Doctoral School on Engineering Sciences
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Extended summary

Analysis of an innovative system to compress natural gas in filling stations for compressed natural gas (CNG) vehicles

Curriculum: Energetic

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Date:23 January 2012

Abstract. The vehicles fuel market is nowadays characterized by an increasing demand of CNG (Compressed Natural Gas) refueling stations, underling a strong attention to energy and economic saving problems.
The aim of this study was to analyze an innovative kind of natural gas refueling station for vehicles.
The innovative aspect of this plant is that it enables construction of methane compression stations characterized by truly low plant costs and energy consumption compared with traditional solutions.
The comparison has been made utilizing the same compressor in both systems, to show benefits resulting from the introduction of intermediate tank farms.
Compression is achieved in the single compressor through three consecutive steps. The compressed gas is stored in intermediate tank farms having three different levels of pressure. Given the single compressor, proper pressure progression is achieved through a constant compression ratio calculated on the basis of pipeline pressure. In the prototype plant the suction pressure is assumed to be 19 bar; the low, medium and high tank farm pressures are 55, 105 and 250 bar, respectively.
Considering the same number of refueling, the innovative system is able to achieve a compression energy saving of 25%.

Keywords. Natural gas, filling station, energy efficiency

1 Introduction

In recent years vehicle emissions have assumed strong importance and it is increased the interest about methane as fuel, because it is less costly and cleaner burning than other fuels.

The natural gas is cheap, in fact it is possible to find it directly in nature, ready to be used without any refining.

It is homogeneously distributed around the world and its reserves are really abundant, so this carry out safety on supply chain and on its transport.

The methane transport is carried throughout pipeline, so it does not increase the road traffic and it give an help to avoid car accidents and air pollution produced by traffic itself.

On the same basis of driven kilometers, the methane is cheaper than other fuels. It shows major energetic content and a more favorable taxation politics. For a methane medium size vehicle, the saving in terms of fuel cost for each driven kilometer is of 60% compared to a gasoline vehicle and of 33% compared with a diesel one [1].

Natural gas is also really ecological, because it get the reduction of greenhouse gas emissions. The transport sector represents a major item on the global balance of greenhouse gas (GHG) emissions. In Europe, GHG emissions due to transport sector amounted to 21% of the total emissions (4151 Mt CO_2-eq) in 2006 (EEA, 2006), and approximately 93% of this was represented by road transport. This is also the only sector that has failed to register a reduction during the period 1990-2006, where emissions have risen by approximately 26%[2]. This is due mainly to the rising number of vehicles on the roads during said period, which increased by 34% for passenger vehicles, and by as much as 62% for heavy goods vehicles.

In an attempt to contain this phenomenon, European policies are being implemented to reduce GHG emissions, e.g. by promoting transport by rail, producing passenger cars with more limited GHG emissions (i.e. that do not exceed a target of 130 gCO_2/km for the end of 2012 [3]), and promoting the use of biofuels (Directive 2003/30/EC) or alternative fuels. The European Union’s Green Paper specifies the need to substitute 20% of conventional fuel consumption with alternative fuels by the year 2020.

The GHG produced in the transport sector are represented mainly by CO_2 deriving from the combustion of fossil fuels and, to a lesser degree, by N_2O produced by catalysts, and CH_4.

It is clearly important to take action reduce the GHG emissions due to transport sector, since there has been such a massive growth in the volume of traffic involved in the last 15 years or so. The potential remedies for combating this growth essentially lie in the use of more efficient vehicles (in terms of fuel efficiency) and of fuels with lower carbon content.

Italy is nowadays the European country with the highest diffusion of CNG (Compressed Natural Gas) vehicles, with 665.000 CNG vehicles at the end of 2011 and with its widespread natural gas filling station net.

It has been demonstrated that there is a strict connection between the CNG vehicle numbers and the filling station diffusion in a country [4].

Numerous analyses have been conducted about natural gas filling stations.

One disadvantage of natural gas as a motor vehicle fuel is the volume required to store the quantity of gas needed to provide a range of travel comparable to that experienced with gasoline. In order to store a sufficient volume of natural gas to provide a reasonable range of travel, it has been thought desirable compress the natural gas to a pressure of about 250 bar.

Because the vehicle tank pressures needed to store sufficient natural gas to provide a reasonable range of travel are relatively high when compared to available consumer line pressures, the refueling of vehicle storage tanks presents yet another problem. Refilling vehicle storage tanks with CNG within a time period comparable to that required to refill conventional vehicle fuel tanks with traditional fuels can necessitate the use of large, expensive, multistage compressors. Alternatively, home or on-board CNG refueling systems are characterized by very low flow rates, necessitating long periods (such as overnight) for refueling [5].

Among the various system for refueling vehicle storage tank that have previously been disclosed, one conventional system uses a large, multistage compressor to compress the natural gas to about 250 bar, then holds the CNG in a large volume intermediate storage tanks at that pressure. During refueling, the CNG is allowed to flow into vehicle storage tanks until the vehicle tank pressure is about 220 bar. After refueling, the intermediate storage is replenished with sufficient gas to again raise the storage to about 250 bar. This system is inefficient because of the repetitive need to charge storage tanks to about 250 bar.

In this contest, the aim of this study was to analyze an innovative kind of natural gas refueling station for vehicles, able to refueling vehicles storage tanks to the required pressures with very low energy consumption.

The innovative system was compared to a traditional one. The comparison was made utilizing the same compressor in both systems, in order to underline the energy saving resulting from the introduction of three level pressures storage.

2 The traditional system

A traditional compression system (Fig.1) to compress natural gas for CNG vehicles increases the pressure from 4 bar to 250 bar throughout a multistage intercooled compressor. This system requires very large compressors because it has to guarantee the same flow rate in each stage.

Moreover the cooling system needs large and expensive heat exchange surfaces. Lastly the cooling system, using mainly air as cooling fluid, has poor performance with high ambient temperatures.

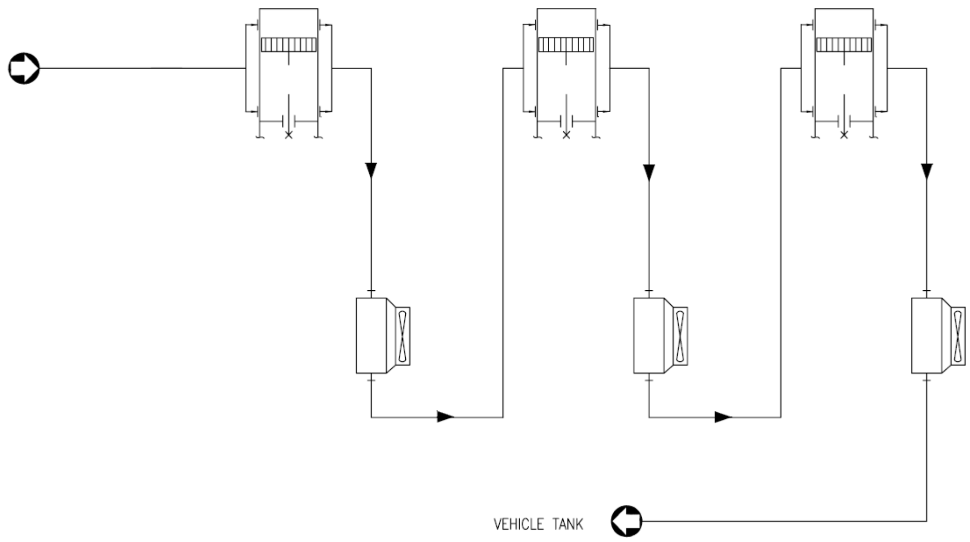

Figure 1. Scheme of the traditional system

In this analysis, we considered one prototype compressor. We compared the traditional system performance with the high-efficiency system one.

The compressor is constituted by two cylinders with the following characteristics:

- Bore - 37 mm
- Stroke - 150 mm
- Rotational speed - 750 rpm

The compressor was designed to work with a suction pressure of 19 bar and to compress the gas into three compression stage up to 250 bar. The flow rate elaborated was about 105 kg/h and the system required a compression power equal to 25 kW.

3 The high – efficiency system

The innovative filling station to compress natural gas for CNG vehicles is constituted by a single-stage single-cylinder compressor. The compression is achieved through three consecutive steps. The compressed gas is stored in intermediate storage tanks at three different pressure levels: low, medium and high pressure. The storage is made into tanks contained in big pools, so they are cooled by water.

The scheme of compression system is shown on figure 2.

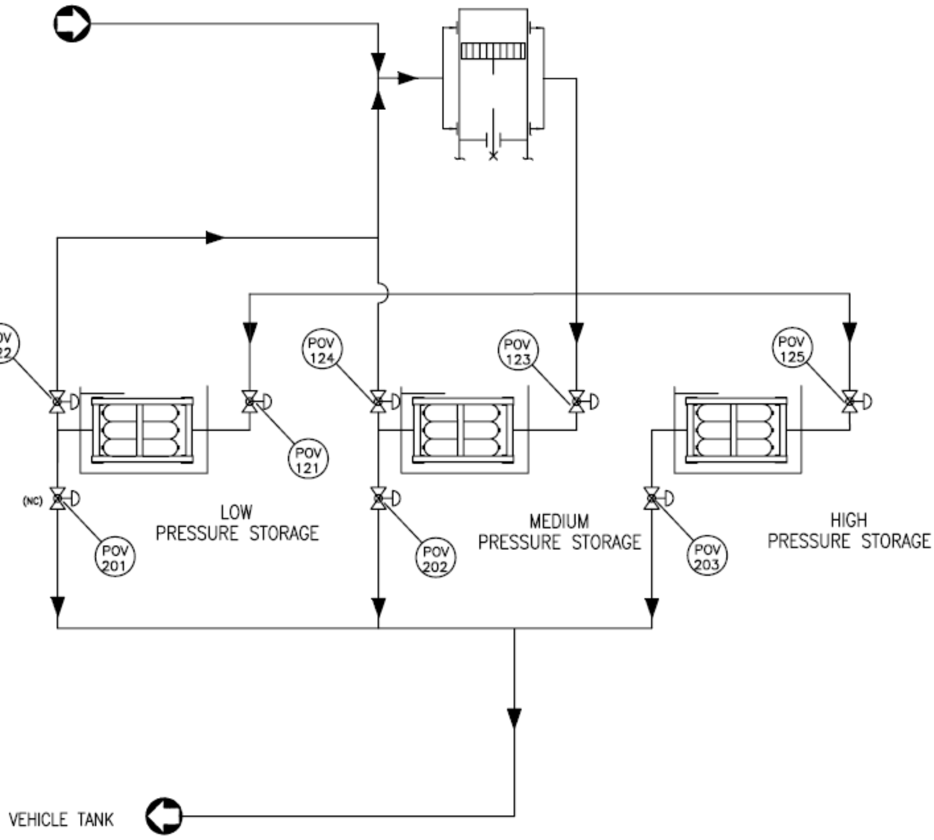

Figure 2. Scheme of the innovative system

3.1 The functioning details

At the beginning all storage tanks are empty.

The system starts to refill the low pressure storage until it is completely full.

Then, the entry valve to this storage is closed and the system open two other valves: the exit low pressure storage valve and the entry medium pressure storage valve.

Now the compressor sucks out from the low pressure tank and compress the gas into medium storage tank, until its complete replenishment.

The same procedure occurs for the high pressure storage.

As in the traditional system, here the suction pressure is 19 bar; the low, medium and high tank farm pressures have a minimum and maximum level of pressure:

- Low storage tank: 37-55 bar
- Medium storage tank: 87-105 bar
- High storage tank: 230-250 bar

We have considered a constant pressure ratio equal to 2,87.

The functioning details to refuel storage tanks is shown in Fig.3, while into the table is visible the scheme legend.

Table 1. Legend

Symbol	Description
POV121	Enter valve - low pressure tank
POV122	Exit valve - low pressure tank
POV123	Enter valve - medium pressure tank
POV124	Exit valve - medium pressure tank
POV125	Enter valve - high pressure tank
A	Valve opened
C	Valve closed
LPS	Low Pressure Storage
MPS	Medium Pressure Storage
HPS	High Pressure Storage

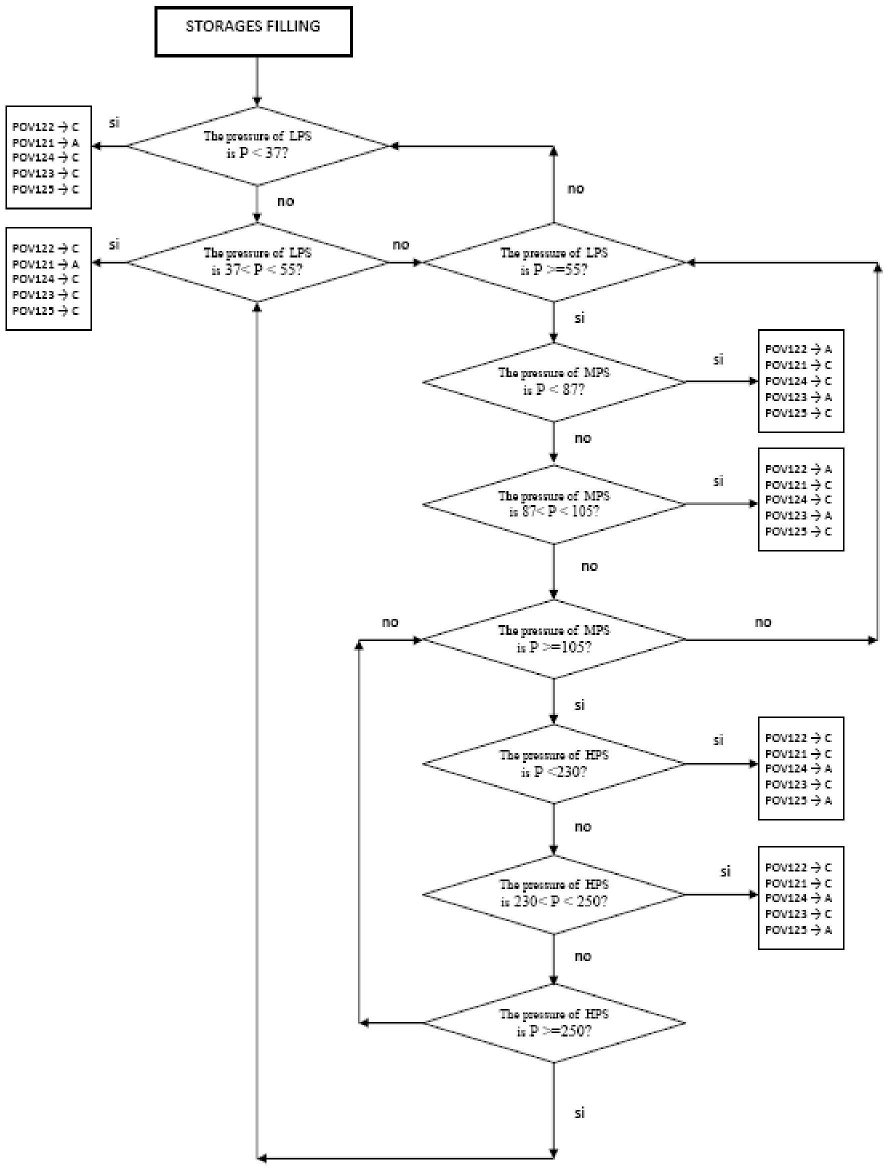

Figure 3. Storages logical filling

All tanks are immersed in pools full of water, in order to control gas temperature.

It can be used different systems to cool water pools, in this case it has been used an open circuit, with well water throwaway.

The cold water is alimented by a pipe system situated in the bottom part of pools, that allows to have an homogeneous circulation within all its part.

This cooling system allows to overcome traditional air-cooling system and let to reduce plant costs.

In Fig. 4-5-6 it is possible to observe the trend of water temperature inside pools and the gas temperature entering and getting out from the same pools, during a working day (8 hours). The data were measured during the experimental tests on the prototype compressor. In figure 8-9 it is shown the compression prototype plant and the cooling system.

The system is provided by a specific logical to fill vehicles. A vehicle starts to be filled by the low pressure storage, until storage pressure reaches vehicle pressure. Then it is filled by the medium pressure storage and at the end by the high pressure tank, until the vehicle pressure is equal to 220 bar.

This method allows to reduce the energy consumption, because permit do not compress all the refueled mass at maximum pressure, that is 250 bar.

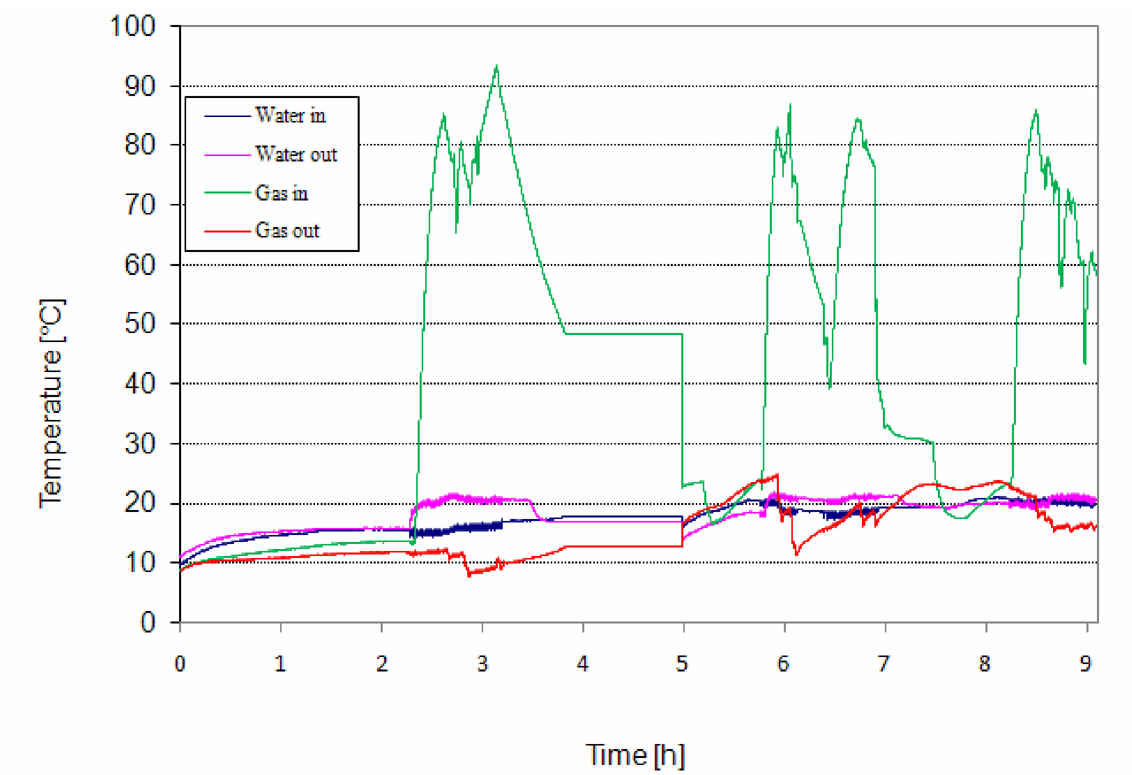

Figure 4. Low storage cooling

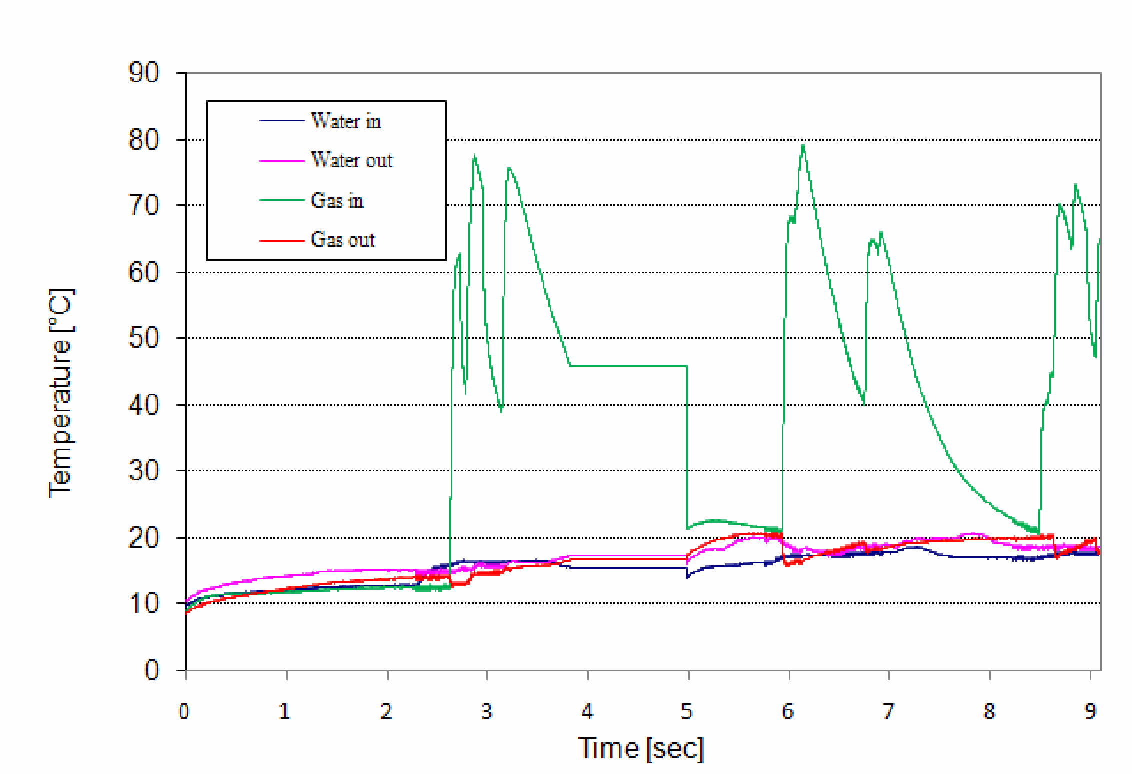

Figure 5. Medium storage cooling

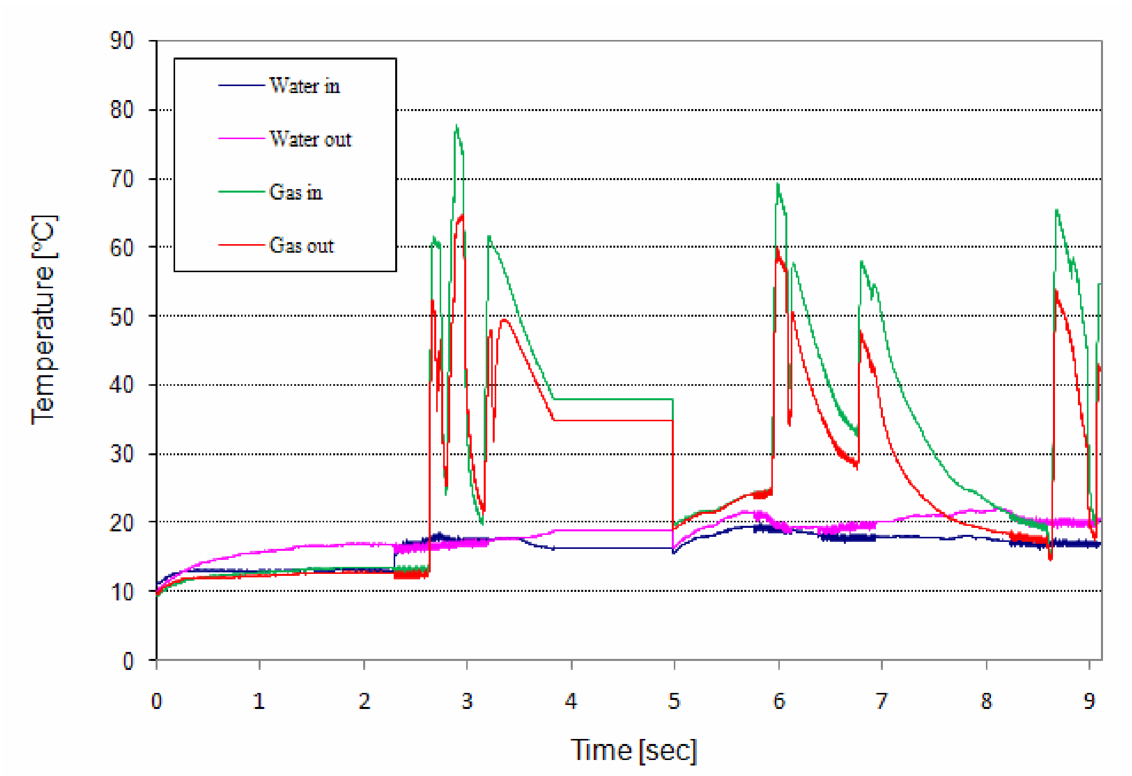

Figure 6. High storage cooling

Figure 7. Compression prototype plant

Figure 8. Cooling system

3.2 The simulation of the innovative system

In this work we have designed a CNG filling station. This station works with the innovative compressor, having the same geometrical characteristics of the prototype one.

The simulation of this system has been developed using Excel and some simulation programs, like EES (Engineering Equation Solver) [6] and HYSYS® [7].

For a filling station, the main elements are the following:

- Number of dispensers, which determine the station size
- Medium time of refueling
- Daily opening time
- Peak period, that is the working time in which the system works at 100% of its own capacity
- Maximum waiting time between two consecutive refueling, in the worst case in which any gas storage is empty and any fueling position is occupied
- Maximum possible refueling number

In this study we designed a filling station with only 2 dispensers and with a 10 minutes peak.
The vehicle tanks have generally a volume of 120 liter.
In the following table were reported the main data of the station considered.

Table 2. Station sizing

Parameters	
Dispenser numbers	2
Refuelling time	6 [min]
Peak period	10 [min]
Max waiting time	11 [min]
Daily opening time	10 [h/day]
Max number of refuelled dvehicles	88
Max CNG daily sold	1335 [kg]

After having designed the station, it was necessary to sizing the storages. The low pressure storage has a volume of 2 m^3, with 26 tanks of 80 liters each; the medium pressure storage has a volume of 1,8 m^3, with 30 tanks of 60 liters each; the high pressure storage has a volume of 1,1 m^3, with 18 tanks of 60 liters each.

The mass flow rate, referred to an entire compression cycle to refill the three level storages, is 318 kg/h and the medium compression power is about 24 kW.

Moreover in this simulation, the time necessary to fill the three storages it is about 11 minutes, corresponding to the maximum waiting time of the entire station.

3.3 Comparison between simulation and experimental results

In this section we compare experimental and simulation results. In table 3 there are shown mass flow rates, compression powers and filling times.

The mass flow rate has been measured during experimental tests.

The medium mass flow rate has been calculated as an average of the three different flow rates elaborated in one compression cycle, weighted on the time involved by compressor to fill each storage.

The same procedure has been followed to calculate the medium compression power, both experimental and simulation one.

The filling times have been determined considering the time involved by the compressor to fill each storage until the maximum pressure.

Table 3. Comparison between experimental and theoretical data of innovative compressor

Parameters	u.l.	Experimental	Simulation	Deviation
Flow Rate LPS	kg/h	125	193	54%
Flow Rate MPS	kg/h	600	463	-23%
Flow Rate HPS	kg/h	1200	866	-28%
Medium Flow Rate	**kg/h**	**328**	**318**	**-3%**
Compression Power LPS	kW	15	14	-7%
Compression Power MPS	kW	40	34	-15%
Compression Power HPS	kW	75	72	-4%
Medium Compression Power	**kW**	**26**	**24**	**-8%**
Filling Times LPS	sec	604	447	-26%
Filling Times MPS	sec	225	165	-27%
Filling Times HPS	sec	71	58	-18%
Time tot	**sec**	**900**	**670**	**-26%**

This comparison shows that the computed mass flow rate is lower in respect to the measured one, regarding the medium and high pressure storages, while it is greater on the low pressure storage. However the medium computed flow rate is only the 3% lower than the experimental one.

The medium compression power calculated is almost equal to the one measured.

The bigger difference it is noticed regarding the refilling times. The filling times of experimental test are bigger, because they considered all inertia of the system.

4 Comparison between the traditional and the innovative system

In figure 9 there are compared mass flow rates elaborated by the prototype compressor in both configurations, the traditional and the innovative one. These data come from simulations.

It is visible that in the traditional system the flow rates are always constant, while in the innovative system they grow in each stage.

In figure 10 is it shown the energy saving that it is obtained let the prototype compressor working in the innovative configuration respect to a traditional functioning.

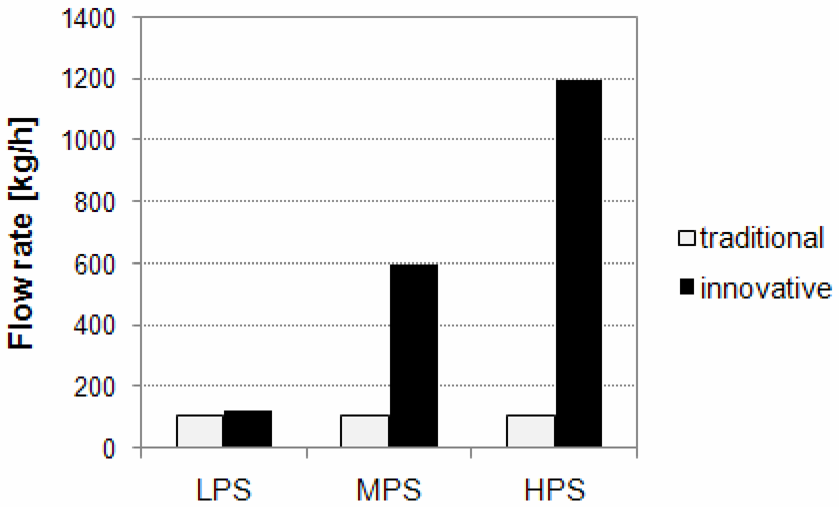

Figure 9. Comparison between mass flow rates of traditional and innovative system during the filling of low, medium and high storage

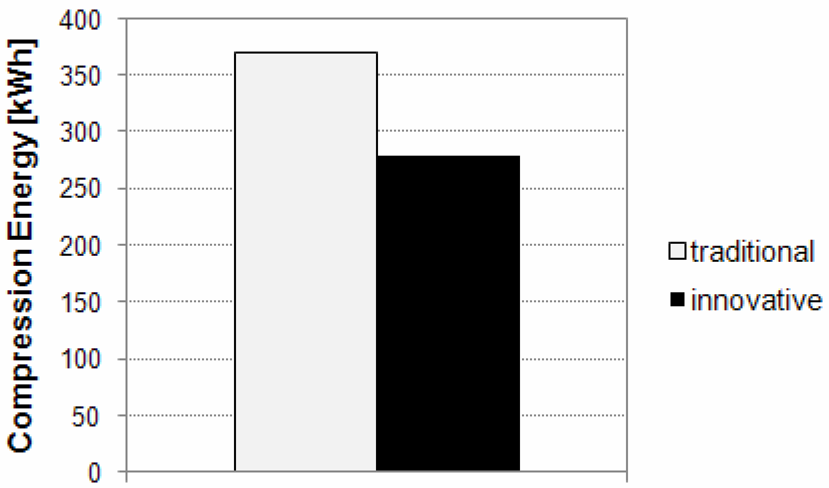

Figure 10. Comparison between the energy consumption of traditional and innovative system, for 100 vehicle refilled

The energy saving of the innovative configuration has been valuated considering a number of 100 vehicles refilled.

In table 4 there are displayed the results obtained. It is underlined the time required to refill vehicle tanks and the compression power of the system.

For traditional compressor the time required to fill 100 vehicles depend only on the flow rate elaborated from the compressor; while, for the innovative system, it depends on the time required to full fill all storages, that is the time required to complete one compression cycle, and on storage design.

The initial hypothesis is that all storages are full.

Moreover, the compression power of the traditional system is valuated as the power required from the three compression stages working contemporaneously, while the compression power of the innovative system as the medium compression power required in one compression cycle.

On the basis of these data, it has been calculated the energy saving (table 4): the high-efficiency system shows a compression energy consumption lower of 25% respect to the traditional one and this implies an additional profitability for filling station administrator.

Table 4. Comparison between the traditional and the innovative system.

	Traditional	**Innovative**
Filled vehicle numbers	100	100
Total mass [kg]	1517	1517
Required times [min]	867	683
Power [kW]	25	24
Energy tot [kWh]	361	273
Energy saving		**-25%**

5 Conclusion

This study analyzed an innovative technology to compress methane for CNG vehicles and compared it with a traditional system.

The comparison has been made utilizing the same compressor in both systems, to show benefits resulting from the introduction of intermediate tank farms.

Considering 100 number of refueling, the innovative system is able to achieve a compression energy saving of 25%.

The obtained results show also that the new kind of compression station is able to guarantee lower management costs, because of its lower energy compression consumption.

This analysis open different future scenarios. It would be possible to improve again this system on the terms of mass flow rates, volume stored and filling times, in the way of optimize the functioning of CNG filling stations.

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