COMPRESSED NATURAL GAS ENGINES. A REVIEW

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Abstract

Resources, production, refuelling stations and physic-chemical properties of natural gas are presented. Technical problems connected with application of natural gas to SI and CI engines are shown and analyzed. Presently most of gas vehicles are converted from gasoline to natural gas application but also many companies produce gas vehicles driven with SI engines originally fabricated as gas vehicles. However natural gas spark ignition engines have lower torque than CI engines normally used in trucks, pick-ups and busses. Therefore CI engines are also adapted to gas fuelling as dual-fuel engines. Comparison of NG SI engines and dual-fuel engines is performed. Performances and emissions of gas automotive engines are presented.

World natural gas reserves, natural gas production physical and chemical properties of typical natural gas, natural gas vehicles and refuelling stations in the world, schematic of CNG fuelling installation of IVth and Vth generation, combustion system, natural gas admission and control in DF NG engine, schematic of ADCR engine adapted to CNG fuelling are presented in the paper.

Keywords: *CNG vehicle, NGSI engine, NGCI engine, CNG dual-fuel engine, ecology*

1. Introduction

1.1. Natural gas as a fuel for combustion engines

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. The proved world NG reserves are estimated at ca. $170 \cdot 10^9$ cubic meters [1]. Almost three-quarters of them are located in the Middle East, Eastern Europe and Central Asia (Russia, Turkmenistan, Uzbekistan, Kazakhstan). Location of the natural gas main reserves are given in Tab. 1. The biggest producer of natural gas is Russia (Tab. 2). Approximately 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 an intensive search of diversification of energy carriers in the face of crude oil crisis. Biofuels can provide only approximatelly 20% of motor fuels supplies and synthetic fuels from coal are also insufficient. Moreover, synthetic fuels are produced from natural gas with the application of Fischer-Tropsch technology (GTL), e.g. by Mossgas.

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%). Natural gas contains also nitrogen (0.2-10.8%) 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.

As a fuel natural gas is distributed:

- in gaseous phase (at ambient temperature and under high pressure ~ 20 MPa) and is called compressed natural gas (CNG),

- in liquid phase (cooled to the temperature of -161oC and at atmospheric pressure) and is called liquefied natural gas (LNG).

Tab. 1. World natural gas reserves [1]

No.	Country	Reserves ($\times 10^{12}$ 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
11	Indonesia	2.55	1.5
12	Malaysia*	2.48	1.5
13	Norway	2.12	1.2
14	Turkmenistan	2.10	1.2
15	Uzbekistan	2.01	1.2
16	Kazakhstan	1.87	1.1
17	Netherlands	1.84	1.1
18	Canada	1.76	1.0
19	Egypt	1.61	0.9
20	Ukraine	1.13	0.7

*source: www.eia.doe.gov

Tab. 2. World natural gas production in the year 2004/2005 [2]

No.	Country	Production ($\times 10^{12}$ cubic meters) per annum
1	Russia*	613.14
2	USA*	510.09
3	Canada*	181.24
4	United Kingdom*	95.69
5	Norway*	91.65
6	Algeria	88.34
7	Indonesia	82.76
8	Iran	81.74
9	Netherlands	68.00
10	Saudi Arabia	64.00

*) in the year 2005

Natural gas can be considered to be a clean fuel. It contains less carbon, sulfates and hydrocarbons per unit of mass of fuel, which in turn during combustion produces less carbon dioxide and particulate matter. Of all hydrocarbon compounds used as motor fuels, methane has the highest knock resistance. Its research octane number is ca. 130. Methane combustion is relatively slow, which contributes to less combustion noise. Methane has also reasonably-low flame temperature what limits formation of nitrogen oxides.

Existing quality standards for CNG [1] 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"

According to the last standard, natural gas as a fuel for vehicles should be controlled on account on the content at [3]: particulate and foreign materials, oil, water, oxygen, hydrogen sulfide, carbon dioxide, methanol (which is used as anti – icing agent).

Natural gas for vehicles is stored in steel containers under the pressure of 20 MPa. Temperature of the gas containers should be higher than pressure – water dew point temperature and pressure hydrocarbon dew point temperature.

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

Tab. 3. Physical and chemical properties of typical natural gas [4, 5]

Property	Value
Relative molecular mass	17-20
Carbon content, mass %	73.3
Hydrogen content, mass %	23.9
Oxygen content, mass %	0.4
Carbon-to-hydrogen ratio	0.25-0.33
Relative density at 15^{o}C, kg/m^3	0.72-0.81
Boiling temperature, ^{o}C	-162
Autoignition temperature, ^{o}C	540-560
Octane number	120-130
Methane number	69-99
Stoichiometric air-fuel ratio, kg/kg	17.2
Vapour flammability limits, vol. %	5-15
Flammability limits (lambda)	0.7-2.1
Lower heating value, MJ/kg	38-50
Lower heating value of the stoichiometric air-fuel mixture, λ=1, MJ/kg	2.75
Methane concentration, vol. %	80-99
Ethane concentration, vol. %	2.7-4.6
Nitrogen concentration, vol. %	0.1-15
Carbon dioxide concentration, vol. %	1-5
Sulphur concentration, ppm (mass)	< 5
Specific CO_2 concentration, g/MJ	38-50
*Maximum flame temperature, ^{o}C	2236
*Rate of flame propagation in the stoichiometric mixture, m/s	0.40

* for methane [5]

The potential for low exhaust gas emission indicates that natural gas should be preferred in city traffic (buses, taxis etc.). However, 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 Tab. 4.

Tab. 4. Natural gas vehicles and refuelling stations in the world [6]

L.p.	Country	Natural Gas Vehicles (total)	Natural Gas Refuelling Stations (total)
1	Argentina	1445581	1687
2	Pakistan	1400000	1450
3	Brazil	1375317	1467
4	Italy	432900	609
5	Iran	292455	203
6	China	200873	486
7	USA	146876	1600
8	Colombia	169119	264
9	Ukraine	100000	200
10	Armenia	81394	148
11	Bangladesh	80000	129
12	Russia	75000	218
13	Egypt	69386	103
14	Bolivia	66410	98
15	Germany	55272	720
16	Venezuela	44146	148
17	Thailand	33982	130
18	Japan	31462	324
19	Bulgaria	25225	37
20	Poland	771	28

The number of refuelling stations in the world is ca. 9000. Natural gas refuelling stations can be divided in two groups: public and private refuelling stations. The first are accessible for anyone, the second are owned by large fleet owners. There exist also private refuelling systems installed at home but they are not very common.

Though natural gas is a good fuel for motor vehicles, its transportation to the place of storage from distant places, where it is extracted from the ground, is four times more expensive than that of liquid hydrocarbon fuels. Natural gas as CNG is transported by gas pipes or in the liquid state as LNG – in cryogenic containers by ships or road vehicles. Then the gas is stored in large containers under low pressure.

1.2. History of natural gas engines

Natural gas as an automotive fuel has a long history. Gas used for lighting was first fuel, which was used by inventors of internal combustion engine [7]. I. De Rivas (1807), W. Cecil (1820), and other inventors used gas as a fuel. Lenoir built and patentet gas internal combustion engine (1861), however without compression stroke, due to that it had very low power. Gas was ignited by the use of electric inductor and spark plugs. In 1876 N.A. Otto build and patented four – strok gas engine (patent nr 532) with initial compression before ignition. From this time natural and fermentative gas was occasionally applied to SI stationary engines. During second world war wood gas (obtained from wood thermal distillation) was applied to SI engines of pickups. At the end of 20th century NG become alternative fuel due to high prices of petroleum fuels.

2. NGSI Engines

Natural gas vehicles (NGV) applied to trucks and busses are in general driven by spark ignition engines (SIE) converted from automotive gasoline ones with increased compression ratio

CR= 12 - 13. (NG has higher octane number than gasoline), thanks to that they have higher efficiency than gasoline engines. Gas engines for trucks pick-ups and buses, which normally were driven by compression ignition engine (CIE) are modified to gas application. Modification depend on decreasing compression ratio and installation of spark ignition equipment. Spark plugs are inserted into the canals of removed diesel fuel injectors.

NGV may by bivalent (bifuelled) fueled with NG and/or gasoline or fueled only with NG. All types of NG should by equipment with gas containers and installation. Modification of motor-cars and heavy duty vehicles to natural gas fueling are offered by Original Equipment Manufacturer (OEM) [6].

Gas vehicle report publishes news statistics on NGV cost and savings connected with modification of vehicles to NG fueling all over the world. At present there is fourth and fifth generation off NG fueling systems: 4^{th} for CNG and 5^{th} for LNG [8]. Scheme of fourth generation is shown in Fig.1 and fifth in Fig. 2.

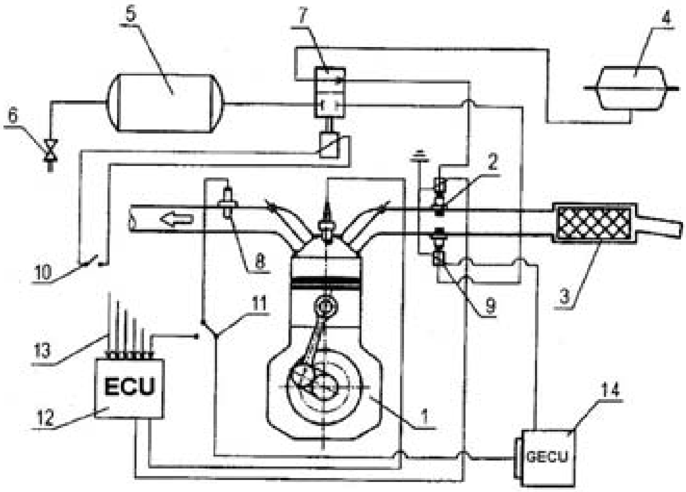

Fig. 1. Schematic of CNG fuelling installation of IVth generation [8]; 1 - engine, 2 - gasoline injector, 3 - filter, 4 - gasoline tank, 5 - gas container, 6 - gas filing valve, 7 - double way electro-valve, 8 - λ-sonde, 9 - gas injector, 10 - CNG-gasoline switch, 11 - λ-sonde switch, 12 - ECU of the gasoline injection system, 13 - signals of vehicle sensors, 14 - ECU of the gas fuelling system

In the case of fuelling with CNG (Fig. 1) NG is injected sequentially into engine inlet manifold with the use of gas injectors when inlet valves are being opened. Beginning of injection and gas dose are controlled by electronic control unit (ECU). In the case of fuelling with LNG (Fig. 2) liquid NG is injected with the use of gasoline type injectors into inlet manifold. Between gas container and injectors there is integrated evaporator – reducing valve.

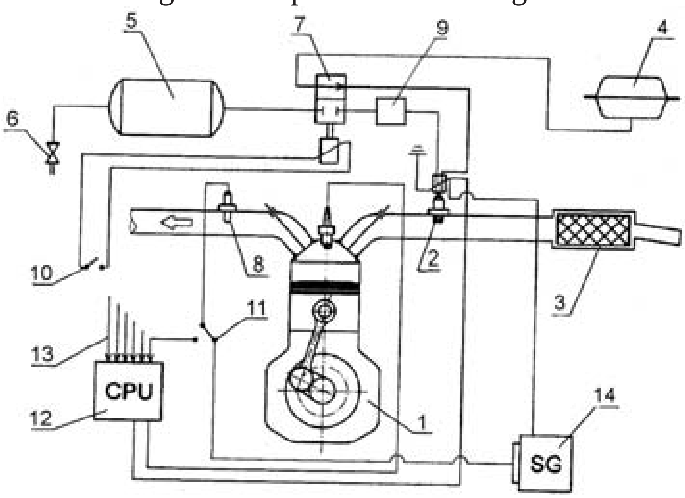

Fig. 2. Schematic of LNG fuelling installation of V^{th} generation [8]; 1-8 as in Fig.1, 9 - evaporator – pressure reducer, 10 - 14 as in Fig.1

The installation of LNG is complicated, there are few refueling stations and this kind of NG fueling is rather not used in Europe. Comparison of performance and emissions of NGSI engine and gasoline DISI ones is as follows [8]:

- NGSI engines have lower power than gasoline due to smaller volumetric efficiency,
- NGSI engines have lower CO emission and much more lower PM emission,
- NGSI engines have higher emission of NO_x and lower HC.

This comparison was performed according to FTP-75 test. Acceleration of the car equipped with SING engine is lower than equipped in gasoline one. However maintenance of NGSIV is much more cheaper than gasoline vehicle. In same bigger engines, e.g. Wärtsilä [9] there are special fuel systems, namely torch ignition chamber based on Gussak patent [10] and applied afterwards in Russian aircraft piston engines and in Honda engine CVCC [11]. This system utilizes lean-burn gas-air mixtures, which is ignited by spark ignited gas in the prechamber, Fig. 3.

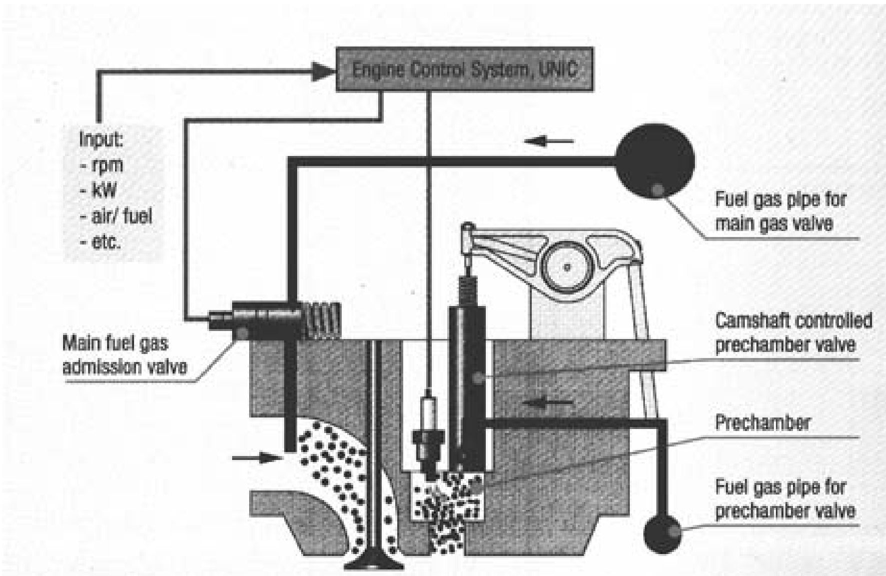

Fig. 3. Combustion system of NGSI Wärtsilä engine [9]

The system however needs two gas fuel systems: for admission gas to the cylinder and to prechamber. Operating window of air-fuel ratio is shown in the Fig. 4.

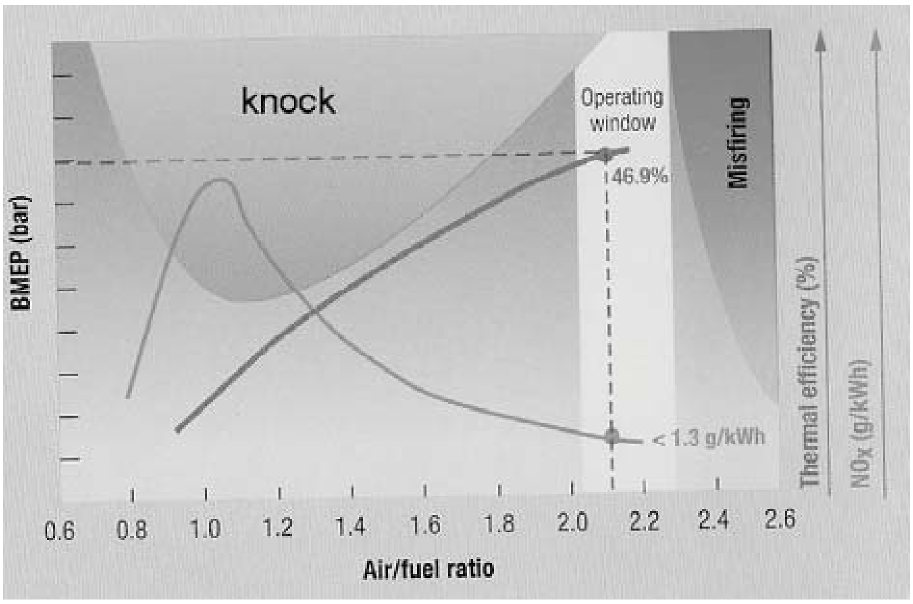

Fig. 4. Operating window of lean-burn NGSI engine [9]

Prechamber valves are operated mechanically, while main gas admission valve – electronically with impulses from engine control system UNIC.

3. NG dual-fuel engines

Natural gas individually cannot be applied to CI engines, because its Cetane Number (CN) is low and it is resistant to autoignition. Assisted ignition with pilot diesel fuel (or other high cetane number fuel) is necessary. This type of engine is commonly named dual-fuel engine (DFE). DFE may by fuelled also individually with diesel fuel in the case of lack natural gas in fuel system. First dual-fuel engine was built by Rudolf Diesel (1896) in Maschinenbaufabrik Augsburg - Nürnberg, MAN. He injected petroleum and natural gas directly into a C.I. engine (named after him diesel). This was the first idea of gas-diesel engine. More recent studies on dual fuelling of internal combustion engines included those by Karim [12] in Canada and by Zabłocki in Poland [13]. Karim carried out many 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 C.I. engine should be adapted to fuelling with natural gas. The most commonly used modern designs of NGDFE are shown Fig. 5.

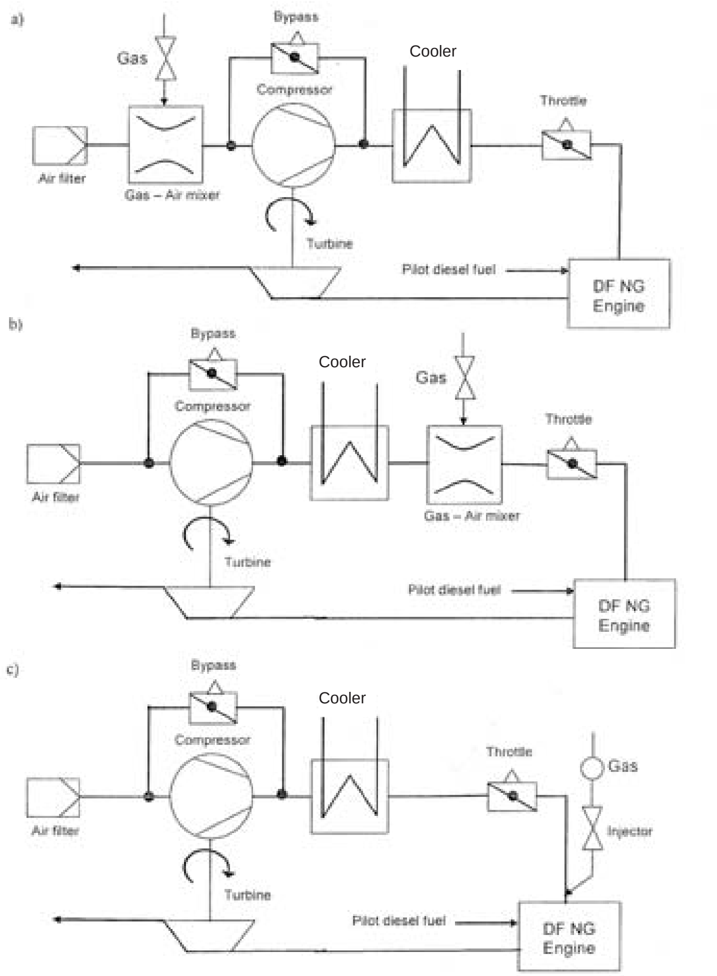

Fig. 5. Natural gas admission and control in DF NG engine: a) gas admission before compressor, b) gas admission behind compressor, c) gas injection into inlet port or directly into the cylinder of the engine [14].

In the case of (a) gas is supplied before the turbocharger, in the case of (b) – after and in the last case – gas is injected directly to engine cylinder or to the inlet duct before the inlet valve of each cylinder (sequential injection system). The case (a) is rather dangerous due to possibility of ignition when compressor rotor – body seizing takes place, the case (b) is inconvenient because gas-air mixture composition depends on by-pass valve opening degree. The case (c) is the most convenient thanks to the possibility of the highest volumetric efficiency and is applied in modern NGDF engines. Very efficient NGDF engines are produced by Wärtisla Co. [15]. Combustion system is built is two versions. In the first DF engine utilizes a lean burn combustion process. CNG is mixed with air in the inlet duct before intake valves during intake stroke. After compression gas – air mixture is ignited by small amount of pilot diesel fuel, which had autoignited before. In the second mode gas diesel (GD) the gas is injected at high pressure after pilot fuel and is ignited by the flame of burring pilot fuel droplets. The amount of pilot fuel is about 5% of the energy input at engine full load. Both types of engine may by switched automatically to liquid fuel mode. Gas – diesel fuel ratio is controlled by ECU in varying working conditions. Gas – liquid fuel energy ratio can vary from 80/20 to 15/85. Fuel sharing window of Wärtisla 32GD engine is shown in Fig. 6.

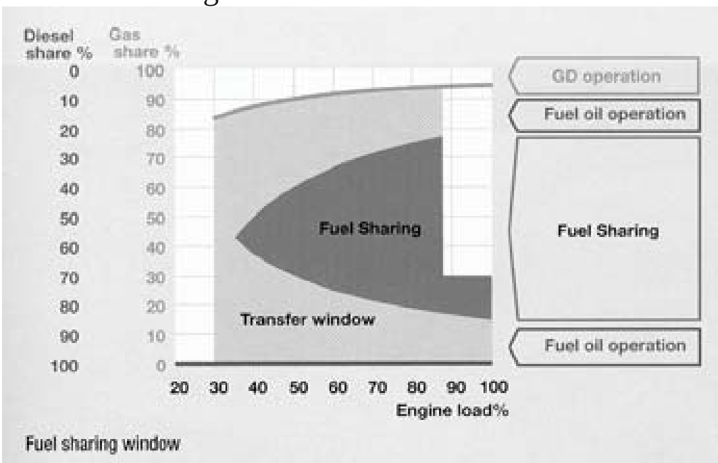

Fig. 6. Fuel sharing window of Wärtisla 32 GD engine [15]

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

In Politechnika Radomska there is realized D&R work on adaptation of diesel engine to NG fuelling. The engine will be dual-fuel with gas to diesel energy ratio in the range of 0-50% (Gas share is limited by knocking combustion), Fig. 7.

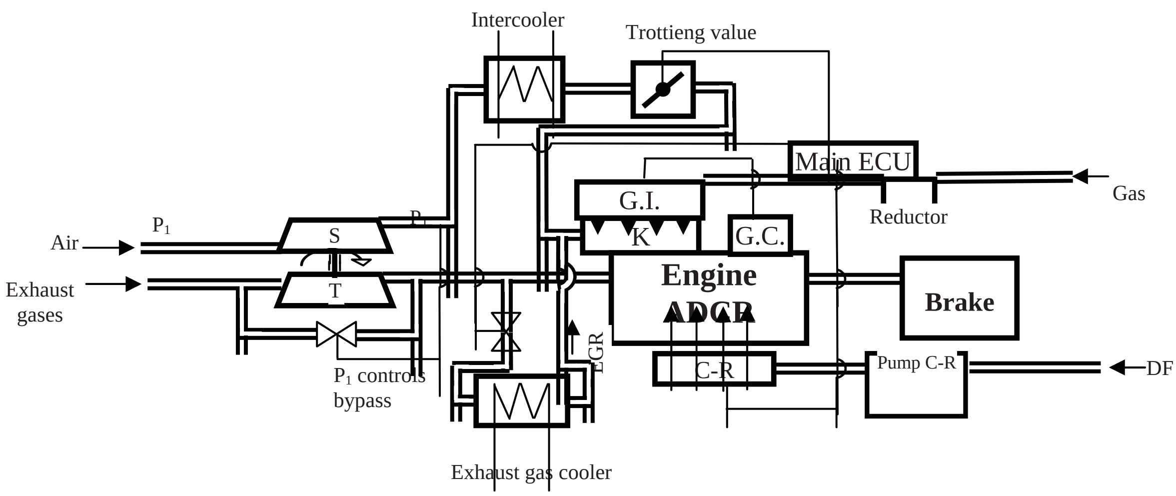

Fig. 7. Schematic of ADCR engine adapted to CNG fuelling

4. Spark ignition vs. dual fuel

Natural gas engines traditionally work much more like gasoline engines than like diesel engines. Compression ratio is limited by the occurrence of knock, especially in supercharged engines. This causes a deficit of torque, especially at low speed. The exhaust gas temperature is about 200^{o}C higher than that of diesel which works with large excess of air. Natural gas lacks the lubricity which is present in diesel. That makes natural gas fuelled spark ignition engines more prone to wear than natural gas fuelled compression ignition engines.

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, with generally better emissions than dedicated compression ignition engine.

In comparison with spark-ignited gas engine, dual-fuel engine has [16-18]:

- extended life and long-term reliability, due to less wear,
- better fuel economy (lower b.s.f.c.),
- better startability in low temperature (cold start),
- higher torque (the higher the pilot diesel fuel, the higher the torque),

requires fewer NG tanks, can be fuelled solely with diesel fuel, in case of NG shortage and is:

- more resistant to knocking combustion,
- 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 buses have shorter payback times in compression ignition engines than in liquefied petroleum gas fuelled spark ignition engine (LPG SI engine) or dual-fuel LPG engine.

5. Natural gas vs. liquefied petroleum gas (LPG) and methane

A comprehensive study on application of three different gases to dual-fuel engine was carried out in [19]. The pilot fuel was diesel fuel and the applied gases were: NG, LPG and pure methane. The following conclusions were drawn from these experiments:

- Dual-fuel engine fuelled with methane produces higher power and has better efficiency than the one fuelled with NG, followed by LPG.
- Methane has higher resistance to knock than NG, while LPG is the most prone to knock (the onset of knock is associated with a drop in thermal efficiency and power).
- LPG as the main fuel produces the highest combustion noise followed by methane and NG.

6. Choice of pilot fuel

In a NG dual-fuel engine the pilot fuel, which generally is diesel fuel, may be replaced by renewable bio-fuel as plant oil or fatty acid methyl esters (FAME). In [20] two pilot bio-fuels were investigated: neat rapeseed oil (RO) and rapeseed oil methyl ester (RME) and were compared with diesel fuel.

The following conclusions may be drawn from these investigations:

- 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 speed in the whole range of load, and for RME almost the same as for diesel fuel.
- Hydrocarbon emissions of dual-fuel engine were similar for RO and diesel fuel and lower for RME in comparison with diesel fuel.

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

7. Control strategy

Pure diesel operation should be possible at idling and when supply of NG is shut off. It means, that diesel fuel injection system should be maintained. Injectors should operate with very small pilot quantity; say 8 mm^3 per cycle with very good repeatability. When an engine is working in dual fuel mode, electronic control unit (ECU) should control gas flow within the optimised range of gas fuel-air equivalence ratio Φ_{NG} with the use of air throttling and control diesel fuel system, which should maintain optimum pilot quantity and its injection timing.

If an engine is charged, compressor by-pass may be applied together with air throttle before the engine inlet (Fig. 5) as well as exhaust gas outlet valve before the turbine, to reduce air pressure behind compressor. The ECU should check and govern whether the engine is overspeed. In this case ECU should give signal to close NG throttling valve.

The control strategy of the engine is qualitative, as in the case of diesel engine: the torque and speed are controlled by total fuel quantity, because air flow essentially is unchanged. However, in the case of knock occurrence or CO and HC reduction, air throttling should be applied (lean mixture may lead to cycle-to-cycle variations and unstable combustion resulting in poor economy and higher UHC and CO). One has also remember, that NG-air mixture composition should lie within flammability limits (for CH_4 $0.59 \leq \lambda_{NG} \geq 1.97$ [5], a little over lean limit). However, Karim [21] showed in experiments with methane, that mean effective pressure of a dual-fuel engine may get its maximum for total equivalence ratio > 1.0 (i.e. for mixture richer than stoichiometric). This case is rather out of application, because of high emissions of HC and CO.

8. Conclusions

It has been shown that application of natural gas to internal combustion engines of automotive vehicles is useful from the point of view of economy, emissions and worldwide energy strategy. Analysis of fuelling spark ignition versus compression ignition engine with natural gas shows, that it is more convenient to apply it to the last type of engines. Fuelling with natural gas does not require 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 emissions of carbon oxide and hydrocarbons, which are normally higher than for diesel operation. Application of natural gas to automotive dual fuel engines, of which operation parameters are changing in a wide range, requires optimisation of control parameters of the engine, mainly such as pilot diesel quantity and its timing as well as natural gas – air equivalence ratio, from the point of view of efficiency and emissions.

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