APPLICATION OF NATURAL GAS TO COMPRESSION IGNITION ENGINES

Małgorzata Wojtyniak

Radom Technical University
Al. Chrobrego 45, 26-600 Radom
tel.: +48 48 3617671 fax: +48 48 3617644
e-mail: malgorzata_wojtyniak@op.pl

Abstract

The paper presents general information on natural gas properties, reserves, production and distribution. Its proved reserves are estimated to have been ca. 6 trillion cubic feet. Main reserves are in Russia. Application of natural gas to automotive vehicles on the basis of literature review has been presented. European Union, US government and other countries have introduced directives for a natural gas application in the transportation sector. Because natural gas has a low cetane number, it cannot be directly applied to compression ignition engines. Such engines have to be adapted to dual fuelling. An assisted ignition with a pilot fuel quantity is necessary. Comparison of the spark ignition versus dual fuel engines, natural gas versus LPG and methane as well as choice of pilot ignition fuel have been discussed in the paper. Most of natural gas refueling stations is in Argentina. Progress in the field of dual-fuel natural gas engines has been presented. Application of natural gas as a fuel to internal combustion engines is useful regarding economy, emissions and worldwide energy strategy.

Keywords: *methane, natural gas resources, natural gas production, dual fuelling, compression ignition engine*

1. Introduction

Natural gas (NG) is one of the most important primary energy sources. Its reserves are about the same order of magnitude as petroleum reserves and they are much more evenly distributed on a global base.

Tab. 1. World natural gas reserves [2]

L.p.	**Country**	**Reserves (trillion cubic meters)**	**Percent of world total**
	World	171.03	100.0
	Top 20 countries	152.66	89.3
1.	Russia	47.57	27.8
2.	Iran	26.62	15.6
3.	Qatar	25.77	15.1
4.	Saudi Arabia	6.65	3.9
5.	United Arab Emirates	6.00	3.5
6.	United States	5.35	3.1
7.	Nigeria	4.98	2.9
8.	Algeria	4.56	2.7
9.	Venezuela	4.28	2.5
10.	Iraq	3.11	1.8

Proved world NG reserves were estimated at ca. 6 trillion cubic feet [1, 2]. Almost three-quarters of them are located in the Middle East and in the Former Soviet Union. Location of the natural gas main reserves are given in Table 1. The biggest producer of natural gas is Russia (Table 2). About 80% of the world natural gas production is consumed locally.
Natural gas has been used to fuel vehicles since the 1930's and it has gathered renewed interest in the transportation sector since the beginning of the 1990's. In transport application it is called NGV (Natural Gas for Vehicles).

The main constituent of natural gas is methane (80-98% – depending on the extraction source). Other constituents are: ethane (1-8%), propane (do 2%), butane and pentane (less than 1%) [1]. Natural gas contains also nitrogen and carbon dioxide (0.2-1.5%) and small quantities of sulphur compounds (hydrogen sulphide and mercaptans). Natural gas is non-toxic, odourless and non-corrosive. It is lighter than air and is slightly soluble in water.

Tab. 2. World natural gas production [3]

L.p.	Country	Production (billion cubic meters)
1.	Russia	16,45
2.	Canada	5,29
3.	Algeria	2,27
4.	Netherlands	2,20
5.	Indonesia	1,95
6.	Iran	1,74
7.	Norway	1,55
8.	Saudi Arabia	1,52
9.	Malaysia	1,52
10.	Mexico	1,04

As a fuel natural gas is used:

- in gaseous form (at ambient temperature and under high pressure – 20 MPa) and is called compressed natural gas (CNG),
- in liquid form (cooled to the temperature of -161oC and at atmospheric pressure) and is called liquefied natural gas (LNG).

NGV can be considered to be a clean fuel. NGV vehicles emit almost no hydrocarbons with more than four atoms of carbon. In particular, no aromatic compounds are detected in the exhaust. Vehicles fuelled with NG emit more methane, but less CO_2, than those fuelled with conventional fuels. Of all hydrocarbon compounds used as motor fuels, methane has the highest knock resistance. Its octane number is ca. 130. Methane combustion is relatively slow, what contributes to less combustion noise. Methane has also reasonable-low flame temperature what limits formation of nitrogen oxides.

Existing quality standards for CNG [2] are:

- ISO 15403:2000 "Natural gas – Designation of the quality of natural gas for use as a compressed fuel for vehicles"
- SAE J1616:1994, "Recommended practice for compressed natural gas vehicle fuel"

Physico-chemical properties of natural gas are given in Table 3.

The potential for low exhaust gas emission indicates that natural gas should be preferred in city traffic (buses, taxis etc.). Also for technical reasons – it is not very suitable for long-range transport. Natural gas-powered vehicles (dedicated or modified) are commonly called NGVs (Natural Gas Vehicles). Already more than four million taxis, buses, heavy-duty vehicles, private cars and specialist vehicles are running on natural gas in 65 countries around the world. The leading countries are given in Table 4. The number of refuelling stations in the world is ca. 9 000. Natural gas refuelling stations can be divided in two groups: public and private refuelling stations. The first are accessible for anyone, the second are in possessing of large fleet owners. Exist also private refuelling systems installed at home but they are not very popular.

Tab. 3. Physical and chemical properties of natural gas as engine fuel [4]

Properties	**CNG**	**LNG**
Density (in the conditions of storage), kg/m^3	160 (15^{o}C, 20 MPa)	425 (-150^{o}C, 0.3 MPa)
Heating value (in the conditions of storage), MJ/kg (MJ/dm^3)	48.80 8.44	49.30 20.95
Heating value of the stoichiometric air-fuel mixture, λ=1, kJ/m^3	3310	3310
Boiling point, ^{o}C	-162	-162
Autoignition point, ^{o}C	540	540
Heat of vaporization, kJ/kg	510	510
Stoichiometric ratio, kg /kg	17.1	17.1
Octane rating MON	105	105
Octane rating RON	110	110

Tab. 4. Natural gas vehicles and refuelling stations in the world [5]

Country	**Natural Gas Vehicles (total)**	**Natural Gas Refuelling Stations (total)**
Argentina	1 457 118	1 452
Brazil	1 011 206	1 138
Pakistan	700 000	766
Italy	382 000	521
India	222 306	192
USA	130 000	1 340
China	97 200	3 55
Colombia	72 136	168
Ukraine	67 000	147
Iran	63 779	96
Egypt	61 590	91
Venezuela	44 146	149
Russia	41 780	213
Bangladesh	41 314	122
Armenia	38 100	60
Bolivia	35 810	62
Germany	27 200	622
Japan	24 648	288
Canada	20 505	222
Poland	771	28

2. Spark Ignition versus Dual Fuel

Dual fuel engine takes advantage of inherent efficiencies of compression ignition engine, but with reduced diesel fuel consumption, what results in an engine, which is both more powerful than dedicated spark-ignited natural gas engine, but with generally better emissions than dedicated compression ignition engine.

In comparison with spark-ignited gas engine, dual fuel engine has [6-8]:
- extended life and long-term reliability
- better fuel economy (lower BSFC)
- better startability in low temperature (cold start)

and:
- requires fewer NG tanks
- can be fuelled solely with diesel fuel, in case of NG shortage
- is more resistant to knocking combustion
- is less noisy.

Moreover, spark-ignited gas engine has higher cycle-to-cycle variations, leading to deterioration of efficiency and power.

As far as economy aspects are concerned, NG engine installation costs in busses refund sooner than LPG SI or LPG + DF in C.I. engines (SI –NG a little sooner than dual fuel) [8].

3. Natural Gas versus LPG and Methane

A comprehensive study on application of three different gases to dual-fuel engine was carried out in [9]. The pilot fuel was diesel fuel and applied gases were: NG, LPG and pure methanol. The following conclusions were drawn from these experiments:
- Dual-fuel engine fuelled with methane produces higher power and better efficiency than the one fuelled with NG, followed by LPG.
- Methane gives higher resistance to knock than NG, while LPG is the most prone to knock (the onset of knock is associated with drop in thermal efficiency and power).

LPG as the main fuel produces the highest combustion noise followed by methane and NG.

4. Choice of Pilot Fuel

In NG dual-fuel engine the pilot fuel, which generally is diesel fuel, may be replaced by renewable biofuel as plant oil or FAME. In [10] two pilot biofuels were investigated: neat rapeseed oil and rapeseed oil (RO) methyl ester (RME) and compared with diesel fuel.

The following conclusions may be drawn from this investigation:
- At low load, ignition delay of RO was longer and at high load shorter than for diesel fuel
- Ignition delay of RME was shorter than for diesel fuel in the whole range of load.
- Brake fuel conversion efficiency was the best for neat RO, especially at middle sped in the whole range of load, and for RME almost the same as for DF.
- Hydrocarbon emissions of dual-fuel engine were similar for RO and DF and lower for RME.

Taking into account the above statements and advantages of RME in comparison with RO, there is no doubt that RME can replace DF as a pilot fuel.

5. New Generation of Dual-Fuel Natural Gas Engines

First dual-fuel engine built Rudolf Diesel (1896) in Maschinenbaufabrik Augsburg- Nürnberg, MAN. He injected directly petroleum and natural gas into C.I. engine (called after him diesel). This was the idea of gas-diesel engine. Further approach to dual-fuelling of internal combustion engines was carried out by Karim [11-13] in Canada and by Zabłocki in Poland [14]. Karim carried out a lot of experiments and showed topic problems, which should be overcome in the field of combustion in DF NG engine. Zabłocki worked out a theoretical background of dual fuelling and showed how CI engine should be adapted to fuelling with natural gas.

New generation [6] of dual-fuel natural gas engines is fitted with electronically controlled multipoint part-injected sequential NG fuel system and Electronic Control Unit (ECU) that integrates with existing Electronic Control Modul (ECM). ECU precisely controls both fuels injection (metering and timing of injection of each fuel) and optimizes combustion in view of emission and efficiency.

US Department of Energy supports R&D work on dual-fuel heavy duty vehicles for transportation. In Cummins ISX diesel engine high pressure direct injection NG system was installed [15]. Engine was turbocharged, charge air and EGR coolers were applied. Analogically electronically controlled is Caterpilar engine that uses NG or propane.

Bus and light-duty vehicles engines fuelled with NG are produced in two versions/types:

- spark ignition CNG engines
- dual-fuel engines (diesel fuel is pilot ignition fuel).

Both types of CNG engines are applied in buses by such companies as Cummnis, John Deere, Detroit Diesel, Volvo, MAN, Caterpillar, Blohm & Voss, MAN B & W Gasmotoren [16], Cummins and Westport (2nd type) [17].

Westport Co. presented high pressure direct injector which injects simultaneously NG and diesel fuel [18]. The injector has two needles: a needle within a needle with separate injector holes for each fuel. The diesel fuel is injected some milliseconds earlier than natural gas; its autoignition is the source of instantaneous ignition of natural gas. Due to that, mixture of both fuels burns quickly in air. The Westport injector was applied in Detroit Diesel 6V-92 TA engine and is planned to be applied in the QSK-19 Cummins prototype [18].

Presently in Europe and in the United States cars and pick-ups are produced that are fuelled with LPG and/or CNG and also occur with bi-fuel engines, which may be fuelled with both fuels LPG/NG and gasoline [19]. EEC established regulations for new vehicles and also established standards for LPG and NG systems [20]. Also standards for LPG and NG fuels used as standard fuels in EURO tests were introduced [21].

The present situation and prospects of CNG as an automotive fuel was reviewed in reference [22]. In many towns exist fleets of city busses fuelled with CNG. There are also a couple of CNG filling stations.

6. Conclusions

Application of natural gas as a fuel to internal combustion engines is useful regarding economy, emissions and worldwide energy strategy.

Analysis of fuelling spark ignition versus compression ignition engine with natural gas results in that, that it is more convenient to apply it to this last type of engines. Fuelling with natural gas does not demand any change of compression ignition engine design as in the case of spark ignition engine, of which materials should be more resistant to wear and compression ratio should be decreased, but only addition of fuel installations, what is necessary also for spark ignition natural gas engine. In comparison with diesel, natural gas dual fuel engine produces less particulate matter, carbon dioxide and nitric oxides. Application of cool EGR may decrease emission of carbon oxide and hydrocarbons, which are normally higher than for diesel operation. For application of natural gas to automotive dual fuel engines, of which operation parameters are changing in a wide range, control parameters of the engine, mainly such as pilot diesel quantity and its timing as well as natural gas – air equivalence ratio, should be optimised from the point of view of efficiency and emissions.

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