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1-D Modelling Comparative Study to Evaluate Performance and Emissions of a Spark Ignition Engine Fuelled with Gasoline and LNG

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Abstract. In this study, a spark-ignition engine fuelled with gasoline and LNG was modelled in 1-D at wide open throttle by using Ricardo-Wave software. Different engine speeds ranging from 1500rpm to 4500rpm with an increment of 500rpm were studied to evaluate the effects of gasoline and LNG on engine performance and exhaust emissions. It is determined that LNG decreases engine performance and emissions as well, at especially high speeds.

1 Introduction

With developments in engine modelling software, it became possible to make predictions for many crucial engine characteristics such as usage of alternative fuels, combustion visualization in cylinder, examination of combustion chamber geometry, effects of all related geometric and operating conditions in terms of engine performance and emissions.

There has been an ever increasing demand on usage of alternative fuels in internal combustion engines. The most widely available and used alternative fuels are LNG (Liquefied Natural Gas), CNG (Compressed Natural Gas), and LPG (Liquefied Petroleum Gas). LNG and CNG fuels are the most popular fuel varieties and approximately 23 million natural gas vehicles are available by 2015 in the world, led by China (4.44 million), Iran (4.00 million), Pakistan (3.70 million), Argentina (2.48 million), India (1.80 million), and Brazil (1.78 million) [1].

Use of alternative fuels in many countries, especially in CNG (Compressed Natural Gas) and LNG (Liquid Natural Gas) is increasing the use of fuel in internal combustion engines. LNG and CNG fuel are the most popular fuel varieties and approximately 23 million natural gas vehicles by 2015 in the world. The natural gas (NG) consists of methane (90%), ethane, propane, other heavier hydrocarbons, fewer nitrogen, oxygen, carbon dioxide, pollutants such as sulphur compounds and water. LNG is cleaner than NG since hazardous contaminants are removed during liquefaction. LNG has higher density than CNG. Volumetric energy density of LNG is 2.4 times greater than CNG, and 60% more than diesel fuel [2]. Designed usage of LNG engines with higher compression ratios and usage of LNG in engines provide improved performance, fuel economy and avoid engine knock due to high octane number rating (~130)

While it is very important to determine the effects of usage of these alternative fuels especially LNG on engine performance and exhaust emissions, there are limited number of published works in literature.

Ha, J. Y. et al. [3] used a direct-injection engine fuelled with CNG. They observed that combustion characteristics at wide open throttle greatly improved with early injection timing. On the contrary, the late injection timing gave better results at partial throttle openings.

Venugopal, T. and Ramesh A. [4] evaluated effects of throttle opening for butanol–gasoline mixture fuel in a spark ignition engine with dual injection system. They measured engine performance, engine detonation and emissions. Lower hydrocarbon emission was reported for increasing throttle opening. Lower NO_x emission was observed with increasing fuel ratio among 35%-100% throttle openings.

Aslam, M. U. et al. [5] used a retrofitted spark ignition engine with CNG fuel. Tests were carried out for different mixing ratios of gasoline and CNG. They determined optimum engine operating parameters according to fuel consumption, exhaust emissions, engine performance.

Verma, G. et al. [6] tested hydrogen enriched natural gas for various H/C ratios. They found that thermal efficiency increased with increasing H/C ratio. Exhaust gas temperature increased with decreasing H/C ratio. NO_x emission at 55Nm torque became highest for H/C ratio of 4.22, however, NO_x emission at full load had the highest for H/C ratio of 4.5. The mixed fuel with H/C ratio of 4.5 showed best overall performance.

Hooper, P. R. et al. [7] used Ricardo-Wave software to build a 1-D engine model for multi-fuel (indolene, kerosene JET A-1) operation. At 3000 rpm, they calculated minimum specific fuel consumption (SFC) of 273 g/kWh and 310 g/kWh for indolene and JET A-1, respectively.

Jahirul, M. I. et al. [8] tested a spark ignition engine with gasoline and CNG fuels. They measured engine performance parameters and exhaust emission. They investigated effects of throttle opening for both gasoline and CNG fuels. CNG was reported to have less engine performance and emissions for all throttle openings.

Usage of LNG in internal combustion engine provides more flexibility in the design of an internal combustion engine because LNG has an auto-ignition temperature of ~853 K whereas gasoline and diesel auto-ignite at approximately 523 K and 483 K, respectively.

In the current study, a complete 1-D engine model including intake and exhaust manifolds was built in Ricardo-Wave software. The engine is spark ignited and fuelled with gasoline and LNG. The engine performance and exhaust emissions were investigated for wide opening throttle at several engine speeds for both gasoline and LNG.

2 1-D Engine modelling

This work specifically focuses on numerical simulation of a commercially engine with Ricardo-Wave software. Technical specifications of the modelled spark ignition engine are given in Table 1.

The engine 1-D model is built including the entire engine from the beginning of the intake line to the end of the exhaust line as plotted in Figure 1.

At the beginning of the engine modelling phase, each engine components (pistons, cylinders, valves, ports, engine blocks, intake and exhaust manifolds, fuel line, exhaust line and throttle) are separately formed by defining their properties in Ricardo-Wave. Then, they are connected to each other by defining the relevant relations and boundary conditions.

Multi-Component Wiebe model is used as the combustion model. Woschni is used as the heat transfer model. In order to read engine data on the 1-D engine model, many sensors, actuators and signal processor are located at certain points on the model. For each engine speed, the analyses were run for 250 engine cycles in order to ensure fully developed steady conditions before reading the data.

Table 1. Technical specifications of test engine.

Number of cylinders	4
Displacement volume (lt)	1.6
Cylinder diameter (mm)	76.5
Stroke length (mm)	86.9
Compression ratio	11:1
Connecting rod length (mm)	141
Wrist pin offset (mm)	4.2
Number of valves	16

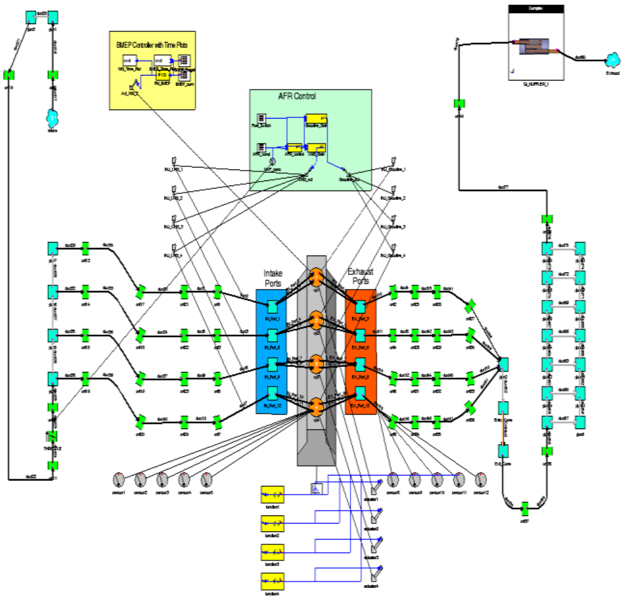

Figure 1. 1-D Engine model.

3 Results and discussion

The 1-D engine simulation model was carried out for seven different engine speeds from 1500 rpm to 4500 rpm at 500 rpm intervals. Parameters of engine performance and exhaust emissions were calculated for all seven engine speeds at wide open throttle.

The results with respect to speeds and different fuels (gasoline and LNG) are presented below in comparative manner by evaluating torque (Fig. 2), power (Fig. 2), fuel consumption (Fig. 3), specific fuel consumption (Fig. 3), indicated mean effective pressure (Fig. 4), volumetric efficiency (Fig. 4), effective efficiency (Fig. 4), NO_x (Fig. 5), exhaust temperature (Fig. 5), CO_2 (Fig. 6) and CO (Fig. 6).

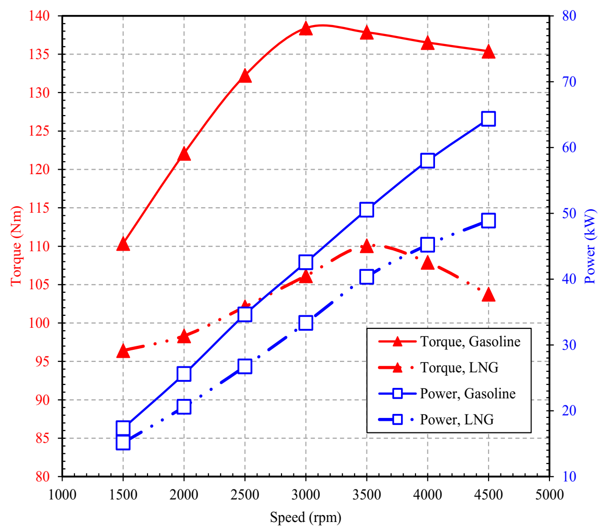

Figure 2. Torque / power – speed.

The torque curve has a nearly parabolic shape with respect to the engine speed for both fuels. These torque curves are consistent with the known engine behaviour which is the torque falls down from its peak due to all kinds of increased losses. The maximum torque values of 138 Nm and 110 Nm are obtained at 3000 rpm and 3500 rpm for gasoline and LNG, respectively. The torque for LNG is about 80% (that varies with speed) less than the gasoline since the lower heating value of LNG for unit fuel mass is 85% less. As a result of this, the indicated mean effective pressure (IMEP) is also low for LNG as plotted in Fig. 3.

As also plotted at the right vertical axis on Fig. 2, the power increases almost linearly due to more fuel intake into cylinder. As a result of less lower heating value of LNG, the power curve for LNG falls under the gasoline curve with increment rates of 1.2 and 1.6 kW/rpm for LNG and gasoline, respectively. The different power slopes are entirely due to the fuel's chemical content.

Figure 3 shows that the volumetric efficiency for LNG is following same trend but lower than gasoline. The calculated volumetric efficiencies are 75-79% and 78-94% for LNG and gasoline, respectively. These values are consistent with reported approximately volumetric efficiency of 75-90% [9]. As also plotted in Fig. 3, effective efficiencies are about thirty percent as expected for typical spark ignition engines.

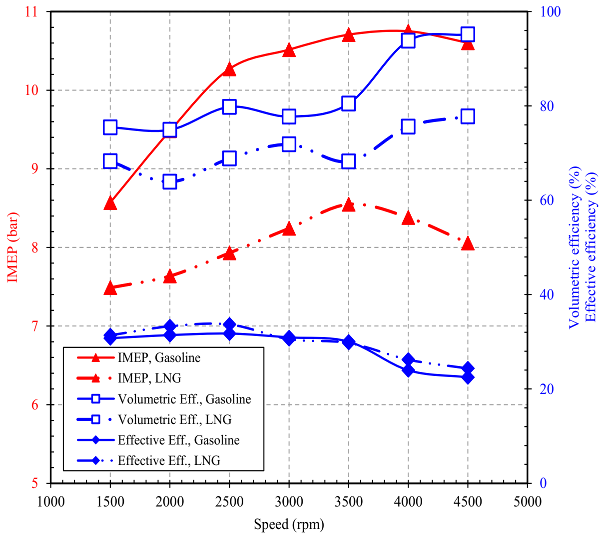

Figure 3. IMEP / volumetric efficiency / effective efficiency – speed.

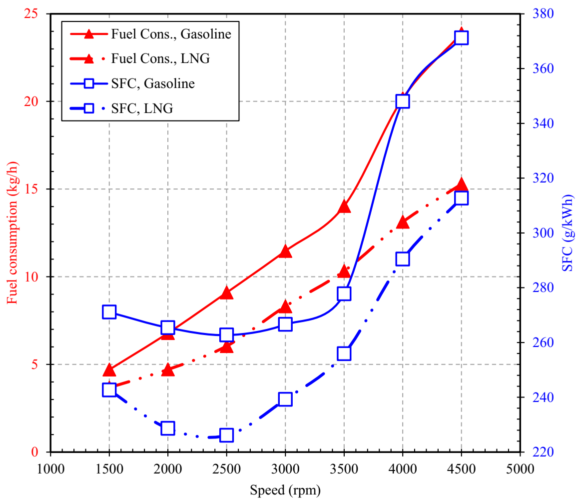

Figure 4. Fuel consumption / SFC - speed.

As seen in Figure 4, the fuel consumption with speed is linearly increasing in parallel to power increase. Gasoline fuel consumption is increasing more than LNG at high engine speeds. The specific fuel consumption (SFC) has roughly a parabolic shape making its minimum at about 2500 rpm (265 g/kWh) and 2300 rpm (225 g/kWh) for gasoline and LNG, respectively. LNG specific fuel consumption curve has very similar trend with gasoline specific fuel consumption curve. These behaviours are consistent with the torque graphs. It is known that the lowest specific fuel consumption is about 270 g/kWh for spark ignition engines [10].

Exhaust temperature and NO_x are plotted in Fig. 5. NO_x with speed increases by making some fluctuations. For the considered range of speed, the average NO_x level for gasoline is slightly less than LNG since the flame temperature of gasoline is lower than LNG. NO_x formation depends on the air-fuel ratio and in-cylinder temperature because nitrogen and oxygen enter the reaction at high temperatures and NO_x are formed. Exhaust temperatures support NO_x trends.

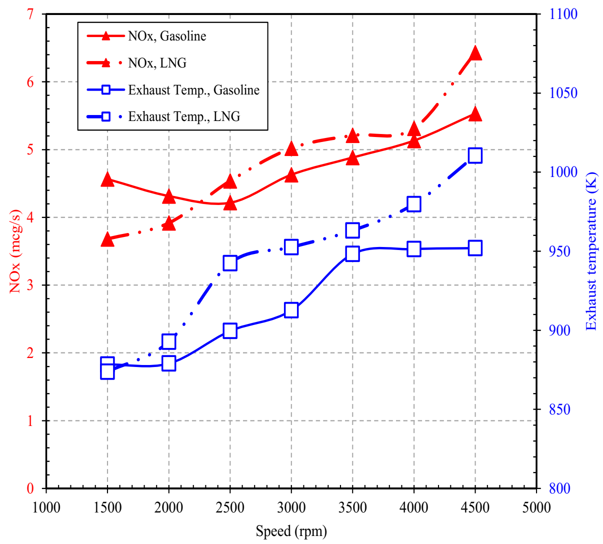

Figure 5. NO_x / exhaust temperature - speed.

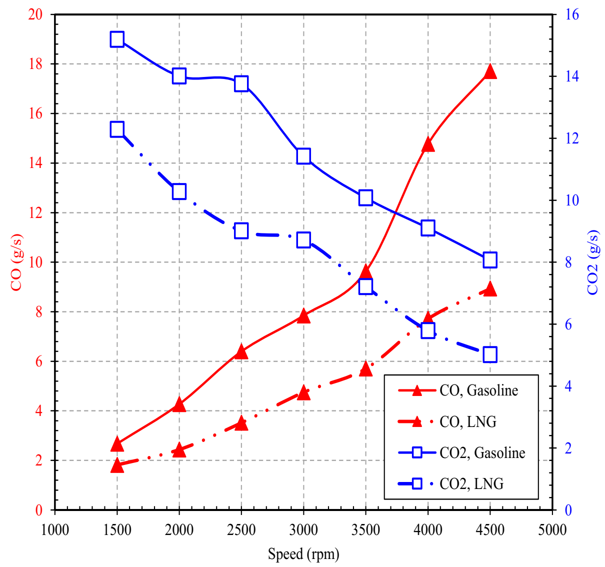

Figure 6. CO_2 / CO - speed.

As seen in Figure 6, CO emission with speed increases faster for gasoline. The emission of CO_2 decreases with increasing speed. LNG has the highest energy/carbon ratio of any fossil fuel and produces less CO_2 and CO per unit of energy. Combustion efficiency decreases at high speed and the partial products of incomplete combustion increases as a result of this CO formation increase. The emissions chart shows that LNG gives lower emissions.

4 Conclusions

In this study, a spark ignition engine performance and exhaust emissions were determined for gasoline and LNG fuels at wide open throttle by using a 1-D model. Findings are listed below.

- The torque and power for LNG is less than gasoline for all speeds since the lower heating value of LNG for unit fuel mass is 85% less.
- Similarly, the IMEP and volumetric efficiency is also lower for LNG.
- Gasoline fuel consumption is increasing more than LNG at high engine speeds. The specific fuel consumption (SFC) is calculated as 2500 rpm (265 g/kWh) and 2300 rpm (225 g/kWh) for gasoline and LNG, respectively.
- LNG has lower emissions for engine operating parameters.

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