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NGV - A Technical Assessment and an Overview of the World Situation

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NGV. - A TECHNICAL ASSESSMENT AND AN OVERVIEW OF THE WORLD SITUATION

(Sessione 2 / Relazione 4)

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This paper describes the aspects related with the use of natural gas as an automotive fuel. Fuel storage, air/fuel-mixture preparation, the in-cylinder combustion process and emissions of natural-gas-fueled vehicles are compared with the situation for the conventional fuels.

Natural gas is an excellent fuel for spark-ignition engines. However, for transport applications its use is hampered by the large storage volume and weight. Moreover, the air/fuel-mixture preparation, combustion process and exhaust-gas cleaning require more research and development effort to make natural gas economically and environmentally competitive with the conventional fuels.

1. INTRODUCTION

Natural gas can be used as a transport fuel for two reasons: the economy and the environment (ref.1). The production costs of natural gas are generally low and so are the costs of its distribution by pipeline. Basically, the price of natural gas could be lower than that of refinery products such as diesel fuel and petrol. However, it is the competition with other fuels and the government-imposed taxation which generally determine the user's price. An additional economic advantage of natural gas is the presence of resources in many countries of which many are politically stable. Factors negatively affecting the economics of natural gas as a transport fuel are the compression costs for high-pressure fueling and the high-pressure fuel-storage system.

The desire for cleaner exhaust gases from vehicles, the environmental reason, is to a large extent also connected with the economy. Clean air is an economic asset and cleaning of exhaust gases generally requires expenditure of money. The environmental impact of automotive transport can be seen in a worldwide context with respect to the greenhouse effect. Rather regional and local problems are the production and emission of acidifying compounds such as NO_x and SO_x. Smog, resulting from photochemically reactive hydrocarbons present in the exhaust gas, and particulate matter deteriorate the air quality. Natural gas can offer advantages in this respect over petrol and diesel fuel because of its lower CO_2 emission per unit of released energy and because of the low photochemical reactivity of methane, the major constituent of natural gas.

Natural gas can also have technological advantages over the conventional transport fuels. Often mentioned are its gaseous state and the higher knock resistance of natural gas compared with petrol. A higher knock resistance allows a higher compression ratio in spark-ignition engines which is beneficial for the engine efficiency. The gaseous state of the fuel would ease the process of mixing with combustion air and give a better homogeneity. Disadvantages are the low reactivity of methane in catalysts and the low cetane number which hampers its use as a diesel fuel. It should be stated here that also technological advantages and disadvantages are rather economic issues. Research and engineering have to serve in developing the technology to allow the application of any fuel required for economic and environmental reasons.

This paper will not deal in detail with the economic issues related with the use of natural gas as an automotive fuel. That would require a complete report incorporating all the different premises from country to country. The paper will rather concentrate on the technologies used for transport use of natural gas, al-be-it sometimes in connection with the local economic situation. Throughout the paper, comparisons between petrol and diesel fuel on the one hand, and natural gas on the other, will be made. Major items to be discussed are fuel storage and fueling, air/fuel-mixture preparation, combustion, and exhaust emissions. The aim of the paper is to show the stronger and weaker points of natural gas with respect to the traditional transport fuels.

4. FUEL STORAGE AND FUELING

In contrast with diesel fuel, petrol and LPG, natural gas has to be stored as a gas. Liquefaction of natural gas is only feasible at temperatures below - 162 °C and storage as a liquid therefore requires cryogenic equipment (ref.2). That equipment is very expensive; moreover, the evaporative cooling of the fuel at standstill of the vehicle by blowing off some gas without burning it will be unacceptable considering the greenhouse effect of methane. An automatic flare to burn the blown-off gas will make the installation even more expensive. Furthermore, the liquefaction of natural gas requires much energy and an expensive installation. It is estimated that the liquefaction of 1 m^3 (standard conditions) of natural gas costs approximately US$ 0.50. The use of liquefied natural gas is probably only economically feasible if it is imported from overseas in the liquid state.

High-pressure storage of the gas at a pressure of 200 bar is generally used (ref.3). The most common storage system is the Cr/Mo-steel cylinder having a deadweight of five times of that of the fuel stored. The specific mass of the tank and fuel is close to 30 g/MJ for diesel oil and petrol and approximately 145 g/MJ for natural gas at 200 bar. The increasing market for compressed natural gas (CNG) stimulates the development of so-called lightweight cylinders made from metal, steel or aluminium, wrapped with fibre glass. All composite cylinders are even lighter, having a weight of less than 50% of the steel cylinders. The problem of the newly developed cylinders however is the high price compared with the steel cylinders. Next to the weight, a drawback of storing the gas in high-pressure cylinders is the large volume, being a factor five higher than that for the equivalent amount of energy of petrol and diesel fuel.

Reduction of the pay load and load volume is hardly acceptable for the modern fleet of trucks. The economics in the transport sector require a high efficiency and load capacity per driver and per vehicle. Extra weight and volume for fuel storage is therefore not welcomed by the industry. This is the major hampering factor for natural gas as a transport fuel. The same applies to some extent for the passenger car. The car models have been optimised for minimum weight and maximum interior volume so that the addition of clumsy fuel cylinders is a drawback in comfort and value for money. Moreover, the fuel-gas cylinders are an addition to the existing fuel tank, since most vehicle owners want to be able to switch from natural gas to petrol in case they have to cover larger distances where no fueling with gas is possible. So, there is a strong incentive for lowering the weight of the cylinders and increasing the energy density of the gas.

A solution for the low energy density of pressurised natural gas can be adsorption of the gas to high surface-area materials (ref. 4). The larger the surface, the larger the adsorption will be. A typical adsorbent is activated carbon, with a specific surface area of 1500 m^2/g. Research is being carried out in Britain, the United States and Canada on new types of adsorbents (ref. 5,6). The major problem with adsorbent systems is that the efficiency decreases with pressure. At pressures up to 35 bar, the systems are very effective but it is difficult to get the same storage capacity as for gas in a cylinder at high pressure. The adsorbtion process is very sensitive to temperature. During adsorbtion, heat is released which has to be removed in order to maintain the capacity. To release the gas from the adsorbent, heat has to be supplied to the system. At the moment, more prospects for a lower storage volume are offered by increasing the 'standard' storage pressure from 200 to 300 bar.

The installations to refuel natural-gas vehicles (NGVs) are well described in the general literature (ref. 7,8). These installations are based on reciprocating compressors. In some cases the compressors are driven by gas expanders in stead of by electric motors. Fast-fill installations require higher investments than slow-fill installations. So-called home fill units require a much lower capital investment (US$ 4500) than commercial-size stations and can be connected to the gas supply of a private home. The energy these units require to compress 1 m^3 of gas (standard conditions) is 2 to 3 MJ, or almost

10% of the lower heating value of the gas. Filling of the fuel tank can take place during the night. A commercial-size station for slow filling of 100 buses will cost about US$ 2 000 000. For comparison, the price of a diesel fueling station is just 10% of that. The energy consumption of the commercial refuelling stations is roughly 3% of the calorific value of the fuel gas. This is much lower than that of the home fill units. A major reason is the intake pressure of the commercial unit being 8 bar instead of the close to atmospheric pressure of the home fill unit. The capital costs and the energy costs of a commercial refueling system add between US$ 0.08 and US$ 0.09 to the fuel costs per m^3. Currently, tests are being carried out to improve the efficiency and reliability of the compression units. An important issue is also the removal of liquids from the compressed gas, be it water, higher hydrocarbons or lubricating oil. The liquids can cause blockage of the reducer valves and initiate corrosion in the storage cylinders.

3. AIR/FUEL-MIXTURE PREPARATION

For a good performance of engines with respect to efficiency, power capacity and emissions, the proper mixture of fuel gas and combustion air should be fed to the engine under all circumstances (ref. 9). Not only should the air-to-fuel ratio have the required value under all circumstances of load and running speed, also the homogeneity is very important. Moreover, the applied carburettor should have a low flow resistance.

A general complaint after conversion of a passenger car from petrol to natural gas has been the loss in engine power, sometimes exceeding 20%. One reason for this is the lower energy content of a stoichiometric mixture with natural gas compared to that with petrol. The lower volumetric energy content of natural gas can cause a reduction in power of more than 10%. An additional reason is the sometimes high flow resistance of the retrofitted gas carburettor. A venturi-type carburettor needs a pressure drop in the air stream to draw in the required fuel gas. In order to have sufficient pressure drop at idle running, the flow restriction was often made so high that running at full power resulted in more than 50 mbar pressure drop. That equals roughly 5% in power capacity. Another reason for the low power is the sometimes large inhomogeneity of the mixture causing some cylinders to run at a rich mixture and others to run on a lean mixture. This could reduce the power capacity by another 5%. The fourth reason for a reduction in power is the slower combustion velocity of natural gas compared with petrol resulting in a reduced shaft efficiency. Advancing the ignition timing can compensate for that. With a good carburettor system and well adjusted ignition timing, the power loss can be limited to less than 15%.

Apart from providing the right air-to-fuel ratio and homogeneity, a carburettor should also have a good step response (ref. 10). A good step response means that the mixture is controlled for the desired air-to-fuel ratio even during changes in power demand of the engine, i.e. variations in accelerator position. This is of importance for the driveability and the low-emission requirements. A simple venturi-based carburettor tends to make the mixture temporarily leaner when pressing down the accelerator and richer during its release. Solutions have to be found by using engine-management systems based on electronics and sensors, as is the case with petrol-fueled cars. The modern carburettor systems for gaseous fuels already use this principle; sometimes a computer is installed in parallel to the existing one for petrol, and sometimes the original computer is being used.

A matter of discussion is still where the control system should interact with the carburetion system. Some conversion-kit manufacturers prefer a controlling action on a common gas-admixing device and some prefer a per-cylinder injection of the fuel. A common admixing device upstream of the intake manifold can give excellent homogeneity and can have a high reliability and serviceability. Injection per cylinder lowers the risk of backfiring and has, at least in theory, a somewhat shorter response time than admixing further upstream. However, per-cylinder injection requires electromagnetic valves (ref. 11, 12) which can operate at the camshaft frequency and have to pass a large volume flow of gas. Since the gas contains no lubricant and the operating frequency is very high, a high wear rate can be present. Of course, gas admission at a relatively high pressure will reduce the volume flow through the valves but the consequence is a reduced depletion of the fuel-storage cylinders. Another problem of per-cylinder admission is the difference in volumetric efficiency from cylinder to cylinder. That requires a per-cylinder calibration of the fuel-admission valves. In the author's opinion, the control of the air-to-fuel ratio with a gas-admixing system upstream of the intake manifold offers the best perspectives at the moment.

Gas quality (ref. 13) does affect engine performance primarily via the air-to-fuel ratio. It has been shown that for carburettor systems where the gas flow is commonly controlled by the pressure drop over a restriction in the connection with the admixing point, the Wobbe index is the determining quality factor (ref. 14,15). The air-to-fuel ratio appears to vary inversely proportional with the Wobbe index. The Wobbe index defined as

$$Wo = H \cdot \sqrt{\frac{\rho_{air}}{\rho_{gas}}} \quad \text{(H=calorific value)}$$

can vary from well to well. Since gas appliances show an identical sensitivity to the Wobbe index, the gas companies control the index within a narrow range. It should be noted that admixing of air to a gas to attain a certain Wobbe index cannot be applied for engines: it will increase the air-to-fuel ratio. Variations in gas temperature, if not accompanied by identical variations in air temperature, will also introduce variations in air-to-fuel ratio. The gas temperature downstream of the pressure reducers between the fuel cylinders and the carburettor will vary depending on the pressure in the cylinders because of the Joule-Kelvin effect (ref. 10). This has to be compensated by either an air-to-gas heat exchanger or an automatic temperature-controlled adjustment of the carburettor setting.

4. THE IN-CYLINDER COMBUSTION PROCESS

Natural gas has a wide ignition range, that means that a homogeneous mixture of gas and air can be ignited in a wide range of air-to-fuel ratios. However, the chemical stability of methane makes that a high ignition energy is required. With the modern spark plugs and high-voltage ignition systems, such a high ignition energy can be provided. The high stability of methane hampers its use as a diesel fuel: its cetane number is very low. The consequence of a low cetane number is a high temperature required for ignition which has to be generated with a high compression ratio. Unfortunately, high process temperatures give rise to a high NO_x production. Some researchers describe the use of glow plugs for diesel operation with gas, but this technology is immature as yet. An alternative application for gas is in the so-called dual-fuel engine: a compressed mixture of natural gas and air is ignited by a pilot flame resulting from the injection of diesel fuel. Such engines suffer generally from high hydrocarbon emissions in the lower load range. It can be stated that natural gas is very suitable for spark-ignition engines, also because of its high knock resistance compared with petrol.

The high knock resistance of natural gas (ref. 16) allows the use of a high compression ratio in spark-ignition engines which is beneficial for the shaft efficiency. Compared with petrol, the compression ratio ratio can be at least 4 points higher. In practice however, this requires a dedicated engine, which is only practical for heavy-duty applications, thus far. The disadvantages of a higher compression ratio are a higher mechanical load of the piston/cylinder combination, more noise production and more NO_x production.

The combustion velocity of a natural-gas/air mixture is lower than that of a petrol/air mixture. This directly affects the initial stage of the flame development in the combustion chamber of engines, which is often called the apparent heat-release delay. A longer apparent heat-release delay results in a retarded heat release in the cylinder process and therefore in reduced efficiency (ref. 17). The proper phasing of the heat-release process in the cycle can be restored by advancing the ignition timing or increasing the turbulence level in the cylinder. With automotive engines, the combustion process is sometimes that slow that a further advancing of the ignition timing is not very effective. Dedicated natural-gas-fueled engines can be designed in such a way that the combustion process takes place in the desired crank-angle interval.

For passenger-car engines, the risk of knocking combustion is very low because of the high knock resistance of natural gas. In heavy-duty engines, especially in turbocharged engines, the pockets of highly compressed mixture that is not-yet burned are larger and the temperatures in these pockets is higher because of the relatively smaller heat losses in larger engines. So in heavy-duty engines, knock can occur even with natural gas as a fuel. A good remedy for combustion knock is a lean mixture (ref. 18). Lean mixtures have not only a higher knock resistance but also result in a lower thermal load on the engine parts. From a reliability and durability point of view, lean-burn heavy-duty engines are approaching diesel engines which are also operating with relatively cool cylinder processes.

Turbocharging on heavy-duty gas engines is imperative for a good competition with the diesel engine (ref. 19). Turbocharged engines have a high specific power capacity, that is the available power per unit of volume and weight. Moreover, the shaft efficiency of a turbocharged engine is higher than that of a naturally aspirated engine, especially for lower torques which are so common for vehicle engines.

Nevertheless, the shaft efficiency of modern diesels is almost unbeatable. Recent developments show that for turbocharged natural-gas-fueled engines, the intercooler can be operated at the jacket-water temperature, which has advantages for NO_x control and for efficiency because of reduced throttling losses.

5. EMISSIONS

The low tropospheric reactivity of the major constituents of natural gas is generally mentioned as an environmental advantage of the fuel for automotive purposes. Basically, this is true since methane is not associated with smog formation. The concentration of non-methane hydrocarbons (NMHC) in natural gas is very low and therefore the direct polluting effect of the untreated exhaust gas of a natural-gas-fueled engine is low compared to that of a petrol-fueled engine. The advantage of low HC emissions of a natural-gas-fueled vehicle over a petrol-fueled vehicle is especially high during a cold start. Difficulties with petrol vaporisation and the therefore required enrichment during a cold start up give a petrol-fueled vehicle high HC emissions. A natural-gas-fueled vehicle does not need enrichment during a cold start up although the emissions level is somewhat higher because of quenching of the flame to the cold cylinder walls compared with the situation in a hot engine. However, the modern vehicles fueled by natural gas are all equipped with three-way catalysts and engine-management systems.

For petrol engines equipped with a three-way catalyst, the mixture of fuel and air is controlled in a window close to stoichiometry. Then, the CO, H_2 and HC in the exhaust gas is used to reduce NO_x to N_2. Apart from a cold start up, when the catalyst is not active and the mixture is too rich, rather low emission levels of all unwanted compounds can be reached. Manufacturers are now working on preheated catalysts and latent-heat-storage systems to clean up the cold start. For natural-gas-fueled engines, the high stability of methane makes that a higher operating temperature of the catalyst is required to onset the oxidising process (ref. 20). Moreover, the lambda sensor used in petrol engines has also difficulty in converting methane. Next to that, the H_2/CO ratio in the exhaust gas of a natural-gas-fueled engine differs from that of a petrol-fueled engine which introduces a shift in the transfer function of the sensor (ref. 21). These complications make that the initial advantage of natural gas with respect to clean exhaust gas is not so apparent in practice.

However, methods are being investigated to improve the catalytic treatment of the exhaust gas of natural-gas-fueled vehicles (ref. 22).

Lean-burn turbocharged heavy-duty engines offer large environmental advantages over the competing diesel engine. The particulate and NO_x emissions of the gas engine can be more than a factor three lower than the Californian regulations for heavy-duty engines for 1994 (ref. 10). Simple oxidation catalysts can reduce the emissions of CO and the higher hydrocarbons to an almost insignificant level. To oxidise the traces of methane in the exhaust gas, special catalysts are available but these cost roughly US$ 150/kW. Especially in inner cities, where the air quality is often poor, buses on natural gas can bring much relief. For city buses, the handicap of requiring much storage space for the fuel is not so severe, since the distances covered are limited and the buses return to the starting point every day. The price of using spark-ignition engines instead of diesels is however the higher fuel consumption.

A higher fuel consumption compared with diesel when using natural gas does not really afflict the financial economy but rather reduces the positive effect on the emission of greenhouse gases (ref. 23). The high hydrogen/carbon ratio of natural gas makes that per unit of released energy much less CO_2 is produced than with diesel fuel or petrol. However, the different engine process, the extra weight of the vehicle and the emission of some methane, which in itself is a greenhouse gas, greatly reduces the advantage of natural gas. Tests with buses in The Netherlands showed roughly a 25% extra energy consumption compared with the diesel, al-be-it that these buses were equipped with naturally aspirated engines. Although the concentration of methane in the exhaust gas is relatively low, methane is said to induce a much higher greenhouse effect per molecule than CO_2. In the author's opinion, there is however no point in comparing transport fuels with respect to their effect on the greenhouse effect. Worldwide, only 14% of the fuel consumption is used for transport and it is not likely that the world can afford to stop the use of oil-derivative fuels. The best way to reduce the emission of greenhouse gases is the improvement of the efficiency of energy-conversion processes.

6. GENERAL OVERVIEW AND CONCLUSIONS

Natural gas is a good fuel for spark-ignition engines. For transport applications, its use is hampered by the large storage volume and weight.

Natural gas can be used in vehicles for economic reasons. In some countries, such as the USA, the energy price is hardly affected by taxation and then, the use of the cheapest fuel will be attractive for the private customers. The presence of indigenous resources of natural gas in a country can make it economically attractive for the nation to use it as a transport fuel. This applies for countries such as India. In the long run, when the resources of oil are depleted, natural gas can be a remaining alternative. However, the oil companies are developing the manufacturing of synthetic fuels from natural gas which can have properties which are more desirable for vehicle fuels (ref. 24).

From an environmental point of view, natural gas can help to immediately improve the air quality in cities by using it to replace diesels, especially for buses and delivery vehicles. This will reduce primarily the emission of CO, NO_x and particulates. However, the diesel manufacturers are putting much effort into research on the reduction of the emissions, by using high-pressure fuel injection, exhaust-gas recirculation, particulate filters and catalytic converters. Compared with diesels and petrol engines, only a very limited amount of research has been carried out for engines fueled by natural gas. For natural gas to be competitive for automotive applications in the long run, not only as a niche fuel, more research and development effort is required.

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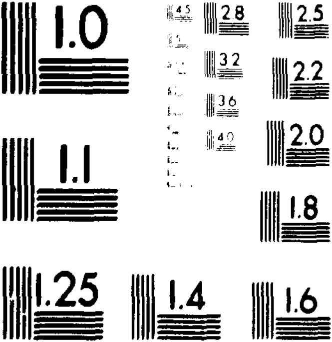

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