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LPG, ALTERNATIVE FUEL FOR INTERNAL COMBUSTION ENGINES

Abstract: *Due to increased pollution and economical challenges of our days, alternative fuels have become one of the most important fields of research. There are many alternative fuels available today, but one with the highest potential is the liquefied petroleum gas (LPG). Already, important steps have been made in developing new technologies and infrastructure for the LPG market. This paper presents the main characteristics and functionalities of LPG, as a more economical, energy efficient and eco-friendly fuel. Also, a comprehensive review of various types of fuel systems have been prepared for better understanding of operating conditions and advantages for a LPG fueled internal combustion engine.*

Key words: *LPG, fuel emissions, internal combustion engine, fuel injection.*

INTRODUCTION

In our days the consumption of petroleum products is in continuous growth due to constant increasing of the automobiles on the road but also due to the industrial and technological development thought the world. For the automotive industry the conventional fuels are obtained from crude oil refining, but this natural resource is limited and will not be sufficient to meet the energy growing demand. Further, there is the environmental issue caused by the huge amount of pollutants emissions generated by the use of conventional vehicles. The environmental pollution and economic challenges of the modern industry is demanding alternative fuels for the automotive sector. Among the various alternative fuels, the liquefied petroleum gas (LPG) it's very attractive due to its eco-friendly properties and economic benefits.

LPG is made of hydrocarbon gases: propane (C_3H_3) and butane (C_4H_{10}) or mixes this tow gases. In the areas where the climate is cold, the LPG contains more propane, and in wormer areas, it contains more butane. LPG contains also butylene, propylene and other hydrocarbons in small concentrations. Due to the fact that these gases are inodorous, ethanethiol is added in order to detect any leaks.

LPG can be obtained by refining oil or from production of natural gas. It is found in natural state in combination with crude oil or natural gas. Today, approximately 60% of the LPG results from plants that process natural gas. LPG is separated from natural gas by using refrigeration and can be extracted from crude oil by using distillation methods. Because LPG has a high energy density and burns easily in the presence of air, it has become very useful in many fields like: domestic use (heating, cooking), industry, agricultural processes, but the most important one is the automotive industry where it's used as an alternative fuel for vehicles. In this field of application LPG is known as Autogas.

2. LPG IN AUTOMOTIVE

2.1 LPG among conventional fuels

The potential benefits of LPG, makes it suitable to be used in spark ignition (SI) engines as alternative fuel or even completely independent and also on compression ignition (CI) engines, but in this case it can be used only in mixture with diesel fuel.

Due to its higher octane number, LPG will be able to fulfil a more smoothly combustion when used on SI engines. Consequently, this aspect will generate a reduced engine wear. The higher octane together with higher ignition temperature, gives a better engine knocking resistance which allows higher compression rations. This means increased engine power and better thermal efficiency, at the end resulting lower fuel consumption and emissions. With a lower energy density per litter compared to conventional fuels (table 1), LPG equivalent consumption will be higher.

Table 1

Comparison of fuel properties according to [4]

Nr.	Properties	Diesel	Gasoline	LPG
1	Formula	$C_{12}H_{18}$	C_8H_{18}	C_3H_8
2	Molecular weight [kg/Kmol]	170	101.213	44.1
3	Density [kg/m^3]	780-860	710-770	510-580
4	Cetane number	40-55	13-17	<3
5	Octane number	20-30	86-94	105-112
6	Boiling point [°C]	163	204	-42
7	Flashpoint [°C]	>52	-46	-104
8	Auto Ignition temperature [°C]	210-257	246-280	405-470
9	Stoichiometric Air Fuel Ratio	14.5: 1	14.7: 1	15.6: 1
10	Caloric Value [kJ/kg]	42 500	44 000	46 300
11	Energy density [MJ/L]	35.8	34.2	26
12	Flammability limit	0.6-7.5%	1.4-7.4%	1.8-9.5 %

We can observe that LPG has a lower cetane number which makes it unsuitable for using on CI diesel engines. Because of its high octane number, LPG can be efficiently used on SI engines. In the fallowing, the benefits of LPG will be presented.

2.2 Benefits of LPG

Environmental and health concerns, pollution, and vehicle emissions have become increasingly important and more and more restrictive legislations are imposing lower limits for emissions. This reflects a real need for cleaner engines fuels. Autogas, the commercial name for LPG when used in vehicles, has numerous advantages and great potential for future technologies applications.

The main emissions that are under regulations today are nitrogen oxides (NO and NO_2, or commonly known as NO_x), hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2) and particulate matter (PM).

Regarding the regulate emissions, Autogas it's better positioned by comparing with other fuels like gasoline and diesel. This is achieved due to the fact that the components of LPG have a simpler and purer chemical composition which allows it to mix easily with air, resulting a more complete combustion. If we take a look at the results obtained from tests performed by the European Emissions Test Programme (EETP) in 2004, we will observe that emissions of NOx (the most important regulated emission gas) resulted from Autogas are much lower than from diesel and gasoline. This NOx reduction is more obviously for Euro5 compliant vehicles (fig. 1).

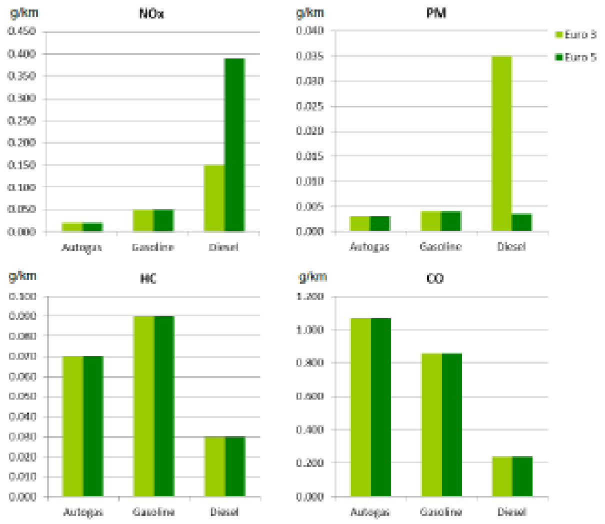
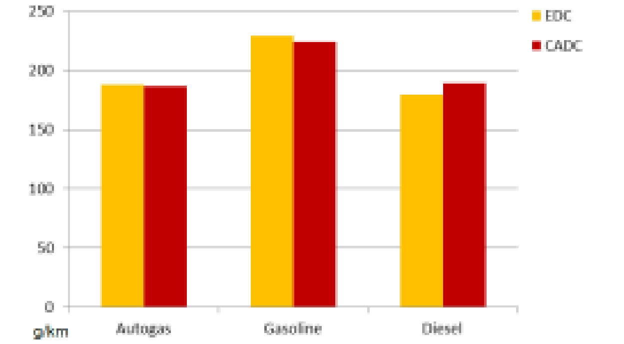


Fig. 1 Regulated fuel emissions of light-duty vehicles resulting from different fuel used [3].

PM emissions are similar between gasoline and LPG, but for diesel engines they remain a major problem. The CO_2 responsible for greenhouse gases is also one important emission that is under regulation. Autogas has lower CO_2 emissions than gasoline and diesel, due to its lower carbon content.

CO_2 emissions measured in 2004 by EETP wore done taking into consideration two test cycles: Artmis cycle (CADC) and European driving cycle (NEDC or EDC). As we can observe in figure 2 [3], in CADC test cycle (which simulates the real driving conditions), Autogas emissions are lower than gasoline and diesel, but in EDC cycle they are slightly higher than diesel.

Another important benefit of LPG is the low cost on the market today. This is possible thanks to reduced taxes policy of governments, being a consequence of its environment friendly aspects. Autogas takes advance of the existing distributing network for convention fuels which makes it less investment needed.



EDC=European driving cycle
CADC=Artmis cycle, which simulates actual driving conditions

Fig. 2 Regulated emissions of light-duty vehicles resulting from different fuel used [3].

2.3 LPG vehicle market

Autogas is the most widespread fuel used as an alternative to the conventional fossil fuels (diesel and gasoline). This fuel has gain an important market in many countries and it has a continuous growth of consumption. As we can see in figure 3 [2], the global consumption of Autogas has reached its peak in 2016, with a value of 26.8 million tones used in vehicle transportation. Since 1990 the only decrease of consumption was in 2017, by 1.2% compared to the previous year. The largest consumer of Autogas is Korea, but there are also other major markets like Turkey, Italy, Poland and Russia.

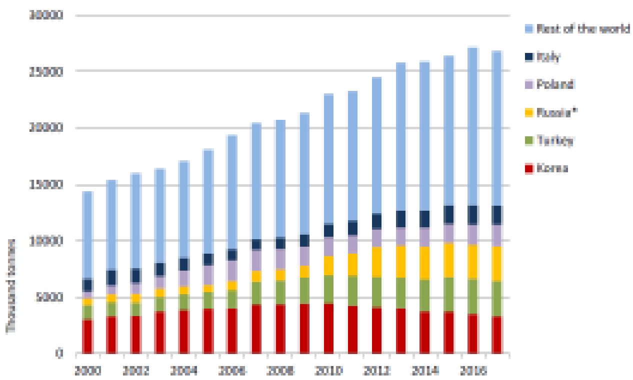


Fig. 3 World Autogas consumption, between 2000 and 2016 [2]

These five countries mentioned above, account 49 % of the word consumption in 2017 and only ten countries, as presented in table 2, are responsible for over 70 % of the entire Autogas consumption. The continuous growth of Autogas consumption is also due to the fact that the automotive market has increased a lot in the last years.

According to the World LPG Association, as presented in table 2, there are over 27 million vehicles that run on Autogas, around the world and approximately 78 000 LPG filling stations. Today, Autogas represents more than 1.2% of total road-transport-fuel consumption.

Korea, the larger consumer of Autogas has almost 2.2 million vehicles, but Turkey, the second larger consumer, has the largest number of Autogas vehicles: 4.6 million.

Table 2

Comparison of fuel properties according to [2].

Country	Consumption [t]	Vehicles	LPG filling stations
Korea	3 314 000	2 122 000	2 037
Turkey	3 116 000	4 617 000	10 297
Russia	3 100 000	3 000 000	4 900
Poland	1 915 000	3 082 000	6 287
Italy	1 675 000	2 309 000	3 979
Ukraine	1 503 000	2 500 000	3 800
Thailand	1 320 000	1 065 000	1 450
Mexico	1 101 000	420 000	2 150
China	1 007 000	168 000	560
Japan	728 000	200 000	1 406
Rest of the World	8 056 000	7 653 000	41 401
Total	26 835 000	27 136 000	78 267

3. LPG FUEL SYSTEMS

Many vehicles that are running on conventional fuels are converted to run on LPG by adding a new, separate fuel system which allows the vehicle to switch between the two fuels. Due to technical reasons, most vehicles that are converted, involve a gasoline SI engine, which is more suitable to run on LPG.

3.1 Convertor and mixer system

One of the first generations of LPG systems contains a convertor and a mixer. This type of system, also known as a “single point” or venturi system, is suitable for carburettor or some early fuel injection engines. It uses a convertor (also known as evaporator) to change liquid LPG into vapour. This vapour is feed to the mixer where, as the name says, is mixed with the air before entering the intake manifold. There are some additional components that need to be fitted on the vehicle as we can see in figure 4.

1- refuelling valve, 2- gas tank, 3- multivalve, 4- gas solenoid valve, 5- convertor/evaporator, 6- control valve, 7- mixer, 8- fuel supply switch, 9- gasoline solenoid valve, A- high pressure gas line, B- low pressure gas line

Fig. 4 LPG convertor and mixer system [5].

The condensed LPG is stored under the gas tank (2). Upon opening a solenoid valve that is part of the multivalve (3), due to the overpressure in the tank, the LPG in liquid form passes through a pipe (A) until it reaches the gas solenoid (4) and from here to the convertor/evaporator (5). In the convertor, the liquid LPG evaporates and its pressure is reduced slightly above atmospheric pressure. The LPG gas is now travelling thought flexible pipe (B), passing by a control valve (6), to the mixer (7) where is mixed with the inlet air before entering in to the engine. For carburettor engines, the fuel supply switch (8) controls the opening of gasoline (9) and gas (4) solenoid valves.

The mixer, which is the specific component of this firs generation of system, is fixed just before the throttle body (fig. 5). It can be also integrated in the carburettor body. Inside the mixer there are little holes through witch LPG gas come out. The mixer incorporates a venturi design in order to draw the fuel into the airflow.

Fig. 5 LPG mixers [6].

This system, fitted mainly on carburettor SI engines, has no automatic control over the quantity of the LPG injected, so this will result in high exhaust emissions. There are also more evolved versions of this generation which are suited for gasoline injection systems that have catalytic convertor and lambda sensor. This LPG system has an automatic control management that ensures the right air-fuel mixture and comes with fuel consumption benefits and lower emissions.

The complete LPG components functionality will be presented on the next major generation of LPG system, as this is the most common and complete system in our days.

3.2 Vapour phase injection

The most popular LPG system in recent years is the vapour phase injection (VPI) system which uses a convertor, like the previous system, but the gas that exits this convertor is injected into the intake manifold thought injectors that are electronically controlled. This makes the system suitable for multipoint gasoline injection engines that have modern technologies integrated. The gas is injected in sequential mode, meaning that LPG injector sprays the gas in a specific order or sequence which equals the injection sequence of the gasoline injectors. This technology is also known as vapour sequential multipoint LPG system.

Figure 6 presents the main VPI system components. These components will be further described in detail from the gas filler neck to the injection LPG gas into the air intake manifold.

The gas filler neck is located near the gasoline filler neck. It has a check valve that, when refilling under pressure, allows the liquid gas to flow only in one direction and stops the liquid LPG flowing in the opposite direction. The liquid LPG flows through rigid high pressure pipes to the LPG fuel tank.

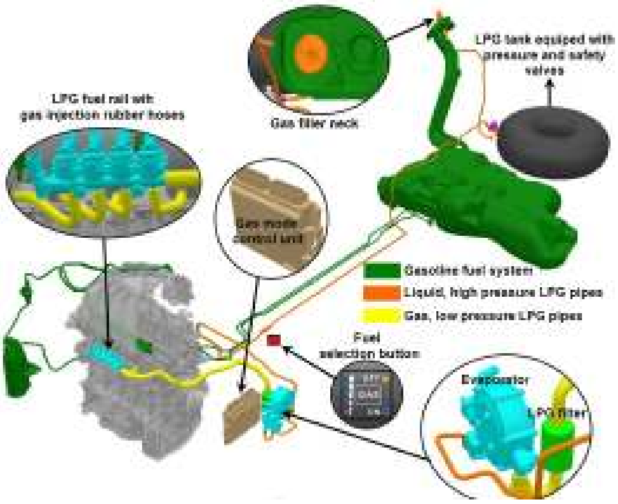


Fig. 6 Vapour phase injection LPG system components.

The LPG tank, presented in figure 7, is usually located in the place of the spare wheel and has a robust design (3-4 mm thick steal), meeting high safety standards imposed by worldwide regulations. The usual pressure inside the tank is between 8 and 10 bar, but the tank is designed to resist up to 30-40 bar.

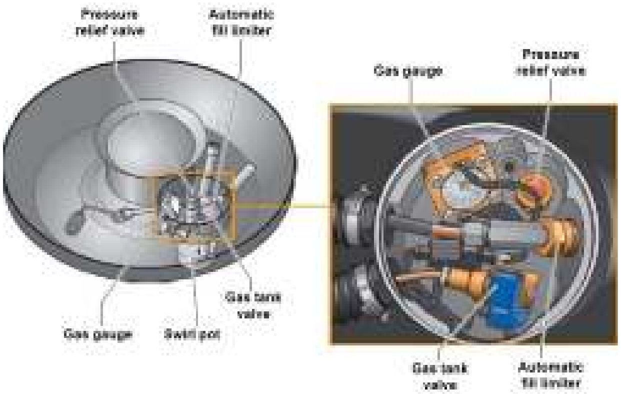


Fig. 7 LPG tank with integrated pressure and safety valves [7].

The liquid LPG enters the tank by an automatic fill limiter which assures the maximum fill of 80% of the tank. This is a safety feature that provides volume for the liquid to expand, depending on the environment conditions. A pressure relief valve is fitted in order to avoid LPG bursting if the pressure inside the tank rises excessively. As soon as the pressure in the tank rises above a safety established value (for example 25-30 bar), this valve opens mechanically until the inside pressure is stabilised. There is a gas tank valve that allows the liquid LPG to flow out of the tank. This is a solenoid valve, operated by the gas mode control unit which opens it during LPG operation. The valve automatically closes and LPG no longer flows toward the evaporator, when the system is switched to gasoline mode, engine is turned off, crash situation or a when a voltage supply fail appears.

There is a swirl pot fitted on the bottom of the tank. It assures a constant supply of LPG to the gas valve, in the most difficult situations, for example hill start or hard cornering. A gas gauge fitted on the tank, shows the LPG level in the tank. This also provides the information that is showed on another gas gauge integrated on the fuel selection button (situated on the passenger compartment). All is managed by the gas control unit.

From the gas tank valve the LPG travels to the evaporator. The liquid LPG enters the evaporator thought the high pressure valve (fig. 8). This valve works and has the same functionalities as the gas tank valve. A filter is integrated into the high pressure valve; this retains the impurities in the liquid in order to protect the sensitive components of the evaporator.

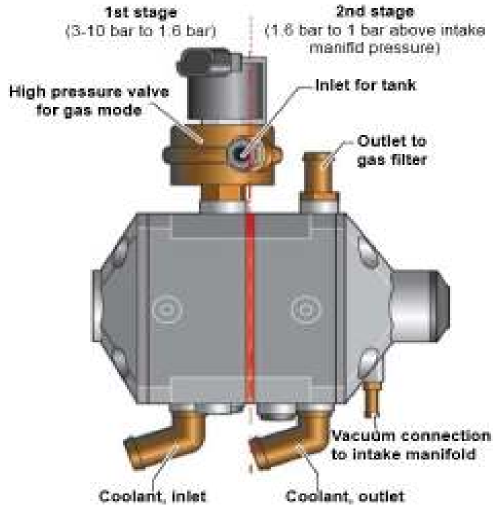


Fig. 8 Evaporator with high pressure valve integrated [7].

The evaporator converts the LPG form liquid state to gaseous state. It also reduces the pressure of the LPG from about 10 bar to 1 bar above the pressure inside the air intake manifold. The LPG expands inside the evaporator in two stages: first stage reduces the pressure to 1.6 bar and the second stage it reduces it more, to 1 bar above the pressure inside the intake manifold. This pressure reduction in two stages assures that the pressure fluctuations are compensated. Inside the evaporator there is also a coolant circuit. Due to the fact that when the liquid LPG expands it draws the thermal energy from its surroundings and it cools down. A refrigerating effect appears which can lead to ice forming inside the evaporator. This is why the evaporator is connected to the engine coolant system, in order to ensure heat inside it. Because of this, the system can switch from gasoline to LPG only when the engine coolant temperature is above 20-25 C°.

Now the LPG gas travels from the evaporator through low pressure pipes (plastic or rubber), to the gas fuel rail. A LPG gas filter (fig. 9) is fitted between this two components in order to filter any impurities resulted from the vaporisation process and so it protects the gas injectors.

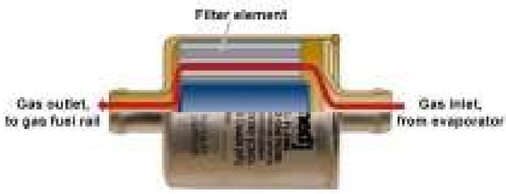


Fig. 9 LPG gas filter [7].

The LPG gas fuel rail (presented in figure 10) is mounted in the engine compartment, usually near the air intake manifold.

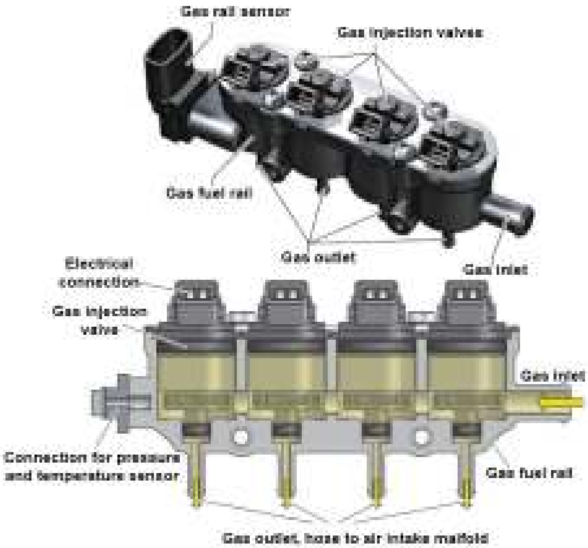


Fig. 10 LPG gas fuel rail, according to [7].

The LPG enters the gas rail witch is fitted with 4 gas injection valves, one for each cylinder. These valves are controlled by the gas mode control unit and operate at pressures of 2-3 bar. The gas arrives into the air intake manifold by houses connected to the injection valves. The gas rail is fitted with a sensor that measures the pressure and temperature of the LPG. These informations are needed by the gas mode control unit in order to calculate and control the opening times of the gas injection valves.

The driver interaction with the LPG system is done only by the fuel selection button, fitted inside the vehicle compartment (fig. 11). The main functions of this component are: gasoline/LPG selection, checking the LPG level in the tank and indicate any malfunctions (flashing/acoustic signal).

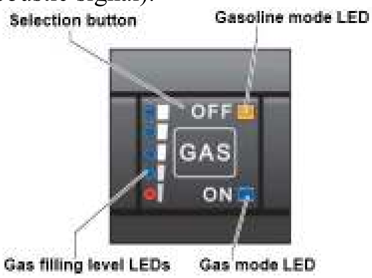


Fig. 11 Fuel selection button, with gas gauge [7].

3.3 Liquid phase injection

A modern LPG system suitable for SI port injection engines is the liquid phase LPG injection (LPI). The main difference in that this system does not use an evaporator and injects the LPG, in liquid state, in the air intake manifold. In this way the LPG vaporises directly inside the air intake manifold and the air around the vaporizing LPG is substantially cooled and this determinates the air density to grow, leading to increased engine power.

The functioning of LPI system, presented in fig. 12 is comparable with that of the gasoline injection system.

Fig. 12 LPG liquid phase injection system [8].

In the LPG tank we can find an internal pump (with valving system integrated) which increases the pressure by approximately 5 bar and then the liquid LPG it's pumped to the pressure regulation unit. This component is responsible for the adjustment and control and adjustment of the system's pressure. It does this by using a solenoid valve which opens when the fuel selector switch is pushed by the driver. The LPG is then pushed to the LPG injectors positioned in the air intake manifold. Ay fuel excess, controlled by the pressure regulator, goes back, via return lines, to the LPG tank.

This system has the advantage of a more accurate injection control, managing the exact time and quantity on injected LPG. Another advantage of the system is that it is not sensitive to influences from the ambient such as temperature altitude or humidity. The dynamic performance of the vehicle are not reduced, on the contrary, they can be higher.

3.4 Liquid phase direct injection

LPI system is dethroned by the liquid phase direct injection (LPDI) which is the most advanced LPG system. LPDI system uses many of the existing components of the gasoline injection system, such as high pressure pump and fuel injectors. The LPG is injected in liquid state directly on the combustion chamber, it vaporises and it cools the entire flammable charge. This give the fuel a good anti-knock resistance which leads to increased efficiency and low emissions.

Fig. 13 LPG liquid phase direct injection system [9].

The system, as presented in figure 13, has a specific fuel selector unit (FSU) that has the function of selecting which fuel to use depending of the driver's choice. From here the fuel arrives to the high pressure pump which increases the pressure up to 150-200 bar before sending the liquid LPG to the injectors. The fuel unused returns form the pressure pump to the FSU and then, via return lines, back to the LPG tank.

This system is unique because is the only one capable to assure the engine start directly on LPG. The gasoline system is only used for back-up and of course if the driver choses to run in gasoline mode. In this way a greater range is achieved having at disposal two fuels stored each in his tank.

4. CONCLUSION

The LPG fuel is one of the most important alternative fuel of the present with huge potential for expansion in the future. Due to its incontestable benefits such as low fuel emissions, higher energy efficiency and lower price than traditional fuels, LPG is the winner of the automotive market. The evolution of the LPG systems has permeated to adapt almost any existing vehicle on the market, managing to overcome the challenges of the newest fuel injection technologies. This system offers a remarkable benefit, allowing the drive to choose between two fuels, at the end resulting an important increase in the vehicle's fuel range.

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