cylinder mixture is dependent of fuel Wobbe number.

Natural gas has many advantages such as its domestic availability, widespread distribution infrastructure, low cost, and clean-burning qualities to be used as a transportation fuel in Iran. Iran has the world’s second largest reserves of natural gas (15.8% of the world’s total) second only to Russia. Iran has the third largest consumption of natural gas in the world after United States and Russia. Iran also has the world’s largest growth rate in natural gas consumption [18]. Due to the distinguished characteristics of natural gas, studying the availability of natural gas in internal combustion engines, and investigating the effects of its composition on performance and emissions characteristics of natural gas fueled engines become one of the utmost important research directions for researchers. This paper evaluates the implications of natural gas composition on the performance of a natural-gas fueled spark ignition engine. Currently, natural gas is available from diverse production areas in Iran. Eventually, the various compositions of natural gas will affect the power and emission characteristics of engines. Thus, the objective of this study is to understand the performance characteristics of natural gases with varying composition in CNG engines, and to establish a correlation that can provide a practical method for determining the power output of CNG engines operating with various natural gases.

### 2. Methane Number and Fuel Composition

The knock resistance of a fuel is determined by comparing the compression ratio at which the fuel knocks to a reference fuel blend that knocks at the same compression ratio. Different scales have been used to rate the knock resistance of CNG including the motor octane number (MON) and the methane number (MN). The differences in these ratings are the reference fuel blends used for comparison to the natural gas. The correlations used by the engine manufacturers for MON as a function of H/C and MN as a function of MON are:

\[
\text{MON} = -406.14 + 508.04\times(H/C) - 173.55\times(H/C)^2 + 20.17\times(H/C)^3 \quad (1)
\]

\[
\text{MN} = 1.624\times\text{MON} - 119.1 \quad (2)
\]

In this paper, six different kinds of gases having various fuel compositions are selected to investigate the performance characteristics of gases: Hereafter, the test gases are referred to as Gases A, B, C, D, E, and F in this paper. The compositions and properties of the test gases are tabulated in table 1. Values for MN are calculated using Eqs. (1) and (2).
Table 1. Compositions and properties of test fuels

|          | Gas A | Gas B | Gas C | Gas D | Gas E | Gas F |
|----------|-------|-------|-------|-------|-------|-------|
| CH₄      | 87.7  | 90.01 | 97.42 | 88.24 | 84.87 | 89.88 |
| C₂H₆     | 3.9   | 3.6   | 0.64  | 3.15  | 9.39  | 2.3   |
| C₃H₈     | 1.4   | 0.99  | 0.075 | 1     | 2.12  | 1.15  |
| N-C₄H₁₀  | 0.25  | 0.24  | 0.045 | 0.26  | 0.55  | 0.33  |
| I-C₄H₁₀  | 0.135 | 0.16  | 0.027 | 0.24  | 0.29  | 0.12  |
| N-C₅H₁₂  | 0.115 | 0.1   | 0.043 | 0.525 | 0.61  | 0.15  |
| I-C₅H₁₂  | 0.1   | 0.09  | 0.05  | 0.13  | 0.07  | 0.17  |
| N₂       | 3     | 2.61  | 0.5   | 3.95  | 0.2   | 2.5   |
| CO₂      | 0.26  | 0.2   | 0     | 0.205 | 0.35  | 0.4   |
| H₂S      | 3.14  | 2     | 1.2   | 2.3   | 1.55  | 3     |
| Total    | 100   | 100   | 100   | 100   | 100   | 100   |
| LHV (MJ/kg) | 47.24 | 47.32 | 47.38 | 48.38 | 49.17 | 49.96 |
| MN       | 68.4  | 72.6  | 91.13 | 68.8  | 66.2  | 72.5  |

3. Engine modeling

GT-Power is a 1-D- simulation program from Gamma Technology, which simulates pressure, temperature and mass flow in different parts. This program is a part the main program GT-Suite. GT-Power is designed for steady state and transient simulations suitable for engine/power train control analysis and can be used to simulate all kinds of LC engines. The software uses one dimensional gas dynamics to represent the flow and heat transfer in the components of the engine model. The user constructs the model by dragging and dropping objects in the graphical user interface GT-SUITE, where the component database offers a broad range of engine components. After linking the components with connection objects the user may define properties for each component, setting up simulation options such as convergence criteria and specify desired output plots before running the simulation [19].

The engine model for an in-line 4-cylinder direct injection engine was developed for this study. Engine specifications for the base engine are tabulated in table 2.

Table 2. General specifications of the EF7 CNG engine

| Engine Model | EF7            |
|--------------|----------------|
| Bore (cm)    | 78.6 mm        |
| Stroke (cm)  | 85 mm          |
| Stroke/Bore ratio | 1.08     |
| Crank radius to connecting rod length ratio | 0.318 |
| CR           | 11.2           |
| Real capacity | 1.65 L        |
| Power (CNG)  | 76 kW @ 6000 rpm |
| Max Torque   | 137 N.m @ 3250 rpm |
| Min BSFC     | 228 gr/kW.hr @ 3000 rpm |
| EVO (CA)     | 500            |
| EVC (CA)     | 735            |
The engine model is shown in figure 1. The specific values of input parameters including the AFR, engine speed, and injection timing were defined in the model. The boundary condition of the intake air was defined first in the entrance of the engine. The air enters through a bell-mouth orifice to the pipe. The discharge coefficients of the bell-mouth orifice were set to 1 to ensure the smooth transition as in the real engine. The pipe of bell-mouth orifice with 0.07 m of diameter and 0.1 m of length are used in this model. The pipe connects in the intake to the air cleaner with 0.16 m of diameter and 0.25 m of length was modeled. The air cleaner pipe identical to the bell-mouth orifice connects to the manifold. A log style manifold was developed from a series of pipes and flow-splits. The flow-splits compose from an intake and two discharges. The intake draws air from the preceding flow-split. One discharge supplies air to adjacent intake runner and the other supplies air to the next flow-split. The last discharge pipe was closed with a cup to prevent any flow through it because there is no more flow-split. The flow-splits are connected with each other via pipes with 0.09 m diameter and 0.92 m length. The junctions between the flow-splits and the intake runners were modeled with bell-mouth orifices. The discharge coefficients were also set to 1 to assure smooth transition, because in most manifolds the transition from the manifold to the runners is very smooth.

The intake runners for the 4-cylinders were modeled as four identical pipes with .04 m diameter and 0.1 m length. Finally the intake runners were linked to the intake ports which were modeled as pipes with 0.04 m diameter and 0.08 length. The valve lash (mechanical clearance between the cam lobe and the valve stem) was set to 0.1 mm. The exhaust runners were modeled as rounded pipes with 0.03 m inlet diameter, and 80 bending angle for runners 1 and 4; and 40 bending angle of runners 2 and 3. Runners 1 and 4, and runners 2 and 3 are connected before enter in a flow-split. Conservation of momentum is solved in 3-dimensional flow-splits even though the flow in GT-Power is otherwise based on a one-dimensional version of the Navier–Stokes equation. Finally a pipe with 0.06 m diameter and 0.15 m length connects the last flow-split to the environment. Exhaust system walls temperature was calculated using a model embodied in each pipe and flow-split [20].

Figure 2. The details of EF7 CNG engine model

4. Model validation

The experimental results obtained from IPKO (Iran Khodro R&D unit) were used for the purpose of validation in this study. EF 7's Engine specifications and present single cylinder direct injection engine model are listed in table 4. Engine speed was fixed at 3000 rpm and in this comparison. The torque and power diagrams have been plotted in figures 3 and 4 respectively. It can be seen that they are in good agreement with the experimental results up to speed of 4500 rpm. Only small deviation was obtained at higher speeds due to the difference between the engine operation conditions shown.
in figure 5. However, considerable coincident between the model and experimental results can be recognized in spite of the mentioned model differences.

5. Results and discussion

5.1. Brake mean effective pressure of the CNG engine

Figure 6 shows the variation of BMEP with engine speed. As expected, by increasing the MN number the BMEP increases resulting in more generated output work and fuel F has the highest BMEP.

5.2. Brake efficiency of the CNG engine

Figure 7 depicts the variation of brake efficiency with engine speed. It is evident that by increasing the MN number of the fuel, the brake efficiency increases and the fuel F has the highest efficiency.

5.3. Power of the CNG engine

The power performance of the converted CNG engine was evaluated at full load condition. Figures 8 and 9 show the power versus engine speed and power as a function of MN at the engine speed of 3000 rpm, respectively. The maximum power was observed at an engine speed of 6000 RPM. Gas F yielded the maximum observed power of 76 kW. The slight difference in the power of the gases is especially noticeable at the high engine speed regions. It was observed that the engine power appears to be proportional to the MN of the gas used. The effect of the fuel composition on the variation of engine power could be estimated using the MN of the gas.

Figure 3. Comparison of engine output torque of simulation and experimental results at full load

Figure 4. Comparison of engine output power of simulation and experimental results at full load
Figure 5. Relative error of the simulation

Figure 6. Variations of brake mean effective pressure versus engine speed

Figure 7. Variations of brake efficiency versus engine speed
Figure 8. Variations of power versus engine speed

Figure 9. Variations of power versus Methane Number at 3000 rpm

5.4. Torque of the CNG engine

Figure 10 illustrates the variation of torque with engine speed. The maximum torque for all gases was observed at an engine speed of 2800 RPM. Gas F showed a maximum torque of 130 Nm. It should also be noted that the torque data at both high and low RPM values varied significantly with gas composition.
5.5. Fuel Consumption of the CNG engine

The effect of fuel composition and engine speed on the BSFC is described in figure 11. It shows that Gas A has the best BSFC. Additionally, the BSFC of Gas F rises rapidly when the engine operates between 5000 and 6000 RPM. The BSFC is expected to be inversely proportional to the MN of the gas [21, 22]. Thus, a low BSFC is expected for fuels having higher MN. However, our results were not consistent with this expectation. It can be explained that these gases were considered to have consumed more fuel in order to achieve the same power production. In addition, the quantity of nitrogen in gases plays a crucial role in the determination of the spark timing, because nitrogen slows down flame propagation. The overall deviation of the BSFC for all of the fuels is less than 10% when the engine speed is below 3000 RPM. However, the deviation is more than 15% when the engine speed is over 3000 RPM. Therefore, a change in fuel composition will require frequent adjustment of the spark timing of the engine to keep it operating at the same power. Failure to make this adjustment will lead to a change in the fuel consumption.
6. Conclusions

This study was designed to explore the effect of fuel composition on emissions and combustion characteristics of a CNG engine at full load. The principle conclusions can be summarized as follows:

- It was observed that there are many other factors affect the combustion and emission characteristics of a CNG engine. Understanding the effect of MN of fuel on them is significant.
- The engine power and torque varies with the MN. The engine power at full load condition was directly proportional to the MN. High power output is obtained as the MN increases. A linear equation was proposed to predict the change in power as a function of MN.
- Gas A showed the best fuel efficiency performance at full load. For all fuels, it can be explained that these gases were considered to have consumed more fuel in order to achieve the same power production.

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