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Dynamic analysis of compressed air energy storage in the car

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Abstract

The article presents a dynamic analysis of the compressed air energy storage in the car. The analysis was used to determine those processes most relevant to achieving highest possible efficiency. A review of the state of the art is presented. Simple technical-economic analysis of usage those kind of cars is also performed and discussed by taking Polish local conditions from an electricity market. Main advantages as well as drawback of the compressed air cars are pointed out

Keywords: Dynamic, Compressed Air Energy Storage, Vehicles

1. Introduction

In an era of intensive environmentally friendly actions in the face of a global economic crisis, increasing emphasis is placed on energy efficiency issues. Although mining technologies are opening up the prospect of exploiting previously unusable fossil fuels, there is no doubt that the overall reserves of natural resources continue to shrink. From the viewpoint of the Polish economy, dependent as it is on gas and oil from abroad, a temporary solution might be found in the shape of either underground coal gasification (which enables the recovery of natural resources from poor quality or otherwise uneconomic seams) or shale gas, assuming gas-rich shale is found. Fossil fuel savings are both desirable for self-evident reasons and achievable through recently built high-efficiency power plants, but the solutions are expensive and it will be quite some time before the Polish energy sector renews its capacity. European Union regulations are driving energy efficiency initiatives such as the gradual elimination of incandescent light bulbs in favor of low energy lighting alternatives. They also set down the rules for marking electrical equipment in terms of their energy efficiency class.

Road vehicles present an ideal area for reducing energy consumption due to their abundance and the interest governments of all persuasions show in new ventures in this field, the latest of which being to ban all petrol and diesel cars from cities by 2050. An eco-car segment is slowly emerging, made up mainly of hybrids catering for different types of journeys. Most of these vehicles combine an internal combustion engine with an electric motor, which allows you to recover braking energy and reduce energy requirements while stationary (also possible in ordinary cars with a start / stop system). Another alternative is to have electric vehicles powered by fuel cells or lithium-ion batteries. But there is one big flaw – these solutions are very expensive, putting them out of reach of ordinary road users. One answer may be a compressed air car which, in addition to lower production costs, will also reduce the car's weight and

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Figure 1: Armando Regusci's car, which managed 100 km on one tank (source: [2])

Figure 2: Compressed air bike built in 1997. (source: [2])

hence its energy needs. Perhaps compressed air cars deserve a little more attention.

The first vehicle powered by compressed air was constructed in France in 1870 by a Polish engineer – Louis Mekarski (more in [14, 16]). This invention was patented in 1872 and 1873 and then in 1876 was tested on the line TN in Paris.

The principle of Mekarski's engine was the use of energy stored in compressed air, passed through a tank of hot water to increase gas enthalpy. Replenishment took place at purpose-built compressor points at tram stops. Mekarski's trams ran on lines in cities across France at various times from 1879 onwards, finally disappearing from the streets of La Rochelle in 1929. Compressed-air trams also appeared in New York, but boasting an engine built in 1882 by Robert Hardi (described in [6]). Since air-powered equipment generally does not sparks and heat it was put to use in HK Porter compressed air locomotives (more in [6]), which were readily used in explosive atmospheres (e.g. mines). Another interesting example of the use of compressed air to drive vehicles comes from Uruguay, where since 1984 Armando Regusci, Ph.D. has been involved in constructing these unusual machines (more on [2, 7]). One of his most successful constructions was a four-wheel vehicle with pneumatic engine which managed (Fig. 1) 100 km on a single tank. The event took place in Maldonado in 1992.

Regusci's engine does not have a rod and the force the compressed air exerts on the piston is converted into torque via a chain dragged by the moving piston. After the up stroke the piston descends slowly to pull the chain again. All this is possible thanks to the fact that the gear is rotated by a chain attached to the wheels via a similar mechanism as in the mountain bike and the chain has a stretcher. This solution enables a standalone start for the engine but unfortunately renders the vehicle incapable of travelling at a steady speed. Regusci also developed a motorcycle and a moped (Fig. 2) powered by compressed air, before widening his intereste to engines running on ethanol from sugar cane, and on ways to obtain hydrogen.

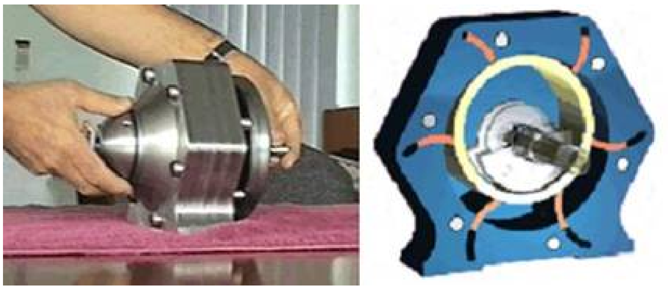

Figure 3: Angelo Di Pietro's motor (source: [4])

One of the most interesting aspects of the pneumatic motor came courtesy of Angelo Di Pietro – an Italian designer currently working in Australia where he founded the company Energineair (fully described in [4]). His invention does not have a conventional crankshaft and the pistons and cylinders and their structure is more like a Wankel's engine due to a single rotating piston (Figs. 3 and 4).

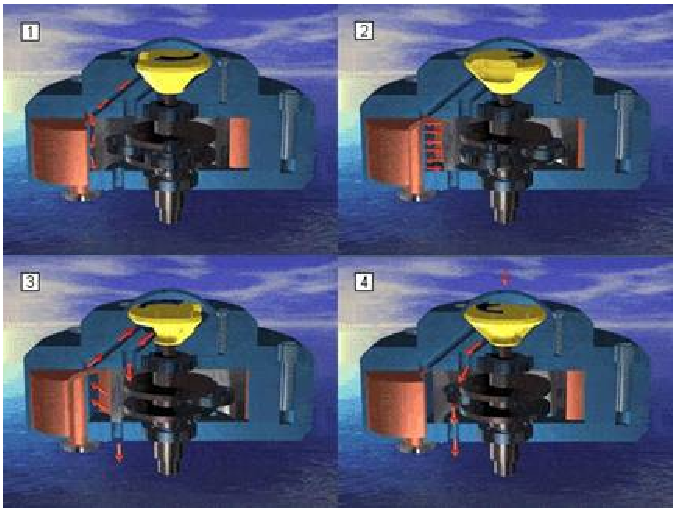

Figure 4: Working principle of Angelo Di Pietro's motor (source: [4])

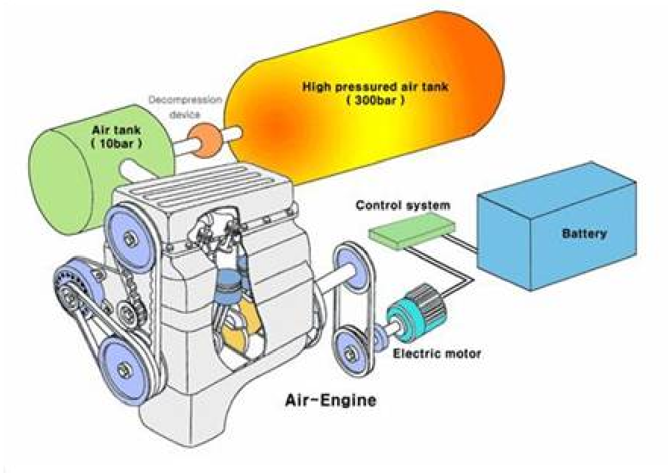

Figure 5: PHEV power scheme (source: [3])

Figure 6: Piston, connecting rod and crankshaft in Nègre's engine (source: [1])

The concept is based on a simple cylindrical rotary piston which rolls, without any friction, inside the cylindrical stator. The space between stator and piston is divided into 6 expansion chambers by pivoting dividers (shown in Figure 3, right side). These dividers follow the motion of the piston as it rolls around the stator wall. The piston, forced by the air pressure on its outer wall, moves eccentrically, so driving the motor shaft by means of two rolling elements shaft mounted bearings (Fig. 4). In the chambers there is a cyclical process of expansion which causes piston movement around the stator. This solution makes it possible to self-start the engine.

The Di Pietro engine weighs only 13 kg and does not require a gearbox, because it is controlled by the pressure difference which allows smooth control of torque and rotational speed. This device can start with a pressure difference of 1 psi (6.8 kPa) by using air film technology, which significantly reduces friction between engine parts.

With torque simply controlled by throttling the air pressure the Di Pietro motor gives instant torque at zero RPM and can give soft start and good acceleration control. Angelo Di Pietro vehicles performed well in supermarkets and on fruit and vegetable markets, and there are boat applications too. A different approach to power cars is presented by the Korean Cheol-Seung Cho – a constructor at Energie company (more on this in [3]).

His car - the PHEV (pneumatic hybrid electric vehicle) - is driven by both compressed air and electricity with a 48-volt battery. During starting and acceleration, when you need serious power, the car is driven by compressed air whereas during normal operation its requirements are met by a small electric motor.

The choice of power source is controlled by a computer unit. Additionally the car has a small pressure container accumulating air (Fig. 5), which enables the car to run at a constant pressure at the inlet (10 bar) without a significant drop in power during discharge, and a main tank with a maximum pressure of 300 bar. This combination gives the vehicle a top speed of 120 km/h. Cars running on compressed

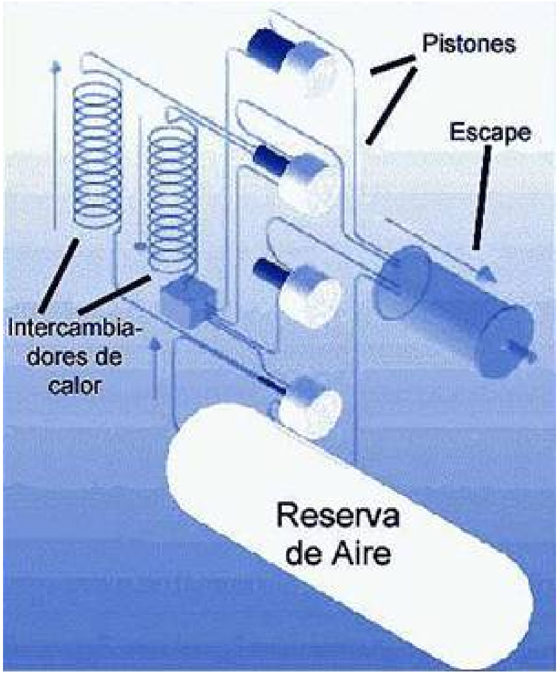

Figure 7: Air distribution system in MDI cars (source: [1])

air have also been designed by retired F1 engineer – Frenchman Guy Nègre, who in 1990 together with his brother Cyril set up a forward-looking company called Motor Development International working out of the French Riviera (as described in [1, 5]). In 2007, Guy Nègre sold a license for technology developed by himself to the Indian giant TATA Motors. Guy Nègre motors are piston devices with an atypical rod structure (visible in Figure 6) so that the piston is in the top position for 70° of the shaft rotation, giving more time for the cylinder to fill with compressed air.

An electromagnetic air distribution system (Fig. 7) controls supplies to each cylinder, thereby enabling a more efficient use of stored energy. Heat exchangers are also visible on Figure 7. These are used to heat air that was cooled before as a result of expansion. This solution improves engine performance. The same expansion due to heat transfer through the wall of the cylinder is not an adiabatic process, which further increases engine efficiency. Through the processes described above, the air leaving the engine has a temperature range from 0°C to −15°C and does not pose the slightest risk to health. Guy Nègre also applied solutions in his engines that enable the use of additional conventional fuels or biofuels (bioethanol, biodiesel, vegetable oils, etc.) in an amount not exceeding 2 liters per 100 kilometers. To minimize energy consumption MDI cars use an automatic, computer-controlled gearbox, changing the gear ratio depending on the speed of the car.

Guy Nègre vehicles are equipped with a moto-alternator connecting the engine with the gearbox, whose task it is to fill up the tank with compressed air using electricity. This device works as an alternator, it also helps when starting and at any moment when you need more power to drive the vehicle. MDI cars are equipped with an engine that stops momentarily when the car is stationary. They also have a pneumatic system that can recover 13% of the energy used during braking. The compressed air tanks mounted in these cars are made of lightweight but very durable composite material containing among others carbon fiber. While working at a pressure of 350 bar, for safety they are tested at a pressure of 700 bar. The body of the car is also built of composite attached to an aluminum frame, assembled using glue, as in aircraft structures, so construction is fast and the resulting product lightweight and robust. The French designer kitted his car out with a radio control system for all electrical devices, which have special microcontrollers mounted. This way all the devices are connected using only one cable, which, according to Nègre reduced wiring weight by about 22 kg.

One of the most advanced ways to improve the efficiency of the air motor was applied by CJ Marquand, whose engine (Fig. 8) is built using heat pipes (described in [6]). Due to their characteristics, heat pipes conduct heat better than any material. These devices can transfer (or supply), large amounts of heat from (to) a small area, and therefore are widely used for cooling laptop CPUs. Because of their versatility they provide great opportunities for all processes in which heat exchange plays an important role.

Over the past few years has published several scientific works based on a concept of air engine. In 2008, Liu and Yu [12] published the results of calculations for the air compressed to 200 bar. They obtained result that normally the total system efficiency is 25–32% and for decompression of 10–30 bar reaches value up to 34%. U. Bossel [8] performed calculations for the tank with a capacity of 300 dm^3 and a maximum pressure of 300 bar. He

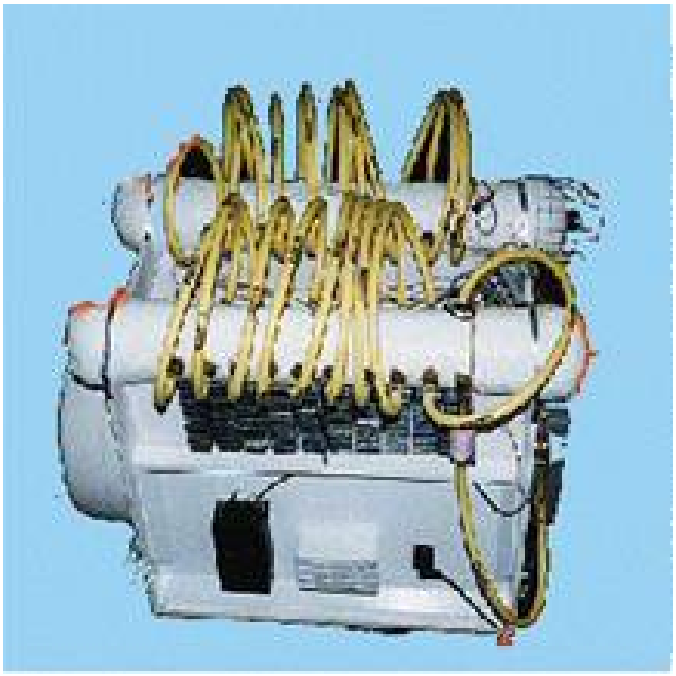

Figure 8: Marquand's air motor (source: [6])

showed that the total efficiency of single-stage system is 9% whereas the four-stages (for both engine and compressor) with a heat exchangers between the stages, the system efficiency can be increased up to 61%. This indicates a huge impact on the efficiency of heat transfer in this process. W. Hei et al. made calculations [15] for compressed air vehicle based on single-screw expander and 0.3 m^3 (tank of 300 dm^3) with maximum pressure of 300 bar. They focused on the selection optimal expansion ratio, the impact of the efficiency of expander and influence of heating up inlet air. H. Chen et al. 9 were considered a system which also include tank with 300 dm^3 volume and 300 bar working pressure for compressed air engine as well as liquid air engine. Overall efficiency for the liquid air engine ranged from 13–23% and for the compressed air engine: 28–46%. They concluded that the usage of liquid air to power the engine is inefficient. All this arguments shows the growing interest in alternative means of transport including compressed air cars.

2. Theory

The calculations shown in the following paragraph were done in commercial software [11]. Dynamic calculations of physical phenomena are described using linear and nonlinear differential equations.

Linear, first order ordinary differential equations take the following form:

$$\tau \frac{dY}{dt} + Y = K f(u) \tag{1}$$

where: t – time, τ, K – constants, Y – variable, $f(u)$ – function of the variable u.

Most of the phenomena are described by using nonlinear equations whose solution usually requires the use of a computer.

Examples of nonlinear differential equations:

$$\tau \frac{dY}{dt} + Y^3 = K f(u) \tag{2}$$

$$\tau \frac{dY}{dt} + Y Y_2 = K f(u) \tag{3}$$

where: Y_2 – variable.

2.1. Methods of solving

2.1.1. Implicit Euler method

Analytical solution:

$$Y_{n+1} = Y_n + \int_{t_n}^{t_{n+1}} f(Y)\, dt \tag{4}$$

where: $\frac{dY}{dt} = f(Y)$

Ordinary differential equations can be solved using the implicit Euler method, which relies on approximations using rectangles. One side of the rectangle is the length of time step (h) and the second side is $f_{n+1}(Y_{n+1})$.

This method is expressed by the following equation:

$$Y_{n+1} = Y_n + h f_{n+1}(Y_{n+1}) \tag{5}$$

2.2. Mass balance

The simplest form of mass balance equations is described as follows:

$$\begin{aligned} &Rate\ of\ accumulation\ of\ mass = \\ &mass\ flow\ into\ system - \\ &mass\ flow\ out\ of\ system \end{aligned} \tag{6}$$

For the tank, assuming ideal mixing in the interior and single component feed, equation (6) is as follows:

$$\frac{d(\rho_o V)}{dt} = F_i \rho_i - F_o \rho_o \tag{7}$$

where: F_i – the flowrate of the medium entering the tank, ρ_i – the density of the medium entering the tank, F_o – the flowrate of the medium exiting the tank, ρ_o – the density of the medium exiting the tank, V – the volume of the medium in the tank.

2.3. Volume balance

Devices that store a quantity of a substance at a constant volume (e.g. vessel) are described by the following equation:

$$V = const = f(\dot{m}, h, p, T) \tag{8}$$

$$\frac{dV}{dt} = 0 \tag{9}$$

where: V – volume of the vessel , t – time, – mass flow, h – holdup, p – vessel pressure, T – vessel temperature.

The volume balance for the vessel can be represented as follows:

$$\begin{aligned} Vol.\,change\,due\,to\,pressure &\;+ \\ Vol.\,change\,due\,to\,flows &\;+ \\ Vol.\,change\,due\,to\,temperature &\;+ \\ Vol.\,change\,due\,to\,other\,factors &\;= \;0 \end{aligned} \tag{10}$$

2.4. Energy balance

The most general form of energy equation is described in the following equation:

$$\begin{aligned} Rate\,of\,accumulation\,of\,total\,en. &\;= \\ Flow\,of\,total\,en.\,into\,system &\;- \\ Flow\,of\,total\,en.\,out\,of\,system &\;+ \\ Heat\,added\,to\,sys.\,cross\,its\,bound. &\;+ \\ Heat\,generated\,by\,reaction &\;- \\ Work\,done\,by\,sys.\,on\,surroundings & \end{aligned} \tag{11}$$

The stream of energy flowing into, or leaving the system is the result of convection or conduction. However, heat is supplied to the system by conduction or radiation.

2.5. The equations describing the flow resistance of the valves

The mass flow of working medium through the valve can be described in the simplest way by the following formula:

$$\dot{m} = k\sqrt{\Delta p} \tag{12}$$

where: $\dot{m}$ – mass flow, k – coefficient representing the inverse of flow resistance (conductivity), Δp – pressure drop across the valve.

The basic equation defining the characteristics of the valves takes into account the coefficient Cv and pressure drop across the valve as a result of flow resistance:

$$\dot{m} = f(Cv, p_1, p_2) \tag{13}$$

where: $\dot{m}$ – mass flow, Cv – coefficient representing the inverse of flow resistance (conductivity), p_1 – inlet pressure, p_2 – outlet pressure.

2.6. Heat balance

The relationship describing heat exchange in a cooler:

$$F(H_{in} - H_{out}) - Q_{cooler} = \frac{d(V H_{out})}{dt} \tag{14}$$

The relationship describing heat exchange in a heater:

$$F(H_{in} - H_{out}) + Q_{heater} = \frac{d(V H_{out})}{dt} \tag{15}$$

where: F – flow of working medium, H – enthalpy of the working medium, Q_{cooler} – cooler duty, Q_{heater} – heater duty, V – volume of the substance in the tube or shell.

2.7. Flow resistance across cooler / heater

Equation (16) determining the flow through the cooler / heater is similar to the relationship for flow through valves (12).

$$\dot{m} = \sqrt{\rho} \cdot k\sqrt{p_1 - p_2} \tag{16}$$

where: $\dot{m}$ – mass flow of working medium, ρ – density of the working medium, p_1 – inlet pressure, p_2 – outlet pressure, k – coefficient representing the inverse of flow resistance (conductivity).

2.8. The equation for compressor and expanders

Both the polytropic and isentropic power of a compressor or expander can be calculated using equation (17).

$$N = F_1\,(MW)\left(\frac{n}{n-1}\right)CF \cdot \left(\frac{p_1}{p_2}\right)\left[\left(\frac{p_2}{p_1}\right)^{\left(\frac{n-1}{n}\right)} - 1\right] \tag{17}$$

where: n – the volume exponent, CF – correction factor, p_1 – inlet pressure, p_2 – outlet pressure, ρ_1 – inlet density of the working medium, F_1 – molar flow rate at the inlet, MW – molecular weight of the working medium.

With isentropic power, the volume exponent should be calculated by relation (18), while polytropic power requires the volume exponent described by equation (19).

$$n = \frac{\ln\left(\frac{p_2}{p_1}\right)}{\ln\left(\frac{\rho'_2}{\rho_1}\right)} \tag{18}$$

where: ρ'_2 – density of the working medium at the outlet for the isentropic process.

$$n = \frac{\ln\left(\frac{p_2}{p_1}\right)}{\ln\left(\frac{\rho_2}{\rho_1}\right)} \tag{19}$$

where: ρ_2 – density of the working medium at the outlet.

The correction factor is expressed by the following equation:

$$CF = \frac{h'_2 - h_1}{\left(\frac{n}{n-1}\right)\left(\frac{p_2}{\rho'_2} - \frac{p_1}{\rho_1}\right)} \tag{20}$$

where: h'_2 – enthalpy of working medium at the outlet for the isentropic process, h_1 – enthalpy of working medium at the inlet.

Power imparted to the working medium in the compressor is described as follows:

$$N_{1-2} = F_1\,(MW)\,(h_2 - h_1) \tag{21}$$

where: F_1 – molar flow rate at the inlet, h_2 – enthalpy of the working medium at the outlet, h_1 – enthalpy of the working medium at the inlet, MW – molecular weight of the working medium.

Power taken from the working medium in the expander was expressed by the following relationship:

$$N_{1-2} = F_1\,(MW)\,(h_1 - h_2) \tag{22}$$

2.8.1. The equations describing the inertia of the rotating equipment

Rotational inertia:

$$I = M\,R^2 \tag{23}$$

where: M – the rotating mass, R – the radius of gyration.

The power needed to change the rotation speed:

$$N_I = I\,|\omega|\,\frac{d\omega}{dt} \tag{24}$$

where: ω – the rotation speed.

2.8.2. Friction loss

Power loss due to friction:

$$N_f = f_{fric}\omega\,|\omega| \tag{25}$$

where: f_{fric} – frictional power loss factor.

2.8.3. Duty

Compressor power:

$$N_C = F_1\,(MW)\,(h_2 - h_1) + I\,|\omega|\,\frac{d\omega}{dt} + f_{fric}\omega\,|\omega| \tag{26}$$

Expander power:

$$N_T = F_1\,(MW)\,(h_1 - h_2) + I\,|\omega|\,\frac{d\omega}{dt} + f_{fric}\omega\,|\omega| \tag{27}$$

2.8.4. Polytropic and isentropic efficiency

Compressor efficiency:

$$\eta = \frac{N_{to\,system}}{F_1\,(MW)\,(h_2 - h_1)} \tag{28}$$

Expander efficiency:

$$\eta = \frac{F_1\,(MW)\,(h_2 - h_1)}{N_{from\,system}} \tag{29}$$

To obtain isentropic efficiency (in HYSYS called adiabatic efficiency) isentropic power from the formula (17) should be substituted into equations (28) and (29). However, polytropic power should be substituted in the case of polytropic efficiency for the same equations.

3. Results

The following processes were considered:

1. Filling a tank with compressed air, including cooling.
2. Simple tank discharging through a turbine operating at constant pressure.
3. Discharging the tank using atmospheric heating of the working medium between two turbines operating at constant pressures.
4. Alternative solutions:
   - Discharging the tank by using two turbines in turn – the first working at a pressure of 100 bar and the second of 20 bar.
   - Discharging as in point 3 for the last case (Δp_{T1}=92 bar, Δp_{T2}=7 bar) bypassing the first turbine and the heat exchanger.

For calculations the following assumptions were adopted:

- ambient conditions: pressure: 1 bar, temperature: 15°C
- working medium: air
- model of the working medium (equation of the state): Peng-Robinson
- volume of the compressed air tank: 200 liters (as at Airone's MDI [13])
- maximum pressure in the tank: 350 bar (as in AIRONE's MDI [13])
- initial temperature of the air in the tank for all cases of expansion has been leveled at 19°C
- fixed compressor adiabatic efficiency of 80%
- fixed turbine adiabatic efficiency of 80%
- adiabatic compression and expansion processes
- power of the motor which drives the compressor: 5.5 kW
- electric efficiency of the motor which drives the compressor: 85% (single-phase motor SBg 213T-2 described in [10])
- pressure drop across the heat exchanger at maximum flow of working medium: 0.5 bar (at minimum: 0 bar)
- temperature of the working medium after the heat exchanger: 0°C

Markings:

Abbreviation	Explanation
C	compressor
E_u	energy from unloading
HE	heat exchanger
m_f	final mass
p_f	final pressure
p_s	starting pressure
RV, RV1, RV2	regulation valves
T, T1, T2	turbines
TANK	tank
t_f	final temperature
t_{outl}, $t_{outl\,1}$, $t_{outl\,2}$	outlet temperature
t_s	starting pressure
V	valve
Δp_T, Δp, Δp_{T_2}	turbine pressure drop
η_{el}	electrical efficiency
η_g	gross efficiency

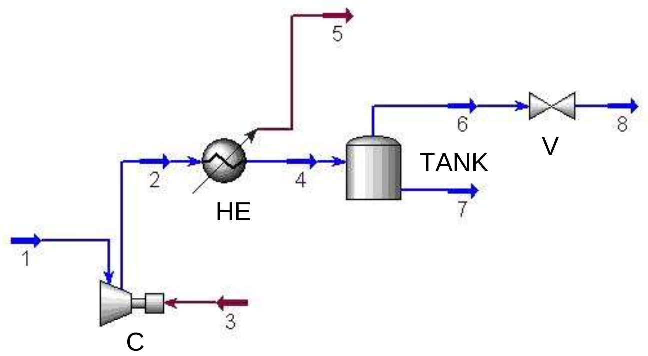

Figure 9: The process of filling with compressed air, including cooling

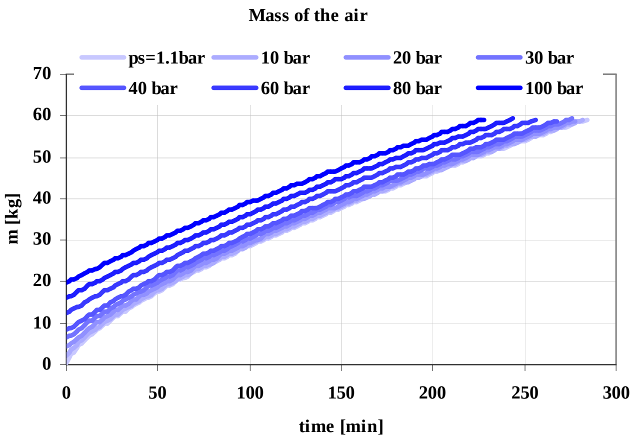

Figure 10: Mass of air in the tank during loading with compressed air, including cooling

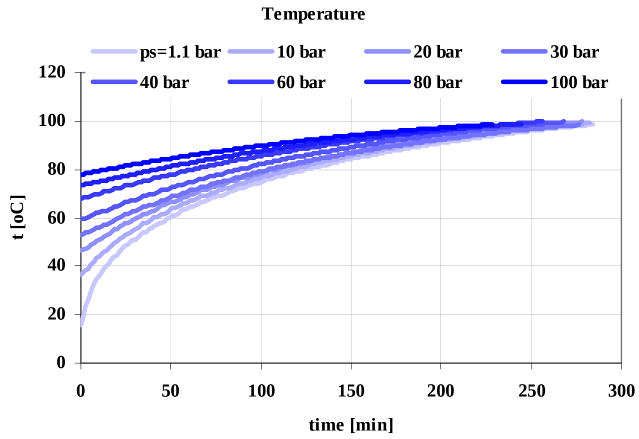

Figure 11: Temperature changes in the tank during loading with compressed air, including cooling

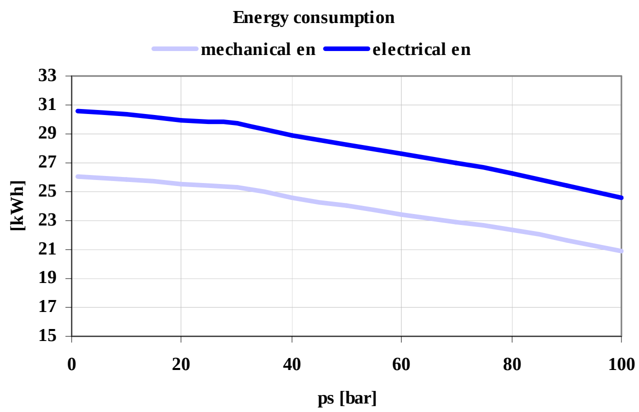

Figure 12: Energy consumption when filling a tank with compressed air, including cooling

4. Discussion

As a result of compression including cooling (Fig. 9) in all cases about 59 kg of air has been pumped into the tank (Fig. 10) due to the assumed final temperature of the process – 99°C (Fig. 11).

The resulting electricity consumption (Fig. 12) ranged from 24.59 kWh (for p_p = 100 bar) to 30.63 kWh (for p_p = 1.1 bar).

It costs $ 2.74 (Polish conditions) to fill the tank from the pressure of 10 bar at night tariff ($ 0.072064/kWh gross for electricity in the night and $ 0.02/kWh gross for distribution of electricity at night at the tariff "Ekonomiczna Dolina" by Energa valid for 2011).

This tank is the same as AIRONE of MDI, which on a single load can achieve 80–135 km.

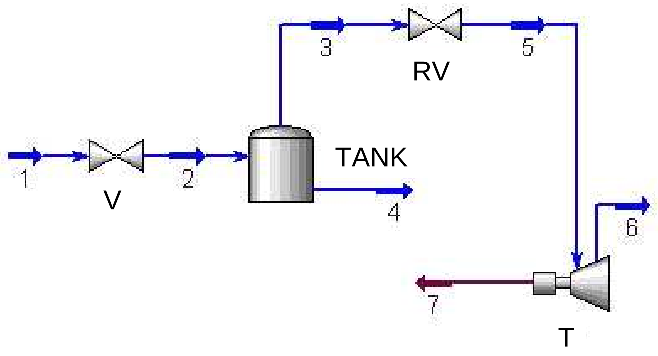

Figure 13: Simple process of unloading the tank at constant pressure before the turbine

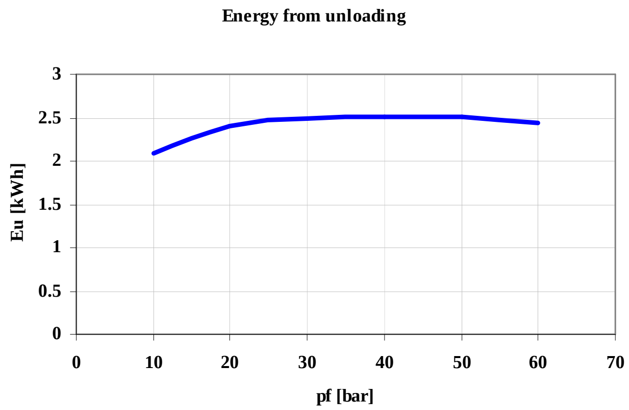

Figure 14: Effect of final pressure (Δp_T + 1 bar) for energy derived from a simple discharge of the tank for t_s = 99°C

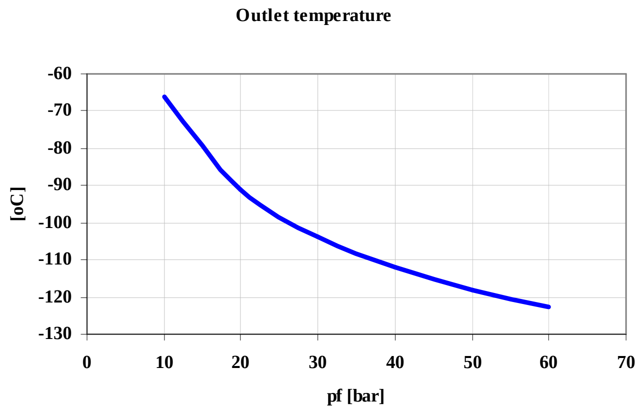

Figure 15: Influence of final pressure in the tank at the outlet temperature for a simple tank discharging through a turbine operating at constant pressure for t_s = 99°C

The real process of loading to the high pressure of 350 bar is done with a reciprocating compressor, not a centrifugal compressor (which would need several stages).

The process of compression is not adiabatic, moreover – the compressor cylinder is fanned and intensely cooled so that the energy needed to compress the gas is lower.

This process is slow (several hours) and the difference in temperature between the compressed gas and the environment is very high, so despite the small area of heat transfer inside the cylinder the difference in electricity consumption should be significant.

For point 1 the work of compression is the greatest possible because the cooling is done only after the compressor.

To bring this process closer to a real case scenario, compression should be modeled using several compressors in a series with cooling for each of them.

For the process of discharging the tank with a turbine operating at constant Δp (Fig. 13) 6 cases were considered – from p_f = 10 bar ($p_f = \Delta p + 1$ bar) to p_f = 60 bar.

Energy from the discharge (Fig. 14) ranged from 2.085 kWh (for p_f = 10 bar) to 2.514 kWh (for p_f = 40 bar).

Maximum occurring in this case, it follows that for large pressure drops in a turbine we obtain a higher enthalpy drop, but there is a larger quantity of air in the tank which is not expanded (the assumption $\Delta p_T = const$).

Temperatures on exiting the system (Fig. 15) are in the range of −66°C (for p_f = 10 bar) to −122.5°C (for p_f = 60 bar) and hence potentially dangerous, so in this case the air leaving the engine should be mixed with ambient air before release to the environment.

The efficiency of the process increases with the final pressure despite a decrease in the discharge of energy from above Δp_T = 39 bar. This is due to decreasing electricity consumption for air pressure from the higher pressure.

The maximum obtained in the calculation of gross efficiency and electrical efficiency reached 10% and 8.9% (for p_f = 50 bar) (Fig. 16).

Noteworthy is the fact that the power on the turbine shaft (example in Figure 17) decreases as the

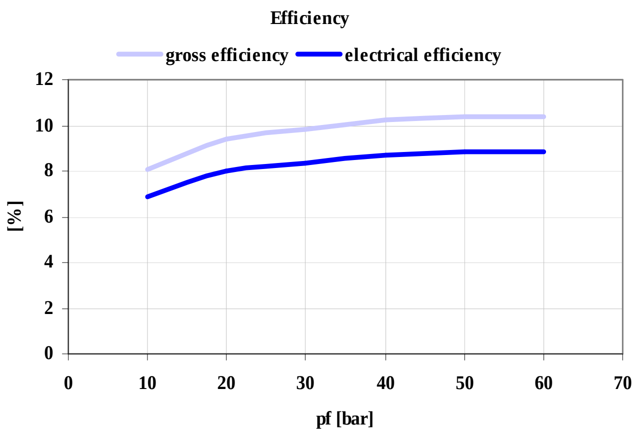

Figure 16: Effect of final pressure (Δp_T + 1 bar) on efficiency of a simple discharge of the tank for t_s = 99°C

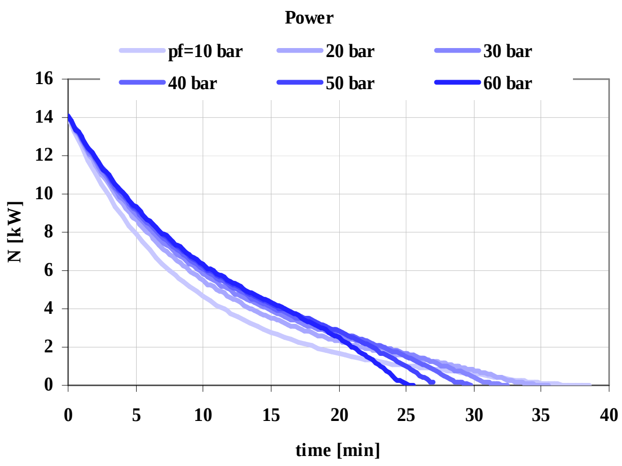

Figure 17: Power changes on the turbine shaft during simple tank discharging through a turbine operating at constant pressure for t_s = 99°C

tank discharges.

This phenomenon is due to the decrease in mass flow of working medium (temperature and gas pressure before the turbine maintain constant values) due to the decreasing pressure differential between the tank and the surrounding.

This situation could be improved if the system contains a reservoir of low pressure as in the case of a PHEV car (Fig 5). This tank could be charged at a time when demand for engine power is lower.

Another possibility for maintain a constant power characteristic is the use of an engine running on variable pressure drop or a piston engine controlled by

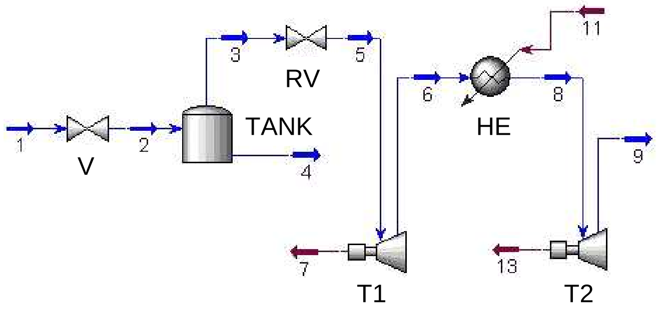

Figure 18: The process of discharging the tank using atmospheric heating of the working medium between two turbines operating at constant pressures

valve opening time.

As in the case of the charging process, discharging is not adiabatic and occurs in a piston engine. That engine block is heated by ambient air, but in the case of expansion the temperature difference between the gas and the surrounding is less than during compression (the gas is cooled before it goes to the tank and the expansion occurs in a smaller pressure difference due to throttling).

For this reason, in a real case scenario the energy of the discharge (the maximum may occur for other final pressure), and the air temperature leaving the engine must be greater than in this example.

In the MDI cars, which include an additional heat-up of the working medium by ambient air, the outlet temperature is in the range 0°C to −15°C (according to [1]).

The efficiency of the real process should be enhanced by the combination of two factors – the use of less electricity to compressed air and gaining more energy from the discharge.

Discharging the tank using atmospheric heating of the working medium between two turbines operating at constant pressures (Fig. 18) was examined for 10 cases – from p_f = 10 bar ($p_f = \Delta p_{T_1} + \Delta p_{T_2} + 1$ bar) to p_f = 100 bar.

Energy from the discharge (Fig. 19) ranged from 2.189 kWh (for p_f = 10 bar) to 2.884 kWh (for p_f = 50 bar).

Temperatures at the exit of the system (shown in Figure 20) were higher than in the previous case, and ranged from −51.5°C (for p_f = 10 bar) to −101°C

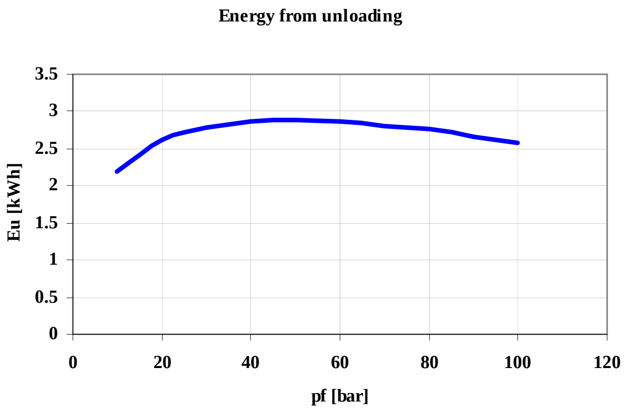

Figure 19: Effect of final pressure ($\Delta p_{T_1}+\Delta p_{T_2}$ + 1 bar) for energy derived from discharging the tank using atmospheric heating of the working medium between two turbines operating at constant pressures for t_s = 99°C

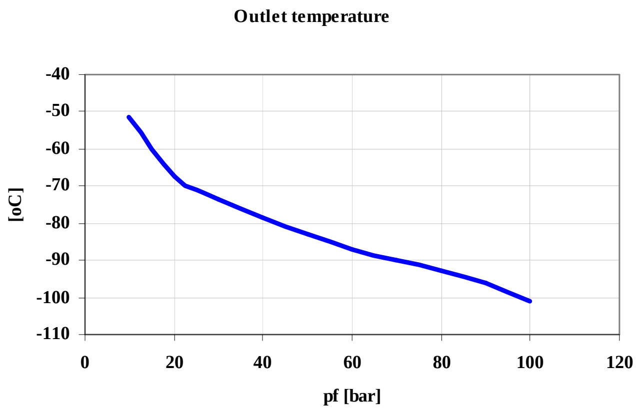

Figure 20: Influence of final pressure in the tank at the outlet temperature for discharging the tank using atmospheric heating of the working medium between two turbines operating at constant pressures for t_s = 99°C

(for p_f = 100 bar).

As in the case of a simple discharge process the efficiency of the discharging using atmospheric heating increase with increasing final pressure (with the previously accepted assumptions.)

For p_f = 60 bar gross efficiency and electrical efficiency (Fig. 21) are 12% and 10% (given to compare with the previous case) and, for p_f = 100 bar – 12.37 % and 11%.

Both the energy of the discharge, the efficiency of this process as well as the air temperature at the outlet for discharge using atmospheric heating of the working medium are greater than in the case of simple discharge.

For the process of discharging the tank by using two turbines in turn (Fig. 22) only one example was considered – Δp_{T_1} = 99 bar and Δp_{T_2} = 19 bar (p_f = 20 bar).

The energy obtained from discharge was 2.863 kWh, which is a much better result than in point 2, although in the example there is no heating of the air.

The medium temperature leaving the system in the first part of the discharge was −134°C, while the second rises to −91°C.

Gross efficiency of the process was 11% and electrical efficiency 9.6%, which shows the superiority of this variant compared to simple discharge.

The better results are due to bigger enthalpy drops

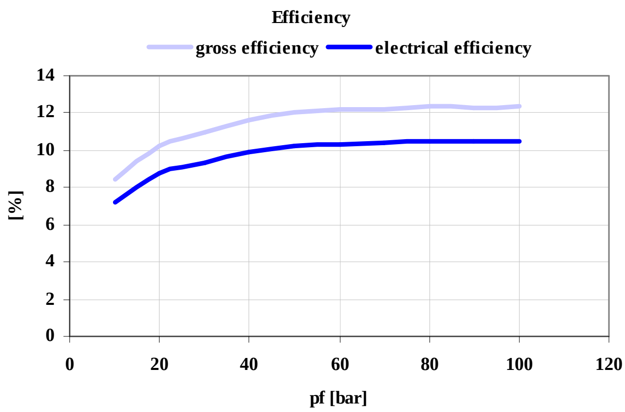

Figure 21: Effect of final pressure ($\Delta p_{T_1}+\Delta p_{T_2}$ + 1 bar) for efficiency of discharging the tank using atmospheric heating of the working medium between two turbines operating at constant pressures for t_s = 99°C

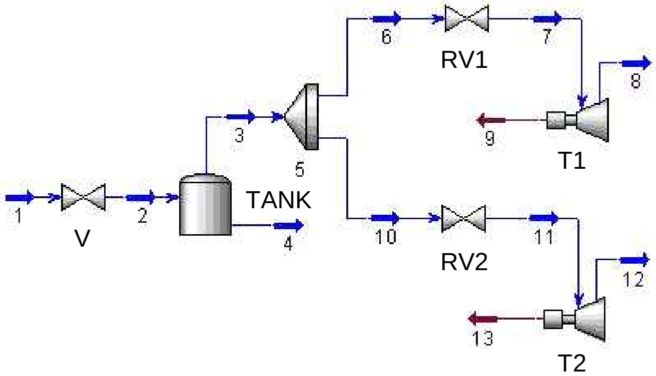

Figure 22: The process of discharging the tank by using two turbines in turn

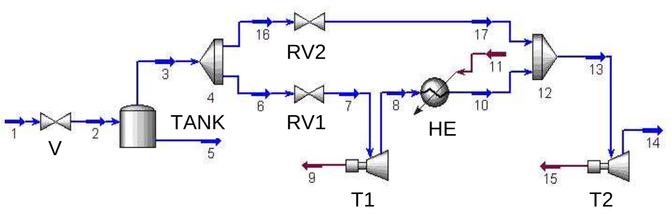

Figure 23: The process of discharging as in point 3 bypassing the first turbine and the heat exchanger

at the beginning (lower throttling losses), and the use of gas remaining in the tank in the turbine with lower Δp.

Four turbines (or pistons) would produce good results, with the same working pressure initially declining in series, then in a series – parallel and finally in parallel. As you move to a parallel connection the exit area would also increase, which would allow for greater flow of the working medium, thereby reducing power loss during discharge of the tank.

To obtain better results, a heat exchanger can be placed in front of each of the turbines with a bypass to heat up (if necessary) the working medium using the heat of the ambient air.

Point 5 (discharge as in point 3 for the last case of using a bypass of the first turbine and heat exchanger – Figure 23) is a combination of points 3 and 4 of the same chapter.

Only one example of this was noted – $\Delta p_{T_1} = 92$ bar and $\Delta p_{T_2} = 7$ bar.

As a result of the discharge 3.22 kWh of energy was obtained, which is the best result of all the cases considered thus far.

Gross efficiency and electrical efficiency of the process were 12% and 11%, and were also the best.

Outlet temperature was initially −101°C, rising later to −56.5°C.

Analysis of these cases shows that the heat exchange with the surrounding has a decisive influence on the amount of energy obtained from the discharge and thus the range of the vehicle.

An interesting solution involving heat exchange would be combining the internal combustion engine with an air engine.

The exhaust gases leaving the small spark ignition engine or compression ignition engine could flow into the same heat exchanger as part of the compressed air supply pneumatic system. The internal combustion engine could also be cooled by the air before it goes to the heat exchanger. A more advanced way of cooling can be achieved by placing the cylinder internal combustion engine and air engine in one block, in which, to achieve a better alignment of temperatures a pump could circulate liquid in the appropriate drilled channels. The amount of fuel would be chosen by the computer so that the air motor can use excess heat from the conventional engine.

With this combination, the two largest engine power losses would be recovered to some extent in the air engine.

5. Conclusions

Cars powered by compressed air are an alternative to hybrid vehicles and to cars powered only by electricity from fuel cells or lithium-ion batteries.

The greatest advantage of air vehicles is their low price – the simplest MDI model costs less than \$ 5,300. For comparison, the most popular hybrid car – the Toyota Prius Luna (bottom of the range) costs \$ 34,000 in 2011.

One feature where the compressed air vehicle outclasses other cars is its light weight (due to its composite tank and simple structure), which easily translates into energy needs.

By contrast, other energy-saving solutions are equipped with a heavy pack of battery or fuel cells. Moreover, these expensive batteries have to be replaced every few years at great cost and with due care given to eco-friendly disposal. A compressed air tank will suffice for the entire lifetime of the vehicle and is safe even during accidents (according to [1] the composite material does not explode but only cracks allowing the reservoir pressure to fall slowly without causing any danger).

Air cars are becoming more comfortable and better equipped, catching up others from the clean vehicle stable: MDI's AIRCity is a prime example and costs a mere 60% of a bottom-of-the-range Toyota Prius.

Electric, hybrid and most compressed air cars perform ultra-efficiently when stationary (not forgetting conventional cars equipped with a start/stop system), thus reducing noise, any emissions and the cost of travel.

Electric and hybrid vehicles can recover a large part of the braking energy, which cannot be said about almost all air vehicles. One exception comes in the shape of MDI products, but they are able to recover only 13% of energy during deceleration (according to [1]).

One major drawback of pneumatic motor vehicles is their poor range, resulting from the limited size of the compressed air tank (low density energy). This disadvantage is only slightly offset by the small mass of the vehicle.

Filling up the 200 liter tank to a pressure of 350 bar at the assumptions adopted previously cost $ 2.74 (in reality, less), which like-for-like is about one-quarter the cost of a gasoline-powered car. This volume of air enables the AIRONE MDI to go about 80 to 135 km (according to [13]).

In its simplest configuration, air motor efficiency is very low, due to the need to cool the compressed air before it goes into the tank.

The best way to improve the efficiency of this engine is to use ambient heat to warm the working medium and engine cylinders.

Another possible way to enhance pneumatic performance is to organize the expansion in such a way as to make better use of high enthalpy decreases early on in the process (when reservoir pressure is greatest) and smaller ones when the tank is low.

Positive effects of energy are also obtained through appropriate charging of the tank by using cooling during the compression process and not only after compression.

While compressed air vehicles do enjoy little niche markets, they are nowhere near ready to replace diesel and gasoline cars at present. And yet all is not lost: a place in the vehicle mix would appear assured for them given the right set of circumstances. Doubtless, in light of the interest they attract, technical advances are inevitable, but the moment of truth will really only come when government gives air the green light. Until then we seem doomed to false dawns sugared slightly by occasional incremental increases in use.

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