A Fast Filling Station for a Compressed-Air Vehicle used for Zero Emission City Delivery and Personal Transportation

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Abstract- A vehicle powered by compressed air is developed, in the context of zero emissions and short distance delivery in a city. The compressed air powering system is composed of a filling station, a transfer line to the vehicle, the vehicle side reservoir and the compressed air propulsion system.
In order to reach a very short filling time of the vehicle, the local filling station is composed of a high-performance isothermal compression system, and a local buffer reservoir. During fast filling, the buffer reservoir is connected to the vehicle, followed by a fast transfer, very similar to the filling of diving bottles. However, the fast transfer results into a heated air in the car reservoir, which is bound with losses while cooling down, and has the consequence of a reduced mass of air in the vehicle reservoir.
An innovative air recirculation method is analysed, allowing, after the pressures having equalized, to exchange the heated air by cold one coming from the local buffer reservoir by recirculation. The result is a higher degree of filling of the vehicle reservoir, and also a higher energy efficiency of the system. The paper describes the complete system, its design, together with the properties of the fast filling including the recirculation system. Experimental results from the demonstrator actually under construction are also included

Index Terms- Compressed air vehicle; fast filling; buffer reservoir. Energetic properties

I. Introduction

The fact that humankind passed the 150% threshold in its use of the planet's resources available each year has only alerted a limited number of individuals. Environmental impacts as the 2010 event of the Gulf of Mexico, or more recently the alarmistic messages from the IPCC on the CO2 concentration in the atmosphere and the related global warming work as triggers of many interrogations. From the scientific community to the political world, there is no doubt that fundamental questions need to be answered, namely that of the unlimited and unconsidered energy consumption per capita [1]. Many sectors of the energy consumption are concerned, but the individual transportation occupies a front place in the list of problematic energy users. After several decades of hesitations following the first oil crisis, the automotive industry finally presented 2010 the first for mass production designed electric car. Significant progress in the energy density of electrochemical accumulators, together with reliable and performant electric propulsion systems using modern semiconductor devices and permanent magnet synchronous motors have contributed to this important development.
Another advantage of the EV's development is their capability to be integrated in the distribution networks as bidirectional sources, able to support the grid's power demand in critical conditions [2], [3].
Beneath interrogations about the available material resources for a wide expansion and mass production of EVs, one remaining open question is their charging time. Important recent developments have proposed very short charging durations in the range of several tens of minutes. This could be achieved mainly thanks to high performance cooling elements integrated in the battery itself.
If these techniques allow to maintain the battery cell's temperature within acceptable limits, the energy efficiency of the high-power charging process remains a questionable subject, as well as the compatibility of such high-power levels with the grid's power capability at the point of coupling.

In the same category of zero emission vehicles, alternative solutions have been studied like liquid nitrogen [4] or compressed air propulsion systems [5]. This last system has been presented as soon commercially available solution for several years, but its manufacturing company has not yet passed the status of prototypes.

Compressed air cars have of course very limited range due to the poor energy content of their pressurised reservoir. But they can be envisaged as a solution for specific application segments like factory areas, airports, mail delivery where known repetitive tracks represent the dominant part of the use.
Together with the energy content of the cars, the refill time must be considered, as a result of the possible power density of the storage system.

This paper presents the development and design of a fast filling station for a compressed air vehicle dedicated to city delivery and personal transportation on short tracks. A simple design of the air capacity is presented, and the focus is set on the performances of the refill station. An original recirculation concept allows to avoid the energy losses related to the heat-up and cooling of the fast-transferred air.

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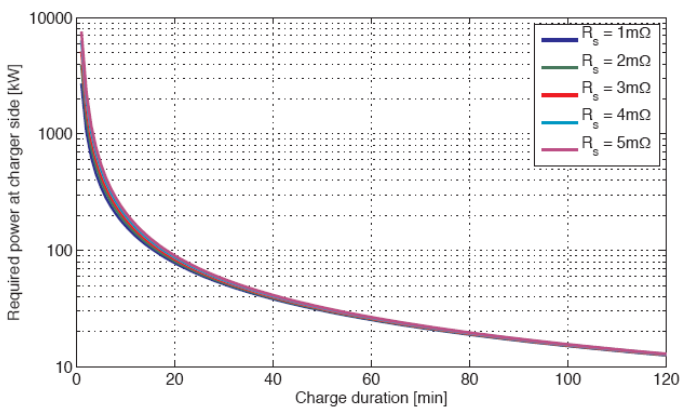
II THE POOR ENERGETIC EFFICIENCY OF THE FAST CHARGING OF A BATTERY

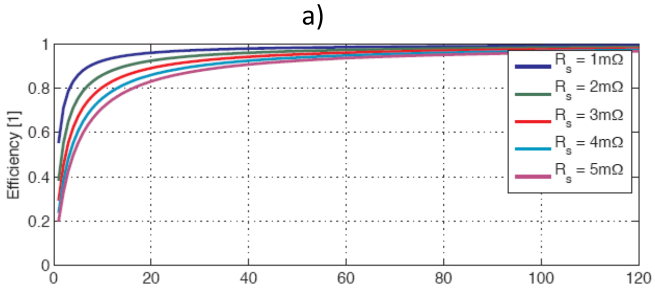
Charging an electrochemical battery in a short time under half an hour demands a high-power according rel. (1), and is affected with high losses in the battery itself due to the corresponding high current. In rel. (1), E is the energy capacity of the battery, R_{int} its internal resistor, and t_{ch} the charging time. Fig. 1a represents the power needed for the charge of a 25kWh battery in function of the charging time. The internal resistance is given as additional parameter. The corresponding charging current is causing high losses in the internal resistance of the battery and decreases the energy efficiency when the charging time is reduced. Fig 1b illustrates the severe impact of the short charging times on the energy efficiency of the charging process of the same battery [6], [7].

$$P_{ch} = \frac{E}{t_{ch}} + R_{\text{int}} \left(\frac{E}{U_0 \cdot t_{ch}} \right)^2 \qquad (1)$$

In opposition to the behavior of the electrochemical battery, the next section will describe the way of achieving the fast refill process of an air reservoir under much better efficiency condition.



a)



b)

Figure 1 Charge of a battery in function of the charging time
a) Required power
b) Energy efficiency

III AN EVOLUTIONARY CONCEPT OF THE FILLING STATION

Figure 2 represents the different solutions for the filling station of a compressed air vehicle, going from the simplest compressor (K_1) directly connected to the vehicle's reservoir (V_2) as shown in Fig. 2a. The size and power of such a compressor define directly the filling time of the car's reservoir. Non-optimal performance in terms of energetic efficiency is generally characterizing this well known industrial machinery, even if they are conceived as multi-stage machines dedicated to high pressure output in the range of several hundreds of bar.

Then, Fig. 2b shows the use of a local buffer reservoir (V_1), allowing a fast filling without using an oversized compressor and upstream power source. For this solution, the flowrate of the rapidly transferred air into the vehicle's reservoir is limited by a nozzle, but this air reaches a high temperature due to fast compression, a well-known phenomenon by the fast filling of diver bottles. After transfer, when the vehicle leaves the charging station, the heated air cools down, with first a consequence of a related energy loss, and second, the pressure level of the transferred air after cooling down is reduced, corresponding to a lower state of charge of this accumulator.

In order to skirt the effects of that loss of heat, an original recirculation system is represented in Fig. 2c characterized by the insertion of an additional return line from the vehicles reservoir back to the station's reservoir, allowing to recover the heated air of the vehicle back to the sender reservoir, and to replace it by cold one coming from the same place. This recirculation process does not use a great amount of additional power, the pressures having reached equality between the buffer and the vehicle reservoirs after the transfer. The nozzle has of course to be bypassed during recirculation. The recirculation compressor (K_2) is himself bypassed during the fast transfer and is only activated after pressure equalization.

Figure 2d illustrates the powering from renewable sources as photovoltaics. A frequency converter placed between the PV panels and the compressor's driving machine allows to adapt the power level of the compression to the available source through variation of the rotational speed of the compressor.

A first estimation of the needed air capacity

The estimation of the needed air capacity in the vehicle is based on a rough calculation according the consumption of an equivalent diesel engine. It is supposed that a small delivery vehicle propelled by a two-liter diesel motor is consuming around 8 liters per 100 km. With a density of 0.83 and a weight energy density of 42.5 MJ/kg for the diesel fuel, the energy consumption (tank) corresponds to 282MJ/100km or 78kWh/100km.

The propulsion energy (wheel) is much lower, based on the low energy efficiency of the classical propulsion system of 0.15 [8]. The final propulsion energy consumption becoming 11.7kWh/100km.

The estimation of the needed capacity of the air reservoir is done first on the base of an air propulsion efficiency of 0.3, including the exergy loss due to the use of a pressure reduction valve between the reservoir and the motor. On this base, the stored energy in the reservoir should be equal to 39kWh/100km. Second, the pressurized air reservoir can provide a volume energy density of 23.8 kWh/m^3 when the air pressure is of 200 bar.

Finally, a range of 50 km for the delivery vehicle would need a compressed air reservoir of 800 liter corresponding to a weight of 190 kg of air.

The capacity of the local reservoir is chosen as 5 times the capacity of the car's reservoir in order to limit the pressure variations during the transfer. When the final pressure in the car is defined as 200 bar, the pressure in the local reservoir must be equal to:

$$P_{V1} = \frac{V_1 + V_2}{V_1} \cdot P_{V2} = \frac{4 + 0.8}{4} \cdot 200bar = 240bar$$

s

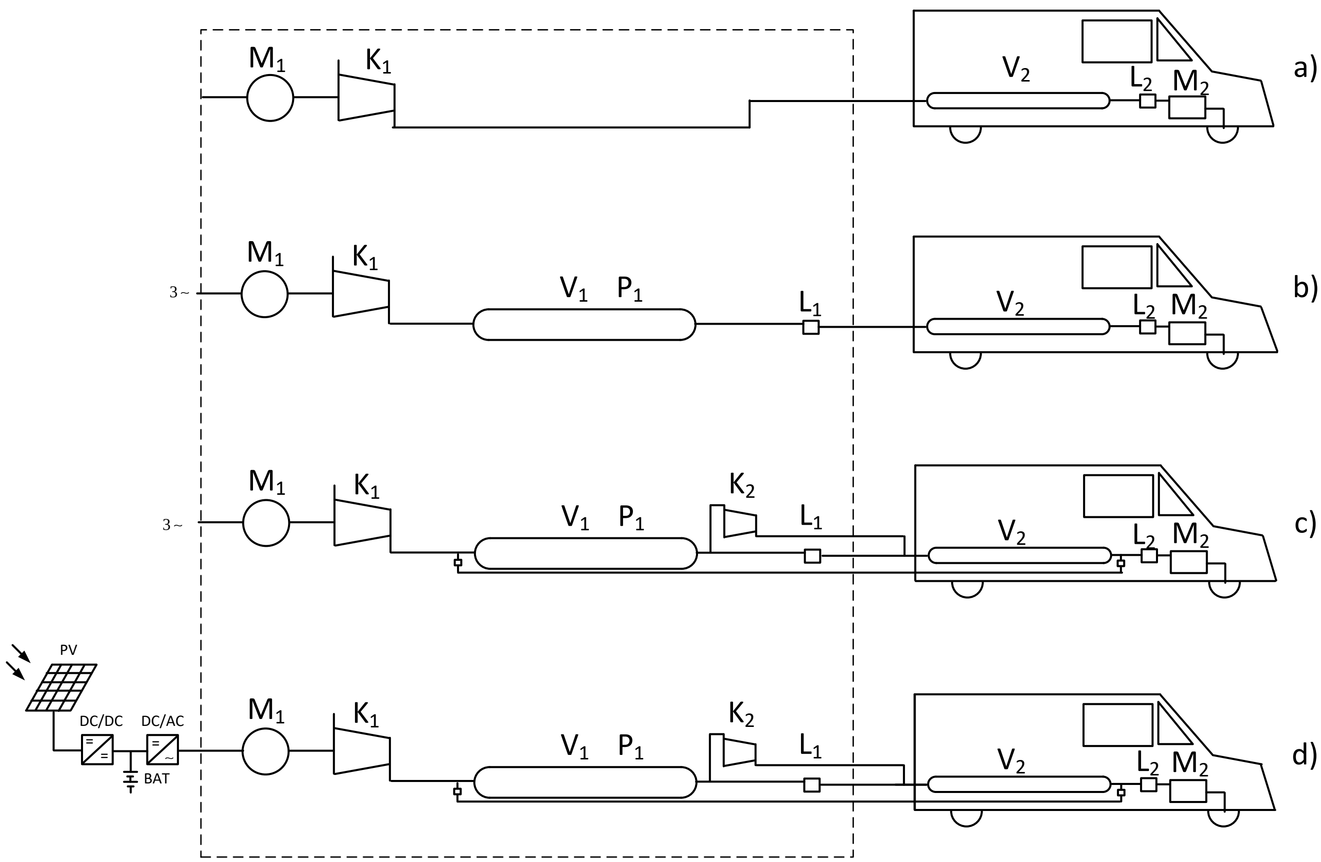


Figure 2 The evolutive concept of the filling station for the compressed air vehicle
a) Simple compressor
b) Compressor with buffer reservoir
c) Addition of the recirculation system
d) Feeding from renewable sources

Fast filling under good efficiency

The fast transfer of the air from the local reservoir to the car is obtained with the help of a nozzle [9], where the air flowrate is limited without dissipation, reaching sonic conditions. These elements allow to fast fill the car's reservoir under good energy efficiency, but this process presents the drawback of rising the temperature in the receiver due to fast rise of the pressure. After transfer with heating up the air in the car, there is the problem of cooling down this air after leaving the filling station, that would lead to a significant reduction of the pressure. The main consequence is that the possible range would be reduced.

In order to « better fill » the car reservoir, a recirculation system is proposed as described through Fig. 2c, with which the heated air in the car is brought back in the local reservoir after the equalization of the pressures. Such a recirculation of the heated air corresponds to replacing the hot air by cold one and needs only to compensate the circulation loss if the pressures are really stabilized. The recirculation of the air brings the temperature in the car reservoir down to nearly atmospheric temperature and increases the air density in the car reservoir as shown in Fig. 3 and 4.

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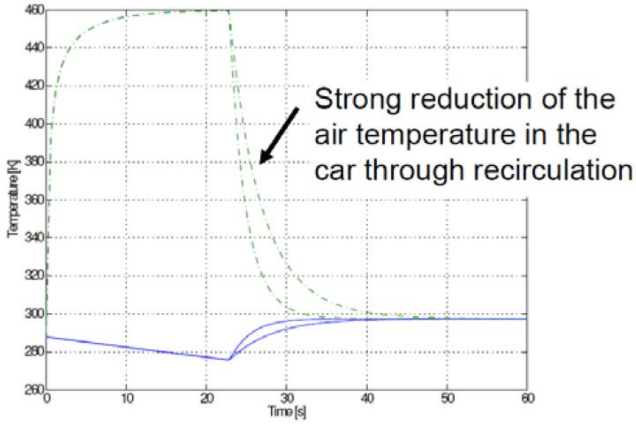

Figure 3 Evolution of the temperature in the car (dotted line) and in the local (full line) reservoirs. The filling lasts from 0 to 23 s, and is followed by the recirculation process. The filling time is adapted to the low volume chosen for a first small volume demonstration equipment, with an air flowrate that causes a similar elevation of the temperature as in the nominal case.

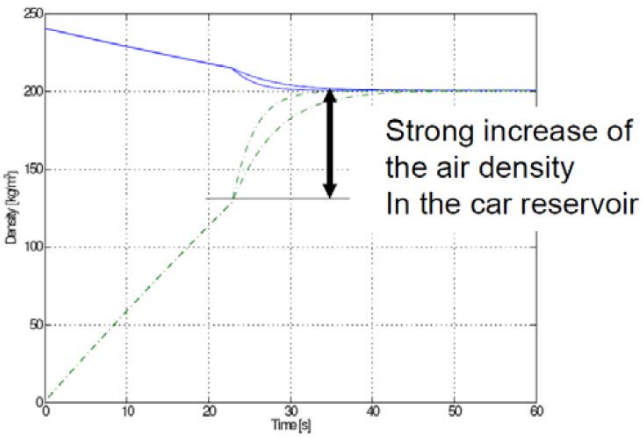

Figure 4 Evolution of the air density in the car (dotted line) and in the local (full line) reservoirs.

In Fig. 4, the effect of the recirculation process on the air densities in both reservoirs is shown. The dotted line shows the main advantage of the recirculation process, which corresponds to an increase of the air density in the vehicle of more than 50% .

IV Experimental set-up

Figure 5 shows the experimental set-up used for the verification of the fast filling process. With this equipment, the transfer time has been designed through an adaptation of the nozzle.

The modified delivery vehicle

Figure 6 is a view of the AirPower motor mounted in the vehicle. Mainly the cylinder head is changed, and the distribution and management components have been added. The motor base is identical to the original engine as well as all other motor auxiliaries and the power transmission to the wheels.

Figure 5 The experimental facility for the verification and final choice of the transfer time by adapting the nozzle.

The crankshaft is redesigned for a 90° phase-shift of the efforts produced by each cylinder [10],[11].

In Fig. 7, the experimental vehicle is shown during the first test runs on the test circuit in Rouen, France.

Figure 6 The AirPower engine mounted in the delivery vehicle (courtesy Anthos AirPower)

Figure 7 shows the delivery vehicle on the test track in Saint-Etienne du Rouvray near Rouen, France.

Figure 7 The compressed air vehicle on the test track (courtesy Anthos AirPower).

V Conclusions

A fast filling station for a compressed air vehicle has been described. The main original contribution consists in a specific recirculation process which avoids the cooling down of the heated

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fluid after the fast transfer and allows the fast filling under very good efficiency. For comparison, the energy loss of the fast charge of an electrochemical battery has been analyzed. The original concept is dedicated to a delivery vehicle propelled by a compressed air motor. Prototype equipment is currently set in operation for a real application.

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