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Overview on the Use of Natural Gas in Spark Ignition Engines

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Abstract: As air pollution and global warming become a priority in sustainable mobility, the evolution of vehicles is facing many regulations that are becoming increasingly stringent in terms of reducing greenhouse gas (GHG) emissions, forcing the automotive industry to search for solutions to make their products more environmentally friendly.
In this environmental and legislative context, considerable attention has been given to natural gas (NG) in spark ignition (SI) engines. Many studies have been conducted to assess the impacts of NG use on engine operation.
This overview paper discusses some aspects of recent studies on Natural Gas (NG) production, its physico-chemical properties, and also, on the influence of the use of compressed natural gas (CNG) in SI engines: combustion characteristics, performance, and emissions.

Keywords: compressed natural gas, spark ignition engine, emissions

1. Introduction

Due to global warming through greenhouse gases, reducing CO_2 emissions put much stress on the vehicle developers which should adopt different solutions in order to achieve the goal. In Europe, CO_2 emissions from passenger car (PC) engines are regulated by EC Directive No 443/2009 [1], which also stipulates that starting with 2012, all manufacturers whose average emission of CO2 exceed the values permitted in already mentioned regulation, shall pay a fee for each calendar year for the emission excess. According to this regulation, for PC with the inertia class of 1380 kg, from 2021, the limit value will be 95 g CO_2/km which corresponds to a fuel consumption of approximately 3.8 l/100 km [2]. The automotive industry invests in vehicle with zero emissions (ZEV), ultra-low emission vehicle (ULEV), plug-in hybrid electric vehicle (PHEV) or battery electric vehicle (BEV), but, until they are reaching a more affordable cost for customer and until the efficiency of well-to-wheel will increase, there are other solutions, such as alternative fuel which will help to reduce the emissions and consequently greenhouse gases.
Out of the currently available alternative fuels, the methane gas is considered to be one of the best substitute for fossil fuels because, on the one hand, it’s compatible with conventional spark or compression ignition engine and, on the other hand, it’s eco-friendly due to its clean nature of combustion [3], [4]. Indeed, the favorable ratio of hydrogen to carbon in methane (1:4) means up to 30% lower CO_2 emissions compared to gasoline [5]. In fact, as stated in [6], [7], methane combustion produces the lowest CO_2 emissions of fossil fuels. Another positive aspect of methane is its wide

availability, as pointed out by the CIA World Factbook [8] in its comprehensive country comparison from NG production.

In conclusion, methane seems to be a good alternative for spark-ignition engines.

2. Literature review

2.1.Natural Gas production

Natural gas can be extracted from nature or can be manufactured from plants or waste.Raw natural gas can be found in 3 types of wells: oil, gas and condensate. The gas extracted from oil wells is named associated gas, the gas extracted from gas wells and condensate wells is termed non associated gas. This gas is mixed with water vapour, CO2, Helium, Nitrogen which should be separated before being transported through pipelines to customer, becoming dry natural gas, which is, in fact only methane part [9], [10].

Bio-natural gas is obtained through waste processing (another problem humanity is facing). It can be created by anaerobic digestion of manure, waste water, plants and even waste food [11], [12].

As mentioned in [13], to obtain about 1 kWh of electrical energy and 1.25 kWh of thermal energy, the following amounts of raw materials constituting a basis for energy production from renewable sources are needed: 5-7 kg of biomass wastes, 5-15 kg of municipal solid wastes, 8-12 kg of manure and organic wastes and 4-7 m^3 of municipal wastes.

2.2. Physico-Chemical Properties of NG

Natural Gas, is a mixture of various gases and its composition differ according to geographic location and period of the year of the extraction. The main components of NG are methane (~90%), ethane (~4.6%), propane (~1%) and others. A list of the most commonly seen components in NG is provided in Table 1.

Table 1. Composition of CNG

NG composition / Component	Symbol	Volumetric						
Reference number	-	[14]	[15]	[16]	[17]	[18]	[19]	average
Methane	CH4	89.10	85.79	94.42	88.98	88.10	95.30	90.28
Ethane	C2H6	4.40	7.86	2.29	6.81	4.20	2.16	4.62
Propane	C3H8	1.10	1.61	0.03	1.12	1.36	0.19	0.90
Butane	C4H10	0.30	0.53	0.25	0.11	0.58	0.04	0.30
Pentane	C5H12	0.10	0.12	0.00	0.02	0.15	0.01	0.07
Hexane	C6H14	0.00	0.00	0.00	0.00	0.03	0.00	0.01
Nitrogen	N2	5.00	2.96	0.44	2.50	5.20	1.86	2.99
Carbon dioxide	CO2	0.00	1.04	0.57	0.43	0.30	0.44	0.46
Oxygen	O2	0.00	0.00	0.00	0.03	0.00	0.00	0.01
Helium	He	0.00	0.09	0.00	0.00	0.00	0.00	0.02
Others	-	0.00	0.00	2.00	0.00	0.08	0.00	0.35
Total		100	100	100	100	100	100	100

So, the main component of natural gas is *methane*. Methane is a colourless and odourless gas. It's lighter than air with a relative density at boiling point of 0.424 kg/dm^3. The melting point of methane is -182.5°C and the boiling point is -162°C. It is an extremely flammable gas, its mixture with air between 5 to 15 % volume becomes explosive [20][21]. Autoignition temperature is 537°C. It should be manipulated with precaution because liquid state of methane on contact with skin can cause frostbites. There are also denied open flames, sparks and smoking near methane area because of its explosive tendency [22]. Chemical formula of methane is CH_4 [20]. It has a molecular mass of 16 g/mol and a tetrahedral form.

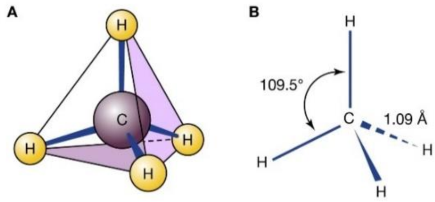

Figure 1. Methane molecular representation [20]

Making a comparison between most used vehicle fuels it can be observed that methane is as good as gasoline and diesel. In terms of A/F ratio, stoichiometric density, flame propagation speed, adiabatic flame temperature and lower heating value (LHV) the compressed natural gas (CNG), liquefied petroleum gas (LGP), gasoline and diesel are pretty the same. CNG makes itself remarkable by its octane number, autoignition temperature and smaller number of carbon atoms (see table 2). These three main characteristics helps in knocking resistance and in obtaining low CO2 emissions when used in internal combustion engines. In present the optimal spark advance is determined using research octane number RON 105 fuel as reference. Using CNG which has a high-octane number, means that we can increase the compress ratio to higher values and together with optimal spark advance (because knocking is avoided) efficiency increases and the fuel consumption decreases.

Methane burning reaction in stoichiometric conditions gives CO_2 and water vapour. The flame is pale, slightly luminous and very hot. In engine, because of low number of carbon atoms, it gives lower CO_2 emissions, comparing with a molecule of gasoline (around eight carbon atoms)

$$CH_4+O_2 \rightarrow CO_2+2H_2O \tag{1}$$

$$C_8H_{18}+12.5O_2 \rightarrow 8CO_2+9H_2O \tag{2}$$

So, can be easily observed that gasoline produces eight times more CO_2 than methane, reported to only one molecule of each fuel. Actually, the higher the number of carbon atom is, the higher the CO_2 emissions will be.

Table 2. Physico-chemical properties of fuels

Fuel / Properties	Gasoline							Diesel				CNG							Hydrogen	LPG
Reference number	[23]	[3]	[24]	[14]	[16]	[25]	Average	[23]	[3]	[24]	Average	[23]	[3]	[24]	[14]	[16]	[25]	Average	[24]	[25]
Chemical formula	C4 to C12	-	CnH1.87n	-	-	C4 to C10	-	C8 to C25	-	CnH1,8n	-	CH4	-	CH4	-	-	CH4		H2	C3 to C4
Molar mass [kg/mol]	-	109	-	106.2	110	-	108.4	-	204	-	204	-	17.3	-	17.74	16.04	-	17.03	-	-
A/F ratio	-	14.7	14.71	14.19	14.6	14.8	14.60	-	14.6	14.49	14.55	-	17.2	17.24	16.5	16.79	17.2	16.99	34.48	15.5
F/A ratio	-	0.0680	0.0680	0.0705	0.0685	0.0676	0.0685	-	0.0685	0.0690	0.0687	-	0.0581	0.0580	0.0606	0.0596	0.0581	0.0589	0.0290	0.0645
Density @15[°C [kg/m3]	-	-	750	749	-	730	743	-	-	827-840	833.5	-	-	0.725	-	-	140	70.3625	0.09	-
Stoichiometric density [kg/m3]	-	1.42	-	-	1.38	-	1.4	-	1.46	-	1.46	-	1.25	-	-	1.24	-	1.245	-	-
Cetane number	-	-	-	-	-	-	-	45-55	45-55	52	52	-	-	-	--	-	--	-		
Octane number	84-93	85-95	95	95.8	80-90	95	95.27	-	-	-		120	120-130	120	-	120	120	120	>120	105
Auto ignition temp [°C]	500	258	280	-	480-550	220	314.5	250	316	250	272	565	540	650	-	645	540	588	585	-
L.H.V [MJ/kg]	43.5	43.5	44	42.23	43.6	43.5	43.39	42.6	42.7	42.5	42.6	48.5	47.5	45	45.71	47.37	47.7	46.96	120	46.1
L.H.V of mixture (stoichiometric) [MJ/kg]	-	2.85	-	-	2.83	-	2.84	-	2.75	-	2.75	-	2.62	-	-	2.72	-	2.67	-	-
Adiabatic flame temperature [°C]	2025	2150	-	-	-	-	2088	-	2054	-	2054	1950	1890	-	-	-	-	1920	-	-
Flame propagation speed [m/s]	-	0.5	-	-	-	-	0.5	-	-	-	-	-	0.41	-	-	-	-	0.41	-	-
Combustion energy [MJ/m3]	-	42.7	-	-	-	-	42.7	-	36	-	36	-	24.6	-	-	-	-	24.6	-	-

3. Use of NG in SIE

3.1. Why compressed natural gas?

The main advantage of natural gas already discussed in §2.2 is its high-octane number which allows a high compression ratio which offers a high efficiency. This can be easily demonstrated using the thermodynamic efficiency formula of Otto cycle [23]:

$$\eta = 1 - \frac{1}{\varepsilon^{\gamma-1}}$$

where:

- $\gamma = \frac{c_p}{c_v}$ is the ratio between specific heat at constant pressure and specific heat at constant volume,
- $\varepsilon = \frac{V_1}{V_2}$ is the compression ratio of the engine.

It is observable that the thermodynamic efficiency of an Otto engine depends only by compression ratio because the adiabatic exponent is always super unitary and the higher the compression ratio, the higher the efficiency is.

Another very important feature of natural gas (if associating it with methane) especially in the current context which aims carbon neutrality is a favourable C/H ratio (1:4), which results in a significant reduction of tailpipe CO2 emission as discussed in § 3.4.2.

Equally, it is important to mention the time for tank refilling. Methane, in its natural state (1.013 bar, 15 °C) has a very low energy density (0.0378 MJ/L) compared with gasoline (34,2 MJ/L) and diesel fuel (38.6MJ/L). To gain some energy, natural gas is compressed to around 250 bar and reaches an energy density of 9 MJ/L compared with natural state [24]–[26]. It is still not comparable with gasoline and diesel fuel, but it is a big step in gaining energy density. Thanks to fast filling process comparable with gasoline and diesel fuel, the low range of the vehicle would not be a problem if the coverage of the refilling stations is favourable.

3.1.1. Short presentation of the particularities of a CNG fuel system

In order to be able to use natural gas to power internal combustion engines, they need a few upgrades. Natural gas fuel system needs some specific parts for best results in running. Starting from tank filling point to the point where the gas goes in the cylinder, is needed [27], [28]:

1. Fuel filler is the place where the gas station is connected for refill;
2. Natural gas tanks which keep the high-pressure gas;
3. Regulator which reduces the high-pressure gas from tank to a lower value accepted by the engine system;
4. Natural gas fuel filter to keep unwanted particles which contaminates the gas;
5. Fuel line to transport the natural gas from tank to injectors. These are usually pipes under vehicle;
6. Specific sensors;

   There are three types of specific sensors, as follows: a) sensor for tank pressure measures the pressure right before first reduction step; this signal is used by the ECU to calculate and actuate the natural gas gauge in the dashboard. b) sensor for gas fuel rail which measures the gas pressure in it; c) thermal safety sensor which allows the gas to be ejected in a controlled manner is case of fire; this sensor has a fluid which expands after a certain time and opens the gate to leave the gas out of tank.
7. Specific actuators. There are four types of specific actuators, as follows:

   a) valve for tank shut-off (one for each tank) they turn on the gas when the ignition is switched on and gas mode is selected, putting the high-pressure side over pressure;

   b) two stages high pressure regulator which reduces the high pressure from the tank (~200bar) to a lower value around 9 bar; this reduction of pressure results in a rapid drop of pressure which can freeze the gas pressure regulator; for this reason, the regulator is connected to engine coolant to heat it up during functionality, keeping it at engine operating temperature;

c) high pressure valve for gas mode lets the gas from tank to enter the regulator; it closes automatically in case of signal crash;

d) injectors - have the same construction and the same functionality as gasoline injectors

8. Electronic control unit (ECU) for controlling the system.

3.1.2. Storage of CH4 and safety conditions of the pressurized cylinder

Natural gas vehicles (NGV) receive NG from high pressure reservoirs. Because of its very low energy density at atmospheric pressure and room temperature, natural gas must be compressed and stored on the vehicle at high pressure – typically, 20 MPa [29].

One can find four major types of natural gas cylinders for NGV accepted by NGV safety standards:

1. All metal cylinder (Fig. 2. a)

The seamless steel cylinder was the most widely used cylinder for natural gas storage of NGV since 1940. In 1970 Italy introduced a lightweight and a high-strength cylinder which was a big step forward in NGV industry, adopted all over the world. This is also the cheapest gas cylinder [30].

2. Hoop Wrapped Composite cylinder (Fig. 2. b)

These types of cylinders have a metal liner and a composite reinforcement on the straight side only. This type of container is a compromise between the low cost of all metal cylinder and the lighter cylinder from type 3 and 4 [30].

3. Fully Wrapped Composite with Metal Liner (Fig. 2. c)

This type of cylinder uses a seamless metal liner over wound on all surfaces by a composite reinforcement which provides between 75 to 90% of the strength of the tank. They are used also in portable applications such as breathing apparatus, medical oxygen storage, aircraft slide inflation [30].

4. Fully Wrapped Composite with Non-Metallic Liner (Fig. 2. d)

These containers have a plastic liner and a full overwrap of carbon fibre or mixed fibre construction. The main disadvantage of these tanks is that they provide no structural strength to the product and, also, they are not gas tight but, the rate of permeation is acceptable for use with CNG [30].

a) b) c) d)

Figure 2. a) Fully Wrapped Composite with Metal Liners; b) All metal cylinders; c) Hoop Wrapped Composite Cylinders; d) Fully Wrapped Composite with Non-Metallic Liners

In table 3. are indicated some prices for each type of cylinder and its mass in kilograms for each litre of tank capacity [30]

Table 3. CNG cylinder types cost and weight

Cylinder type	**Cost [$/L]**	**Weight [kg/L]**
Steel type 1	6 to 10	0.9 to 1.2
Aluminium type 1	8 to 10	0.9 to 1.0
Metal, hoop wrapped	10 to 15	0.8 to 0.6
Fully wound composite, aluminium liner	20 to 25	0.3 to 0.4
Fully wound composite, plastic liner	20 to 25	0.3 to 0.4

CNG cylinders standards has a very complete series of safety criteria related to performance of the tank which covers burst pressure, life cycle, resistance to damage and effects of the extreme environment conditions. Because it’s a safety piece, it has to pass some mandatory tests as mentioned in ISO 11439.

3.1.3. Infrastructure in Europe

It is well known that accessibility to fuel stations is very important. Just as petrol and diesel stations are widely available for all car ranges, so should be those for refuelling with CNG, and even more so, given the low energy density of CNG.

In Europe, the number of CNG stations are 3932 and 363 of LNG, according to Natural & bio Gas Vehicle Association (NGVA) Europe (figure 3) [31]. According to [32], in Europe are 43140 LPG stations which means that NG stations are 90% fewer as number compared with LPG gas stations, but keeps increasing. Most developed infrastructure for NGV is in West Europe and Italy. In Romania there are 3 CNG gas stations and none of LNG. [31]

Figure 3. CNG refilling stations in Europe [31].

These being presented, methane gas has potential in terms of use for vehicles adapting them to the needs of sustainable mobility in the current context but also in the short to medium term.

3.2. Influence of NG on SI Engine Operation

3.2.1. Combustion Characteristics

For a better understanding of what happens inside the cylinder when running in CNG mode, in [33] a comparison between a turbocharged direct injection (DI) gasoline engine and same engine port fuel injected CNG was made and they faced the major problem that every manufacturer and investigator is facing: the torque loss in CNG operating mode [3], [33]. Due to stoichiometric (air-fuel) AF ratio of CNG(17.2) [33] higher than the one for gasoline (14.5) [33], discussing at iso-air filling, the amount of natural gas injected or which goes inside cylinder is smaller than the gasoline one. Furthermore in this experiment, the CNG was injected in a gaseous state into the intake port and that meant an unfavourable volumetric efficiency which cumulated with the stochiometric AF ratio of CNG, means that the total energy of CNG was lower than gasoline, which is one of the possible reason for the torque loss [33].

Another possible reason for torque loss is the low flame propagation, [18], [3], [34] which is lower than gasoline. This means that for the same spark advance applied the duration of combustion will be higher for CNG. In [33] an earlier spark advanced ignition timing was applied and the duration of combustion was nearly identical after top dead centre (TDC). Also, in [3] the same recommendation is made in order to have the same duration of combustion. Another consequence of low flame propagation is the longer ignition delay compared with a diesel or a gasoline engine. Consequently, the duration of combustion becomes longer. Bi-fuel engines are optimised with more advance spark timing in gasoline cases and a pilot injection for the diesel engines which ignites the CNG [3]. Ignition delay can be also improved by changing the combustion chamber geometry [3] or using a direct injection of CNG which proves similar performances as a DI gasoline engine [35].

These two parameters, low flame propagation and ignition delay, entail temperature and cylinder pressure modification. In [36], for the same spark advance applied the pressure inside cylinder is significantly smaller especially near TDC because the gas occupy volume in the admission collector and the air which goes inside is less and because the burning velocity of the methane is smaller. Also, the temperature flame of the methane and air mixture is lower than gasoline mixture, so the ignition delay is longer which makes a reduction in cylinder pressure and in temperature as well. The increasing of the spark advance for natural gas operation and together with the elimination of the cooling effect of the fuel vaporisation leads to higher temperatures inside the cylinder which explains the higher values of NOx [18],[33], which many investigators faced with. Cylinder pressure is also higher due to spark advance modification in order to obtain maximum brake thermal efficiency without going over maximum cylinder pressure of the engine [19], [33] (mechanical limitation).

3.2.2. Engine Performance

The external effects of the in-cylinder effects are quantified with the dyno. Break mean effective pressure is lower than gasoline operation with around 16% [16]. The reason was already explained in §2.4.1. as being an effect of the low flame propagation cumulated with ignition delay. That means that the torque decreases between 14% [18] and 15% to 20% for retrofitted engines [3] confirmed also in [16]. Power decreasing is a consequence of the torque decreasing.

Higher octane number of CNG in concordance with the spark advance applied has consequences about exhaust gas temperatures, too. In [33], excepting the low speed part where the manifold pressure was different, the exhaust temperature was reduced so much that no enrichment was needed. Also, in [3] a decrease of 6.8% of the exhaust temperature was observed.

Brake specific fuel consumption was always lower in CNG operating mode which can be explained by three main factors: higher heating value of CNG than gasoline, lean and slow burning of CNG and earlier spark advance applied in CNG mode which also improves brake thermal efficiency (BTE) up to 5-12% [33], [3]. The lower value of BSFC is in range 12% to 20% lower than gasoline [16], [18], [33], [3]. In [37] is presented the influence of compress ratio for a diesel dual fuelled engine on BSFC, which also help in decreasing it. This is the main advantage of a spark ignited engine which operates with CNG.

3.2.3. Emissions

In [36], a naturally aspirated gasoline engine port fuel injected was compared with itself but with CNG fuel. The spark advance was not modified. In this case the torque was lower with 19% than the gasoline operating mode. The authors presented all the pollutants as being lower than the operation with gasoline and mentioned that CO_2 is reduced up to 90% and the UHC is reduced up to 12% to 96%, as function of load. The NOx depends on the combustion temperature and it is reduced around 68% in full load and up to 90% in partial loads.

About carbon monoxide (CO) emissions, in [38], 37 CNG vans were tested in two different laboratories and in contrast with their gasoline counterparts, they produced 40% lower CO emissions. According to [38], [39], CNG particles size are smaller than diesel (0.1 μm) and gasoline (0.01-0.08 μm) with ranges

between 0.01 to 0.07 µm with a majority between 0.02 and 0.06 µm. Same study shows that the average total particulate mass (PM) of CNG engine is only between 7 to 9% of the emissions of a diesel engine [38], [40].
About particulate number (PN), an Euro6 CNG car in real driving emissions test, the number of particles greater than 23nm were as low as a diesel particulate filter equipped engine. Measurements on the Euro 6 D-temp CNG vehicle shows that PN > 2.5nm levels are below the current regulation limits even without particulate filter on the exhaust line [41], [42].
Further to this literature review, it is clear that the natural gas will reduce the exhaust emissions for spark ignited engine, as already did in Delhi [43] where the air quality was improved with the help of CNG.

4. Conclusions

After all arguments presented, natural gas vehicles should be part of the future of the internal combustion engine. Natural gas is available in many world locations; however, the necessary infrastructure should develop quicker than planned in order to ensure a more rapid use of this complementary clean fuel. Thanks to fast filling process, a natural gas vehicle has a main advantage in front of an electric vehicle car: filling time, which is comparable with a filling time of a gasoline or diesel car. The artificial production of bio-methane is also a high step because it can be produced from waste (water and food). It can easily be adapted to actual engine technology by adding some specific sensors and actuators. Direct injection CNG seem to be a solution in obtaining performances similar with a DI gasoline engine. Emissions are reduced with a high percentage especially in part loads where many vehicles operate day by day. CNG improves BSFC and BTE which has a direct impact in CO_2 reduction. The results made on the retrofitted engines with CNG are promising regardless of the combination of CNG with other fuels or using pure CNG, and probably will have their best if a dedicated CNG engine will be created (combustion chamber, compression ratio) and fully optimised (spark advance, fuel injected mass).

Abbreviations

AF	air fuel	LNG	liquefied natural gas
BEV	Battery electric vehicle	LPG	liquefied petroleum gas
BP	brake power	NG	natural gas
BSFC	brake specific fuel consumption	NGV	natural gas vehicle
BTE	brake thermal efficiency	NGVA	Natural & bio-Gas vehicle association
CNG	compressed natural gas	PC	passenger car
CO	Carbon monoxide	pcyl	cylinder pressure
CR	compress ratio	PHEV	plug-in hybrid electric vehicle
DI	direct injection	PM	Particulate matter mass
DoC	duration of combustion	PN	Particulate number
ECU	electronic control unit	SI	spark ignition
EGT	exhaust gas temperature	Tcyl	cylinder temperature
GHG	green house gases	TDC	top dead centre
ID	ignition delay	UHC	unburned hydrocarbons
IMEP	indicated mean effective pressure	ULEV	ultra-low emission vehicle
LHV	lower heating value	ZEV	zero emission vehicle

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