NATURAL GAS VEHICLES-AN OVERVIEW

P. L. Mtui
University of British Columbia, Institute of Production Innovation
P.O. Box 35075, Dar es Salaam, Tanzania

ABSTRACT

This paper reviews the state of the art of the natural gas vehicles where emphasis is based on the engine technology and emissions of spark ignition engines. Usually, natural gas engine produce relatively low emissions of carbon monoxide (CO) and particulate matter (PM) but oxides of nitrogen (NOx) can be fairly high. The techniques to reduce the NOX in engine combustion include stoichiometric operation using a three-way catalyst and "lean-burn"/"fast burn" engines with NOX controlled through reduced flame temperature. Both spark and compression ignition engines have demonstrated excellent emissions performances-exceeding the 1994 Environmental Protection Agency (EPA) standards. Optimized natural gas engines are significantly more efficient than present gasoline engine, with lean-burn natural gas engines approaching diesel efficiency.

INTRODUCTION

Natural gas engines hold both economic, environmental and technical promise through improved efficiency, reasonable costs, and reduced pollutant emissions [1].

Economically, the future of gas engines look promising. Firstly, natural gas is readily available at reasonable costs from abundant domestic supplies through the existing transportation and distribution systems. The Natural Gas Vehicles (NGVs) show a considerable potential for reducing oil consumption and improving balance of payments (as well as urban air quality) in may developing countries.

From environmental point of view, it has been shown that a substantial reduction in the emissions of oxides of nitrogen, carbon dioxide and exhaust hydrocarbons can be effected in the premixed charged natural gas engines[2]. In addition natural gas has low properties of soot formation and hence is known to be a clean gas. Thus, natural gas seem to be a good candidate as an alternative fuel both for spark ignited engines as well as compression ignition engines.

Technically, the existing technology of engine manufacturing and infrastructure act as a base for the natural gas engine. Moreover, these natural gas engine have an advantage of being adaptable to biogas technology which may emerge in future.

NATURAL GAS AS A VEHICLE FUEL

The natural gas supplied in pipelines is a mixture of various species. Typically, 85-99% by volume of the gas is methane[3]. Other constituents include inert gases like nitrogen and carbon dioxide. The non methane hydrocarbon existing in the natural gas mixture are ethane and propane where ethane constitutes about 78% of the non methane hydrocarbons. The mix of these minor constituents differ greatly on the source and the processing technique of the natural gas.

Unlike liquid fuel, natural gas mixes readily with air which makes it very suitable for spark ignition engines. With this easy mixing it makes it easier for cold starting as it does not need evaporation.

Knock Properties

The high ignition energy of natural gas makes it highly resistant to self ignite when compared to diesel and gasoline fuels. Pure methane has octane number of 130 which is the highest of the commonly used fuels. Octane number is define as the measure of resistance of fuel to ignite as it si ignited by the energy source like spark plug. Because of the high anti-knock properties of methane, higher compression ratios as high as 15:1 can be afforded compared to 8-10:1 for gasoline fuel. With high compression ratio, significant higher thermal efficiencies can be achieved.

Knocking phenomena

As the unburned gases in the engine cylinder are compressed ahead of the flame front, their temperature increases and undergo a pre-chemical reaction. Given sufficient time and high temperature, they will auto-ignite explosively ahead of the flame front and high pressure spikes results. These shock waves can damage the engine, and also tend to interrupt the boundary layer of the combustion chamber walls, increasing heat transfer to the walls and thus possible causing engine overheating. Methane is extremely high resistant to knock and hence poses an advantage to be used for engine as alternative fuel without a major possibility of onset of knock.

Flame Speed

The flame speed of natural gas is lower than other hydrocarbon fuels. This low speed is mainly due to the higher ignition temperature and the fact that methane has got the negative pressure index. That is to say the higher the pressure the lower the flame speed. With this low flame speed, it means longer combustion period. To circumvent this problem of slow combustion, the ignition timing is properly advanced to compensate for the ignition delay and combustion. The need for advanced timing can be offset to a considerable degree by the use of high compression ratios and compact, turbulent combustion chambers. These increase flame speed and decrease the distance the flame travels.

Power Output

Because of the low density of the natural gas, a stoichiometric mixture of natural gas and air occupies about 10% more volume than the similar stoichiometric gasoline/air mixture with the same energy content. When applied to a fixed engine displacement, an air fuel mixture that can be induced for burning in each stroke is about 10% less resulting a penalty of about 10% less in power output. This means that a gasoline engine operating at full throttle will produce about 10% less power[4]. When natural gas applied to diesel engine, it is usually injected at a high pressure (of the order of 200 bar) thus provide practically the same efficiencies and power output as diesel engines[5].

ENGINE TECHNOLOGY AND EMISSIONS

The ignition and combustion of fuel allows the flame kernel to be created and grow in size. Following this, the flame front spreads in the combustion chamber. The rate of spread of the flame speed, air fuel ratio, turbulent level as well as the temperature in the combustion chamber.

Work output from an internal combustion engine is equal to the product of fuel input per stroke, the efficiency of the fuel conversion to work and the number of strokes per minute. Regarding to the thermal efficiencies of the engine, a theoretical thermal efficiency of the Otto-Cycle engine is given by $\eta=1-1/r^{\gamma-1}$ where r is the compression ratio and y is the ratio of specific heats for constant pressure and temperature respectively. It is therefore seen that the higher the compression ratio the higher the thermal efficiency. However, the rate of improvement by increasing the compression ratio becomes small above 12:1 because the frictional losses tend to increase with the increasing compression ratio.

Fuel Injection and Control

Precise control of fuel air ratio and ignition timing is necessary to minimize emissions from natural gas vehicles while maintaining good performance and fuel economy. This requires an engine control system capable of reacting to rapid changes in engine speed and load typical to automobile services.

All natural gas engines require some mechanisms for mixing and controlling amounts of air-fuel ratio prior to combustion. These systems are generally designed to maintain a fixed nominal air fuel ratio over most of the operating range, often with a separate levels of idle and full operations. Both mechanically and electronically fuel-air metering and injection systems exist. A special concern in a compressed natural gas vehicle exists since the temperature of the gas after the expansion (to regulated pressure) is a function of the storage tank which varies during the operation.

Over the course of 1980's, the air fuel control and injection systems have evolved away from mechanical systems to electronic control. For the application to natural gas engines, the fuel injection systems have been designed as a retrofit package for gasoline engines. The basic engine control systems and sensors required for stoichiometric natural gas engine control systems are the same as those required for gasoline engine. Some fuel condition sensors (eg fuel temperature and pressure) may be needed to account for the greater variability in fuel conditions with the natural gas engines.

The possibility of operating the engine lean exists as long as there is a detector which detects the engine "running rough"[5]. This roughness could be detected by measuring the variations in the engine rotational speed over a combustion cycle. To improve performance and fuel economy, some high performance spark ignition engines incorporate knock sensors which allow them to retard spark timing to correct it before it becomes significant.

Air Fuel Ratio

The ratio of fuel to air in the combustion chamber is the key design for Otto-Cycle engine design. An air fuel mixture in which there is exactly as much air as required to react completely with the fuel is called a stoichiometric mixture and is given as an equivalent ratio, $\Phi=1$. A mixture with a grater amount of air is called lean and has $\Phi<1$ while the rich mixture has greater amount of fuel with $\Phi>1$. The air fuel ratio has an important effect on engine power, efficiency and pollutant formations. Fig 1 shows a typical variation of pollutant emissions with $\Phi>1$. The air fuel ratio has an important effect on engine power, efficiency and pollutant formations. Fig 1 shows a typical variation of pollutant emissions with Φ for a spark ignition engines. At Φ's above 1.0 there is too little oxygen to react fully with fuel so that CO and HC emissions increases. NOx emissions show peak at around $\Phi=0.9$ where the flame temperatures are high and excess oxygen is available. For the leaner mixtures, the flame temperature decreases. The lean limit (show in Fig 1) is the level where there an excess air such that below this limit ignition or combustion to occur is impossible.

Ignition System

Natural gas is rather hard to ignite, and thus requires high energy spark. The amount of energy required increases as the air fuel ratio becomes leaner. Spark duration is also important. Fluctuations in the air fuel mixture due to incomplete mixing can result is misfire if the spark duration is too short. As a rule of thumb for optimal combustion, ignition should be timed so that the centre of combustion (50%) burned point) occur about 10 deg after top dead centre (TDC[7]. As the mixture becomes leaner flame speeds are lower and thus advance of the plug spark timing is necessary. However, earlier ignition results in more compression of partially burned charge resulting higher NOx emissions and loss of efficiency. For this reason, design features to increase flame speeds and reduce combustion duration are very important for lean burn.

Combustion Chamber Design

In order to reduce knock and improve efficiency, the combustion chamber should be designed to maximize the flame speed and burning rates and/or minimize the distance the flame has to travel. This is quite important for high compression, lean burning engines using homogenous charge. The longer the total combustion time, the more changes the remaining unburned mixture.

Fast combustion and high compression ratio allows leaner mixed to be burned, reducing emissions and further improve thermal efficiency. This is the basis of the so called "leanburn/fast burn" engines. Such engines commonly achieve a 15-20% less fuel consumption compared to stoichiometric engines as well as substantially lower precatalyst for CO and NOx emissions. Natural gas looks to be a potential candidate for high compression lean burn fuel.

Combustion Systems

Three combustion arrangements are possible for natural gas engines. The first one is the homogeneous charge engine where mixture surrounding the spark plug is nominally the same composition as the bulk of the mixture in the cylinder. The second category is the stratified charge engine which uses lean mixture, but in the vicinity of the spark plug the mixture is richer which enhances ignition. Thirdly, is the pre-chamber type engine where ignition occurs in the rich mixture in the pre-chamber. The burning turbulent jet from the pre-chamber enters the main chamber at high temperature and pressure and ignite the charge in the main chamber. This method of ignition and combustion allows combustion with very lean mixtures.

Pollutant Formation

The pollutant emissions which are of major concern for natural gas engine are oxides of nitrogen (NOX) and particulate matter (PM). Both NOx and PM are environmentally unfriendly which is a major concern worldwide. NOx contributes to the depletion of ozone layer in the atmosphere while the particulate mater (PM) are considered to cause cancer. The particulate matter are microscopic solid particles coming out from the engine exhaust. Fig 1.0 shows the formation of NO which seem to depend very much on the availability of oxygen and the adiabatic flame temperature. Emissions of total hydrocarbons is lower for natural gas since natural gas is slower to react than most hydrocarbon. In the case of very lean mixtures, flame speed may be too slow and in worst case, incomplete combustion may result. This condition result in high emissions of HC. On the other hand, solid particulate matter occur as a result of combustion of very rich mixture.

Exhaust Catalyst

Three types of catalytic after-treatment are used with natural gas engines. These are (i)oxidation of HC (ii) non selective reduction of NO and (iii) selective reduction of NO.

The typical first category of catalysts are platinum and/or palladium. This catalyst increases the reduction of oxygen in the exhaust and the unburned hydrocarbon together with CO. On the other hand, the non selective catalyst for NOx reduction is rhodium which converts NO to nitrogen and oxygen. Regarding to the selective catalysts, the platinum/palladium/rhodium based catalyst can simultaneously and selectively oxidize HC and Co while reducing NOx. This type of catalyst is commonly known as "three-way" catalyst.

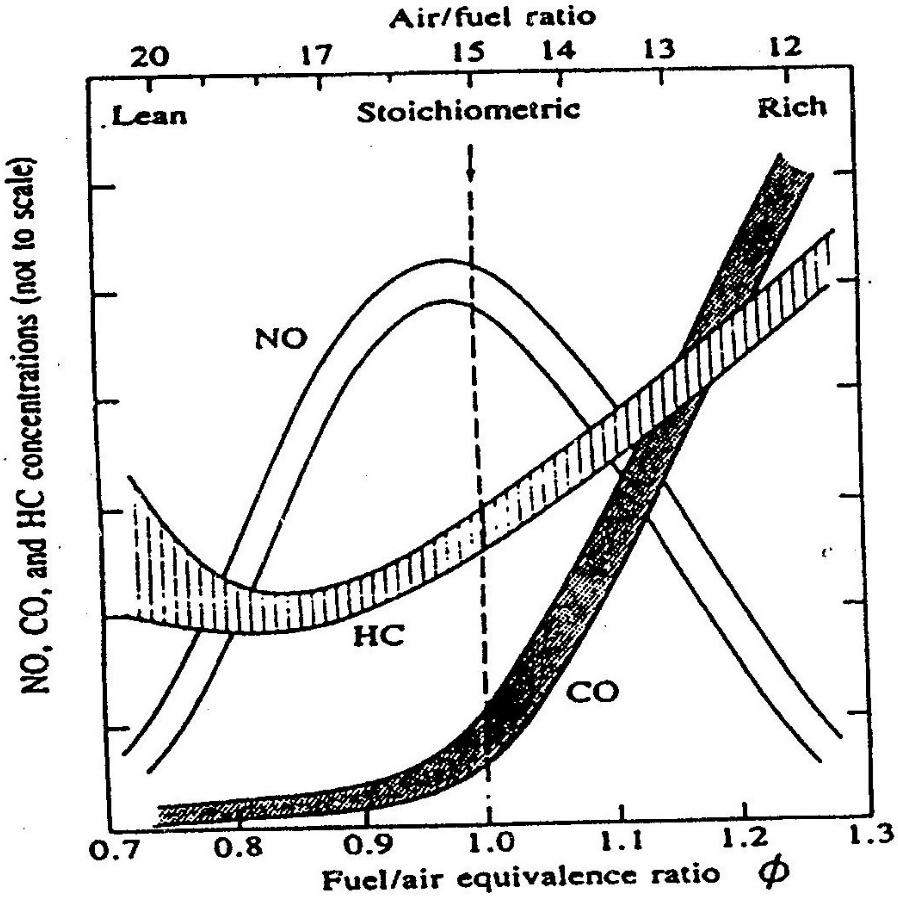

Fig. 1: Typical Emissions for Otto-Cycle Engine [7]

LIGHT DUTY PERFORMANCE AND EMISSIONS

The emission and performance data for dedicated, optimized, light duty natural gas vehicle using three-way catalyst system have been rarely reported in the literature. A large number of gasoline vehicles have been converted to natural gas operation, and many of these use closed-loop air-fuel ratio control systems when operating on gasoline. Many of these have used mechanical natural gas carburation system, with varying effects on emissions control [3].
More recently, a limited number of vehicles have been tested using

feedback control. Table 1 summarizes some of these test data. As this table shows, emission results were mixed, with a trend towards higher NOx, lower CO, and higher total hydrocarbons (THC), but lower non methane hydrocarbons, compared with the same vehicle operating on gasoline. It should be emphasized that all of the system shown in Table 1 were retrofits, with varying degree of optimization, and non can be considered representative of a fully optimized emission control system.

Table 1: Emissions performance of light duty vehicles with feedback emissions controls on natural gas and gasoline:

(The units of emissions of THC, NMHC, CO and NOx are in grams/mile)

Vehicle	THC	NMHC	CO	NOx
1984 Olds Delta 88/CNG, [6]				
Gasoline	0.40	0.26	9.84	0.4
Natural Gas	2.46	0.08	1.69	1.18
Difference	2.05	-0.18	-8.15	0.78
% Difference	507.9%	-68.3%	-82.8%	195.0%
1987 Chevrolet Caprice, [8]				
Gasoline	0.33	N/A	6.28	0.88
Natural Gas	1.79	0.20	3.40	0.78
Difference	1.46	N/A	-2.88	-0.10
%Difference	442.4%	N/A	-45.9%	-11.4%
1986 Buick Park Ave, [9]				
Natural Gas	1.991	0.188	0.071	0.438

Achievable Emission Levels

The light duty emission data presented in Table 1 are bey no means a representative of what could be achieved in light duty engine optimized for natural gas. Such engine would have higher compression ratio, optimized timing, and probably a three way catalyst composition optimized for natural gas engine.

This approach would result in low non methane HC and very low CO emissions, due to both the elimination of cold start enrichment and inherently lower emissions of these pollutants from natural gas vehicles. CO would be higher than with the lean burn engine, however, due to the trade-off between NOx and CO control in three way catalyst. Still lower NMHC and CO emissions could be achieved with a three-bed catalyst (three-way plus oxidation (with a secondary air injected between the beds.

Based on the above data, an optimized vehicle could be expected to at least to match the NOx performance of the best current gasoline engine, while significantly performing better for NMHC and CO. This would result in certification of NOx emissions below 0.4 gram/mile, NMHC around 0.05-0.1 gram/mile, and CO emissions below 1.0 gram/mile with fuel efficiency 15-20% better than emission controlled gasoline vehicle. IN the longer term, however, further improvements in fuel economy and NOx emission might be achieved through the application of "fast-burn" technology from lean burn engines.

CONCLUSION

Natural gas possess numerous advantages as "clean" fuel for motor vehicles. Substantial emission benefits have been reported even with the existing relatively undeveloped technologies. Ongoing technologies promise to reduce emissions still further, while increasing efficiencies well above the limits attainable with gasoline. In heavy duty vehicles, lean burn natural gas engines appear capable of efficiencies nearly equal to those of diesel engines with much lower emissions.

REFERENCES

1. G.A. Karim, On the Emissions of Carbon Monoxide and Smoke from Compression Ignition Engines Proceedings of 2nd Int. Clean Air Congress, Academic `press pp 617 (1970)
2. R.W. McJones and R.J. Corbeil, Natural Gas Vehicles: Exhaust Emissions and Operational Characteristics, SAE Paper No. 700078 (1970)
3. L.D. Siebers and F.C. Edwards, Auto-ignition of Methane and Natural Gas in Simulated Diesel Environment, SAE Paper No 910227 (1991)
4. G.A. Karim, The Dual-Fuel Engines of Compression Ignition Type - Prospects, Problems and Solutions, SAE Paper No 831073 (1983)
5. P.L. Mtui , Dual-Pilot Combustion of Compressed Natural Gas in CI Engines, Thesis Progress Report, Univ of British Columbia (1994)
6. British Columbia Research Corp, Exhaust and Performance Measurements of CNG Fuel Systems: Generation II Spark , Ignition Dual Fuel Engines
7. J.B. Heywood, Internal Combustion Engine Fundamentals, McGraw Hill, New York (1988)
8. R.I. Bruetch, Emissions, Fuel Economy and Performance of Light Duty CNG and Dual Fuel Vehicles, EPA/AA/CTAB - 88-05, US EPA MVEL, Ann Abour, MI, June 1988
9. California Air Resources Board, Definition of Low Emission Motor Vehicles Compliance with Mandate of Health and Safety Code Section 39037.05, El Monte, CA, 1989

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