Evaluation of Exhaust Emissions Reduction of a Retrofitted Bi-Fuel Spark Ignition Engine

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Abstract

This paper presents the experimental results carried out to evaluate the exhaust emissions and performance of a computer integrated bi-fuel spark ignition engine that has been retrofitted for two fuels namely compressed natural gas (CNG) and base fuel gasoline, operations under steady state with lean burn condition. The used engine was a Proton Magma 4-cylinders spark ignition engine. The emission results such as CO, HC and NO_x were measured and compared between the above two fuels. A locally produced three way catalytic converter (TWC) consisting of platinum (Pt), palladium (Pd), cerium oxide (CeO_2) and rhodium (Rh) was used to assess the emissions. The CeO_2 was used in TWC as an oxygen storage capacity (OSC) to enhance the oxidation process for CO and HC oxidations. The results show that the arrangement of retrofitting catalytic converter and operation with lean burn condition is very effective to reduce exhaust emissions. From the investigation, it is found that CNG produced 15% less brake power, 15%-18% less specific fuel consumption (SFC) and 10% higher thermal efficiency than gasoline fuel. The emission results showed at the entrance of TWC that CNG produced 30% higher NO_x emissions and lower 12% and 90% HC and CO respectively. The details about the emissions management system together with the catalytic and engine performance results have been presented and discussed. The results of this investigation will be used to develop new monofueled natural gas engines as well as to develop CNG emissions based TWC.

Nomenclature

CNG	compressed natural gas
OSC	oxygen storage capacity
rpm	revolution per minute
sfc	specific fuel consumption

Introduction

Malaysia is trying to produce new natural gas engines to replace gasoline and diesel fueled vehicles. Currently, Petronas NGV Co. Ltd. is involved in exploring the feasibility of converting existing diesel and gasoline engines into natural gas fueled engines. The number of registered vehicles in Malaysia is about 12 millions with 51% of them using gasoline engines. At present, there are seven to ten thousands taxi cab running on bi-fuel system and the government is trying to promote bi-fuel high way car vehicles. Currently, the price of natural gas is 55% lower than gasoline fuel shown in Fig. 1. This country has 50 years gas reserve as compared to ten years petroleum reserve. The government planned regarding refueling stations for CNG can be seen in Fig. 2. With this reserve status, the government is trying to promote the utilization of NG through replacing fossil fueled vehicles with CNG fueled vehicle. The implementation will be done in two ways such as (a) development of a new monofueled natural gas engine; however, the development of this engine is very difficult to produce within short time as it requires new ignition, combustion and injection system. In addition, refueling infrastructure and gas storage are required for long distance and long duration. (b) Rapid modification of existing gasoline engine to bi-fuel solution besides developing of a new monofueled engine. This could be a realistic way to increase CNG based bi-fuel vehicles.

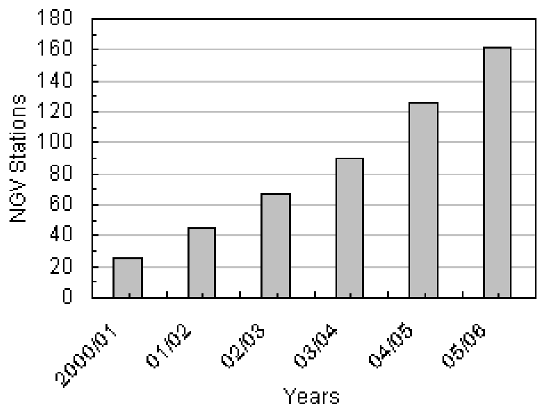


Fig. 1 Price vs. fuels (year 2005)

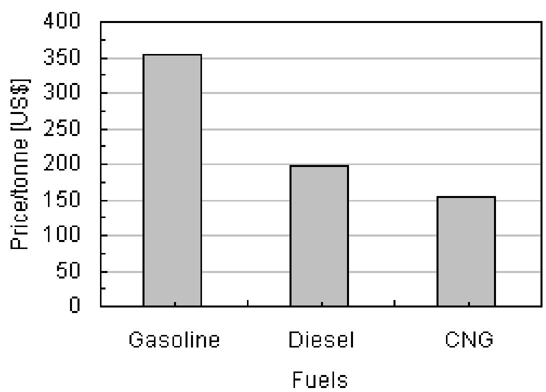


Fig. 2 Planned NGV stations vs. years in Malaysia

The retrofitting is more justifiable in the sense that the petroleum reserve is still not finish and it has to be used, and the gas reserve and refueling infrastructure is not over surplus. Hence, retrofitting is suitable that can use both the fuels. In addition, retrofitting is cost effective in terms of low cost engines retrofitting optimization and low NG cost that is combined potential to reduce environmental pollution. Recently, manufacturer are converting gasoline engine into bi-fuel engine in order to satisfy customer demand rather than producing new dedicated NGVs as currently happening in Malaysia [1]. In the past [2], most of the light-duty vehicles were actually adopted for bi-fuel solutions. However, they were not properly retrofitted for natural gas as optimization of spark advance.

This paper presents performance and emission results of a computer integrated bi-fuel spark ignition engine that has been retrofitted for both fuels together with a new three way catalytic converter fitted on the exhaust manifold to reduce CO, HC and NOx emissions.

The objectives of this investigation are:

- To evaluate the performance and the exhaust emission of retrofitted bi-fuel spark ignition (SI) engine.
- To evaluate the effectiveness of TWC converter in reducing engine exhaust emissions.

Experimental Setup and Procedures

A schematic diagram of the experimental apparatus is given in Fig. 3. The CNG stored under a maximum pressure of 200 bars flowed to the engine through a gas conversion kit. The kit supplied CNG to the engine carburetor at approximately atmospheric pressure (0.8 bar) so that carburetor can effectively use it. Specification of test engine and gas conversion kit is shown elsewhere [3].

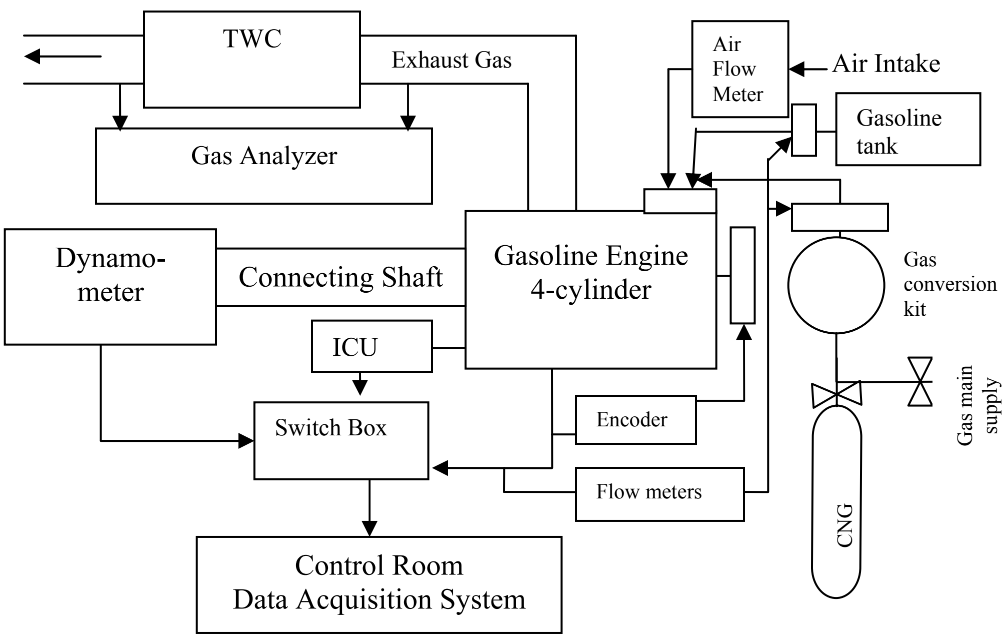


Fig. 3 Layout of the experimental set-up

An Auto-check (Model 974/5) and a Bacharach model CA300NSX analyzers (standard version, k-type probe) were used to measure the concentration of carbon monoxide (CO), unburn hydrocarbon (HC) and oxides of nitrogen (NOx). Compressed natural gas (CNG) used in this experiment is based on the storage and compositions standard maintained by the government of Malaysia. Natural gas composition, physicochemical properties (including gasoline fuel used in Malaysia) can be found in elsewhere [3].

A locally produced three-way catalytic converter has been used to reduce the unwanted pollutant gases like CO, HC and NOx from the exhaust gas stream. The catalytic material consists of platinum (Pt), palladium (Pd), rhodium (Rh) and Cerium oxide (CeO_2). The Pt and Pd are used to oxidize CO and HC to CO_2 and H_2O. The Rh is used to reduce NOx to N_2 and O_2. However, the efficiency of the three-way catalytic converter depends on the availability of O_2 and the temperature in the exhaust gas stream. The role of CeO_2 in TWC is to afford as an O_2 storage capacity (OSC) which liberates or adsorbs O_2 if the air to fuel ratio is perturbed. The details about work function of CeO_2 in the TWC can be found elsewhere [4-5].

The catalytic bed was placed in the exhaust pipe (near manifold) where the maximum temperature (catalytic bed temperature) reaches about 560 ^oC. This high temperature is required to oxidise HC (as well as unburn CH_4) in the exhaust gas from natural gas combustion. The details about the catalytic bed placement in the exhaust system can be found elsewhere [6].

Result and Discussion

Engine performance

The performance test was done with open throttle condition from engine speed 1500 rpm to 5500 rpm. From the performance test engine brake power, SFC, thermal efficiency and relative AFR were obtained as discussed below.

Brake power

The brake power output versus engine speed over the range from 1500 to 5500 rpm for both gasoline and CNG fuels is shown in Fig. 4. It can be seen that the maximum brake power obtained by gasoline fuel is 47 kW followed by CNG fuel (39 kW) which occurs at 5000 rpm. The CNG fuel produces an average (over all the speed range) of 15% less brake power due to the effect of reducing charge energy density per injection into the engine cylinder as compared to gasoline fuel. Similar results were obtained in another investigation done by [7].

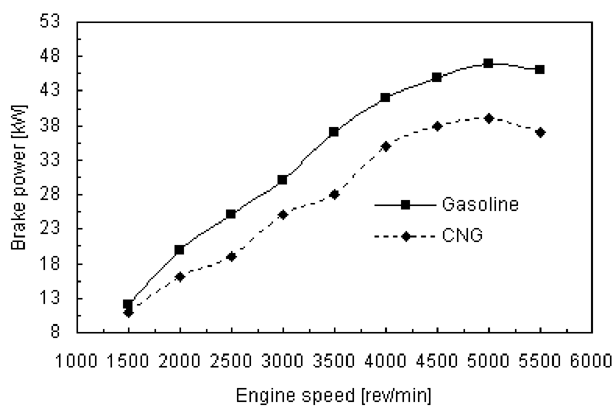


Fig. 4 Brake power vs. engine speed at WOT

Specific fuel consumption (SFC)

Fig. 5 shows the variation of specific fuel consumption (SFC) versus engine speed. It is found that the specific fuel consumption is lower for CNG fuel. This can be explained that the net weight (in mass basis) of CNG gas per injection into engine cylinder is lower than that of gasoline fuel due to gaseous nature of CNG fuel. The SFCs for CNG and gasoline fuels are 300 g/kW.h and 380 g/kW.h respectively at 5000 rpm. On average, CNG reduces 15% -18% lower SFC than gasoline fuel. The minimum SFCs found for CNG and gasoline are 260 g/kW.h and 320 g/kW.h respectively at 3500 rpm.

Relative air fuel ratio lambda (λ)

The relative AFR is measured prior to injection into engine cylinder as shown in Fig. 6. All over the speed range, the lambda varies from 1.25 to 1.47, which indicates as lean burn engine operation. The maximum lambda (λ) values found from CNG and gasoline fuels are 1.472 and 1.453 respectively at engine speed of 4000 rpm. The average lambda values for CNG and gasoline fuels are 1.391 (with standard deviation 0.067) and 1.374 (with standard deviation 0.064) respectively. It is found that lambda value for CNG is slightly higher than gasoline fuel. This is mainly due to low energy injection into engine cylinder as compared to gasoline fuel.

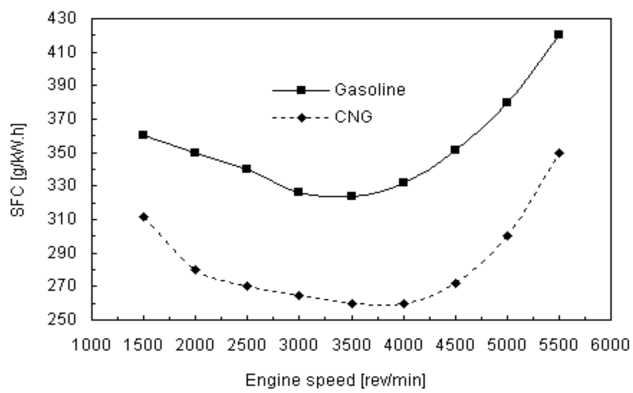


Fig. 5 Specific fuel consumption vs. engine speed at WOT

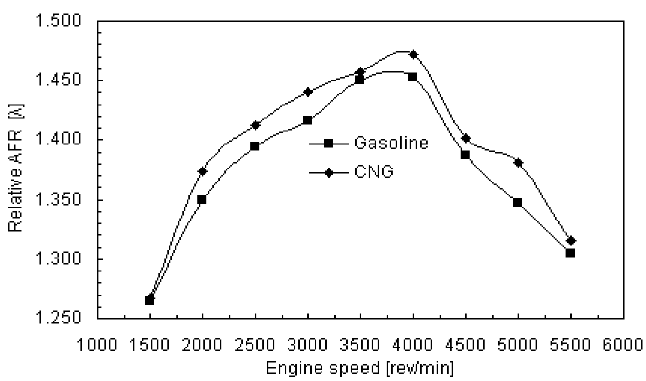


Fig. 6 Relative AFR vs. engine speed

Thermal Efficiency

Thermal efficiency is a measure of the efficiency and completeness of combustion of the fuel, or more specifically, the ratio of the output or work done by the working substance in the cylinder in a given time to the input or heat energy of the fuel supplied during the same time. The brake thermal efficiency is shown in Fig. 7. It is found that all over the speed range thermal efficiency of CNG was higher than gasoline. The maximum efficiency obtained from CNG is 28% followed by gasoline fuel with 25% at engine speed between 3500 rpm and 4000 rpm. The average thermal efficiency over all the speed range for CNG and gasoline are 0.26 and 0.23 respectively or 11% higher than gasoline fuel.

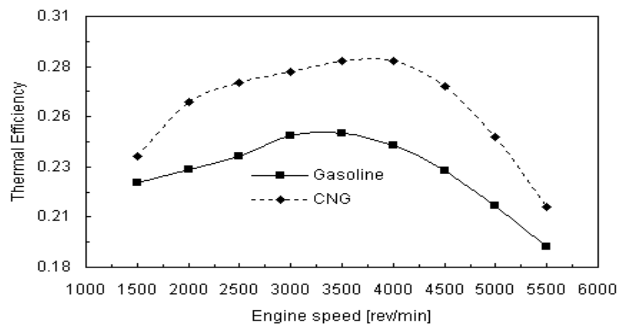


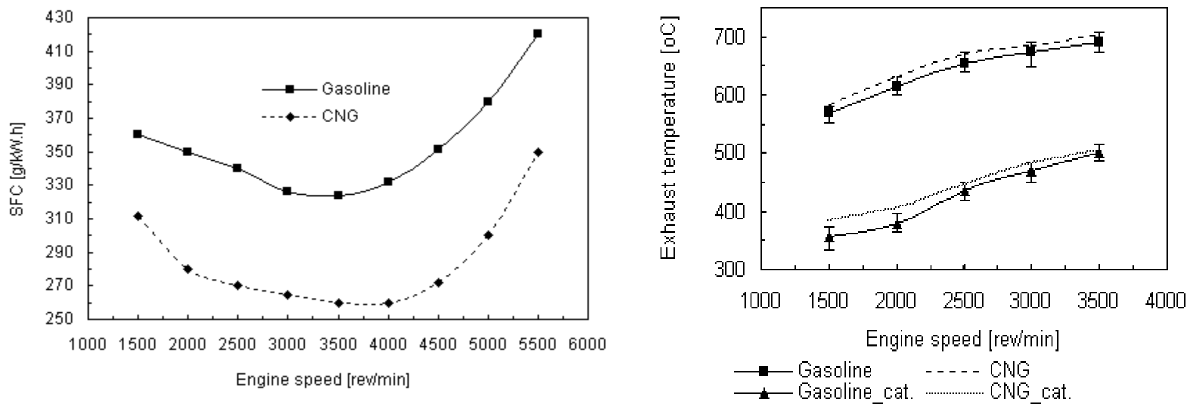
Fig. 7 Thermal efficiency vs. engine speed

Exhaust emissions

The emission test was done with different constant load for different engine speed as mentioned earlier on above. Figs. 8 to 12 show emission characteristics results. The emission test is repeated three (3) times and the results are shown with the sample means at different engine speed as well as the variation around the sample mean.

Exhaust gas and catalyst temperature

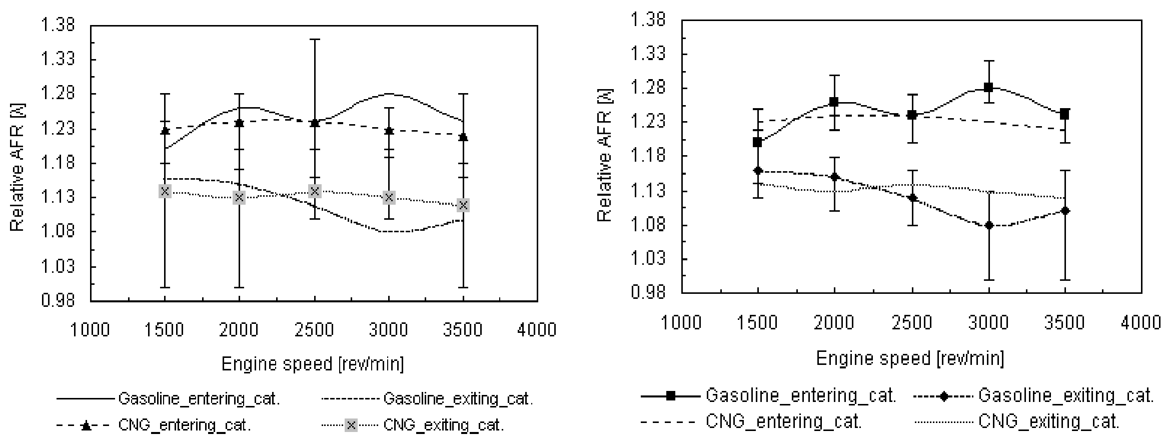
Fig. 8 shows exhaust manifold temperature and catalytic bed temperature. The catalyst temperature is obtained from the average value of inlet and outlet temperatures of the catalytic bed. The error bar in Fig 8(a) is obtained from CNG results that show the sample means at different engine speed as well as the variation around each sample mean. Fig. 8(b) shows similar results with error bar on gasoline fuel. From the analysis of results consisting of comparable symbol (error bar), it can be said that the temperature variation is quite stable for both the gasoline and CNG fuels except at 3000 rpm (Fig.8(b)), where the temperature variation for gasoline (at theentrance of catalytic converter) fuel is slightly higher than other test points. It can also be seen from all over the speed range, that increasing engine speed from 1500 rpm to 3500 rpm increases exhaust gas temperature from 572 ^oC to 690 ^oC for CNG and from 568 ^oC to 694 ^oC for gasoline fuels. Similarly the catalyst temperature increases from 385 ^oC to 504 ^oC for CNG and from 328 ^oC to 498 ^oC for gasoline. The higher temperature produced from CNG fuel is mainly due to high combustion temperature and combustion duration as compared to gasoline fuel as discussed by [8].



(a) With error bar on CNG result (b) With error bar on gasoline result

Fig. 8 Exhaust temperature vs. engine speed

Fig. 9 shows relative AFR (λ) for both the gasoline and CNG fuels at the entrance and outlet of the catalytic converter. The lambda is measured and calculated by the authors of this paper, based on exhaust gas emissions as described in [3]. The result shown with comparable symbol (error bar) in Fig. 9(a) is obtained from CNG fuel that shows the sample means at different engine speeds as well as variation around the sample mean. At the entering of catalytic converter the lambda variation is higher at 2500 rpm as compared to other test speed. At the outlet of catalytic converter the major variation is found at 1500 rpm, 2000 rpm, and 3500 rpm Fig. 9(b) shows the error bar is for the gasoline results. It can be seen that the major variation is found at engine speed 3000 rpm and 3500 rpm at the leaving point of the catalytic converter.



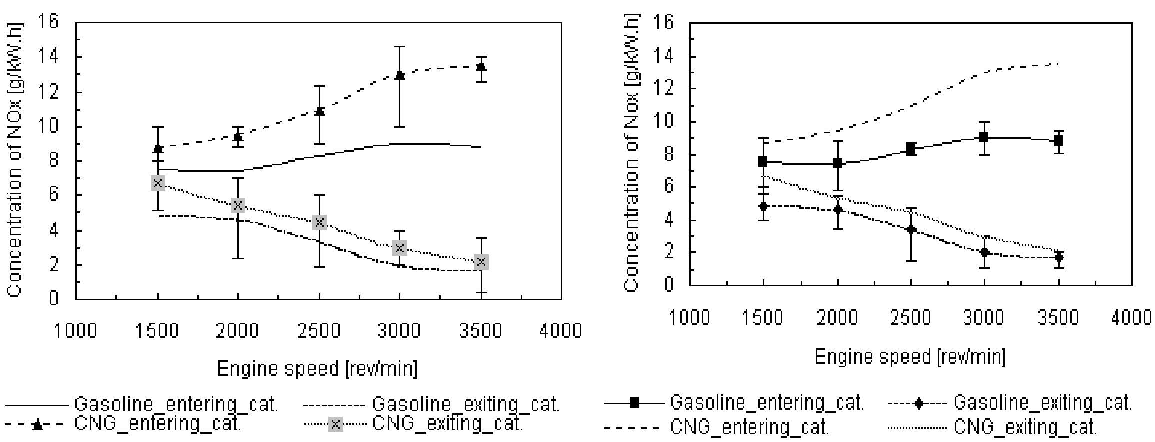
(a) With error bar on CNG fuel (b) With error bar on gasoline fuel

Fig. 9 Relative AFR vs. engine speed vs engine speed

It is found that lambda reduces after catalytic converter for both the fuels. This is mainly due to conversion of CO to CO_2 as well as HC oxidized and conversion of NO_x to N_2. On average, the lambda value at the entrance of catalytic converter for CNG and gasoline fuels are 1.23 and 1.24 respectively. At the outlet of catalytic converter lambda for CNG and gasoline fuels are 1.13 and 1.12 respectively.

NOx emission

NOx emissions characteristic (entering and exiting catalytic converter) is shown in Fig. 10. The results shown with comparable symbol (error bar) in Fig.1 0(a) is obtained from CNG fuel that shows the sample means at different engine speeds as well as variation around the sample mean. A similar result with error bar obtained from gasoline fuel is shown in Fig. 10(b).



(a) With error bar on CNG fuel (b) With error bar on gasoline fuel

Fig. 10 NOx concentration vs. engine speed vs. engine speed

Entering catalytic converter

It can be seen that CNG produces on average 30% higher brake specific NOx emissions over all the speed range as compared to gasoline fuel. Lean burn conditions (as compared to gasoline) and high combustion temperature of CNG are the main reasons that generate higher NOx emissions. It is found that the NOx value for CNG and gasoline are 13 g/kW.h and 9 g/kW.h respectively at 3000 rpm.

Exiting catalytic converter

It is found that NOx conversion/reduction increases with increasing engine speed for both the CNG and gasoline fuels. This is mainly due to increasing catalytic bed temperature together with the availability of oxygen (for lean burn) in the exhaust stream. Hence, it is expected that rhodium is effective to reduce NOx to N_2 with the help of CeO_2. The average NOx reduction efficiency over all the speed range for CNG fuel is 60% and for gasoline is 63%. At 3000 rpm, the NOx reduction efficiency for CNG fuel is 69% and for gasoline is 78%. Similar NOx emission result from gasoline fuel was found by [9].

CO emission

Fig. 11 shows brake specific CO emission versus engine speed. The result is shown in log axis with error bar that contains sample means at different engine speed as well as variation around the sample mean. The formation of CO in internal combustion engine is a result of incomplete combustion of the fuel. This occurs when there is insufficient oxygen near the hydrocarbon (fuel) molecule during combustion. Moreover, incomplete combustion could be caused by the quenching of the hydrocarbon oxidation near a cold surface in the combustion chamber.

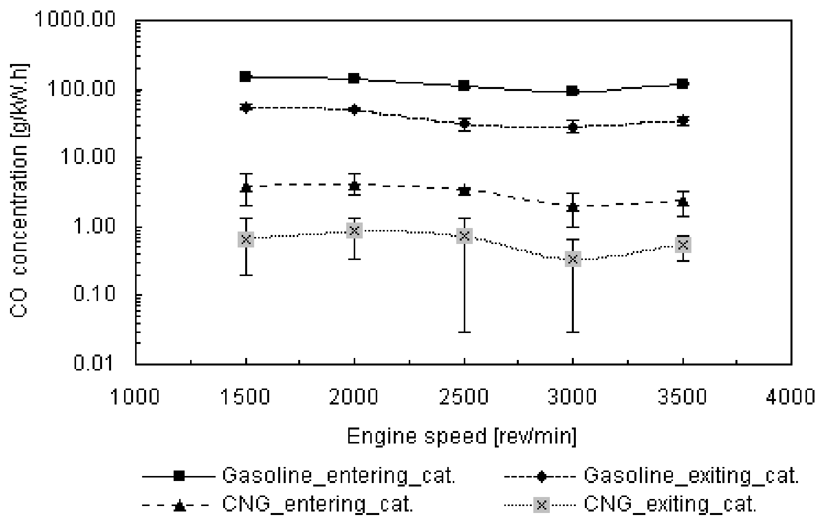


Fig. 11 CO concentration vs engine speed

Entering catalytic converter

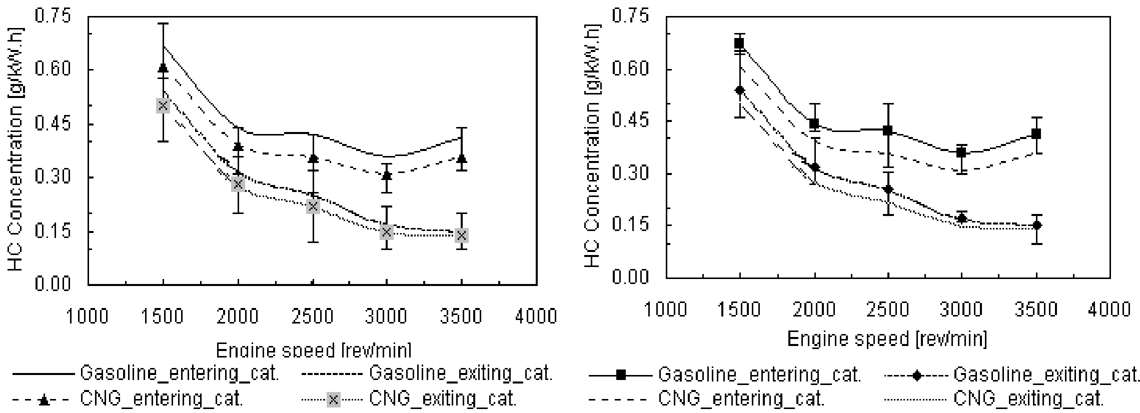
It is found that CNG produces, on average lower level of CO emissions due to lean conditions as compared to gasoline fuel. CNG produces on average 90% lower CO emission than gasoline fuel. At 3000 rpm, CNG produces CO emission of 2.05 g/kW.h while gasoline produces 92 g/kW.h.

Exiting catalytic converter

It is shown that the catalyst oxidizes CO emission from both CNG and gasoline fuels. This result reveals that CeO_2 is effective as an OSC that supports platinum (Pt) to oxidizes CO into CO_2 at low to high temperature [10]. The CO conversion efficiency on average over all the speed range for CNG fuel is 80% and for gasoline is 68%. It can also be seen that at the exit of catalytic converter, the variation of CO was higher than gasoline.

HC emission

Fig. 12 shows brake specific HC emission versus engine speed.



(a) With error bar on CNG fuel (b) With error bar on gasoline fuel

Fig. 12 HC concentration vs. engine speed

Entering catalytic converter

It is found that CNG reduces over all the speed range 12% lower brake specific HC emission (non methane HC) mainly due to lean burn condition than gasoline. At 3000 rpm, CNG produces 0.31 g/kWh and gasoline produces 0.36 g/kWh.

Exiting catalytic converter

It is found that the catalytic material is effective to oxidize HC with increasing engine speed or increasing catalytic bed/catalyst temperature (Fig 8). On average, the reduction efficiency of CNG is lower than gasoline fuel such as CNG 35% and gasoline 40%. At 3000 rpm, the HC conversion efficiencies for CNG are 50% and for gasoline 55%. At 3500 rpm, the HC conversion efficiency for CNG and gasoline fuels increases to 60% and 65% respectively, indicating that the conversion efficiencies increase with increasing catalyst temperature. This is evidence that higher temperatures are required to oxidize more HC gases [11].

Conclusion

The following conclusions may be drawn from the present study:

Performance test

- CNG reduces 15% brake power and 15% -18% SFC as compared to gasoline fuel.
- The relative air fuel ratio (lambda) for CNG and gasoline fuels is 1.391 and 1.374 respectively.
- Thermal efficiency of CNG is 11% higher than gasoline.

Emission test

- CNG produces slightly higher temperature than gasoline at the manifold as well as at the catalytic bed.
- At the entrance and outlet of the catalytic converter, the average lambda values for CNG are 1.23 and 1.13 respectively; and for gasoline are 1.24 and 1.12 respectively.

- CNG produces 30% higher NO_x emission than gasoline fuel at the entrance of catalytic converter.
- Catalytic efficiency found for CNG emission is 60% and for gasoline fuel is 63%.
- At the exit of catalytic converter, CNG reduces 90% CO emission than gasoline; catalytic efficiency found for CNG emission is 80% and for gasoline is 68%.
- At the entrance of catalytic converter, CNG shows 12% lower HC emission than gasoline.
- Catalytic efficiency found for CNG emission is 35% and for gasoline is 40%.

Hence, bi-fuel engine could be useful with TWC to reduce harmful emissions. The results of this experiment will be used to develop new natural gas engines as well as new catalytic material to reduce CNG emissions.

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