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# Energy and thermodynamical study of a small innovative compressed air energy storage system (micro-CAES)

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## Abstract

There is a growing interest in the electrical energy storage system, due to the high penetration of the energy produced by renewable sources, the possibility of leveling the absorption peak of the electric network (peak shaving) and the advantage of separating the production phase from the exertion phase (time shift). Compressed air energy storage systems (CAES) are one of the most promising technologies of this field, because they are characterized by a high reliability, low environmental impact and a remarkable energy density. The main disadvantage of big systems is that they depend on geological formations which are necessary to the storage. The micro-CAES system, with a rigid storage vessel, guarantees a high portability of the system and a higher adaptability even with distributed or stand-alone energy productions. This article carries out a thermodynamical and energy analysis of the micro-CAES system, a result of the mathematical model created in a Matlab/Simulink® environment. New ideas will be discussed, as the one concerning the quasi-isothermal compression/expansion, through the exertion of a biphasic mixture, that will increase the total system efficiency and enable a combined production of electric, thermal and refrigeration energies. This is something promising for the development of an experimental device.

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*Keywords:* Energy storage; Renewable sources; performance analysis; Integrated energy system;

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## 1. Introduction

The development of renewable energy, inevitably leads to the study of energy storage which guarantee the energy availability, and enable a leveling of the absorption peak of the power grid (peak shaving), thus making it up for the drawbacks characterizing the distributed energy production [1]. In the literature there are different energy storage systems each with different energy conversion processes: electrochemical tanks, water - PH reservoir systems (pumped hydro), fuel cells, flywheels, SMES (superconducting magnetic energy storage), hydrogen storage and CAES (compressed air energy storage) [2, 3]. Choosing the most appropriate system depends on different aspects. The main criteria examined are: charge/discharge time interval, storage capacity, global efficiency and realization costs. Compressed air energy storage systems (CAES) represent one of the most developed technologies for powerful systems (10-100 MW) because they guarantee a remarkable charging capacity and a long-time intervals for the discharge phase, but at the same time they present some disadvantages, as: the compression heat dissipation and their dependence on the geological formation for the storage [4-7]. In this paper a mathematical model is developed simulating the operational aspects of an innovative MicroCAES system. The modeled system is a *quasi-istothermal micro-CAES* allowing, thanks to the quasi-isothermal compression, to avoid the dissipation of compression heat. Moreover, since it was chosen not to use fossil fuels during the expansion phase, it is possible to exploit the output liquid characteristics to comply with the cooling load requirements [8, 9]. The system was implemented in a *Matlab/Simulink*® environment through the help of the *Thermolib*® library. Moreover energy and exergy analysis were carried out to evaluate the micro-CAES performance and behavior. The system optimizes and maximizes both phases, compression and expansion, thanks to the thermal recovery thus allowing the combined production of electric, thermal and refrigeration energies, and that is what makes it so innovative and fit for energy saving solutions [8, 10-13].

## 2. System description

The system here examined is a micro-CAES system. It is a high-pressure compressed air storage system (50 bar); it is a small system (3 kW) with quasi-isothermal expansion and compression and a constant volume storage (1m3). Two phases characterize the system: one of compression and the other of expansion. During low demand periods, the energy is stored compressing the air in an artificial tank. To extract the energy stored, the compressed air is expanded in the turbine (Fig. 1). This system enables to compensate the peak periods, allowing a better grid balancing together with a remarkable economic profit. Moreover, the choice of exerting quasi-isothermal compression/expansion was due to both the thermodynamic advantages and a possible thermal recovery in the two main phases. The first aspect, a quasi-isothermal compression/expansion (Ericsson cycle), allows a higher efficiency than an adiabatic process (Brayton cycle).

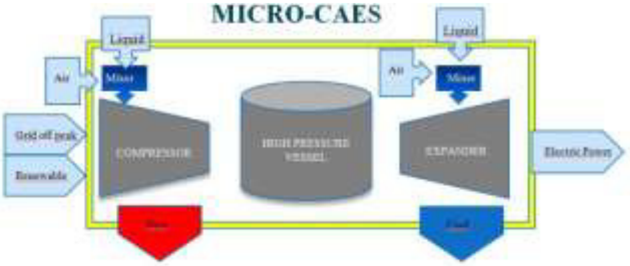

Fig. 1 Simplified diagram of a quasi-isotheral micro-CAES

This is due to the fact that the result is a lower work during the compression phase and a higher work during the expansion phase. For what concerns the second aspect, it is possible to recover the heat of the compression phase and supply a thermal load, whereas during the expansion phase, without preheating the gas (on the other hand it is something that happens in conventional CAES or adiabatic systems), the fluid output can be used for the cooling process of an environment, thus generating a trigeneration system.

## 3. Mathematical model

The model implementation was performed in a Matlab/Simulink environment with the help of a dedicated library named Thermolib.

### 3.1. Quasi-isothermal compression/expansion

To evaluate the Micro CAES system the following models were used: J. Hugenroth model for the quasi-isothermal compression/expansion in an Ericsson cycle [9] and the I. Bell models on the compression/expansion ”flooded” in a scroll-type volumetric machine [14, 15]. Other studies were used to future connections: studies by Kim Y. on a trigeneration micro-CAES system with quasi-isothermal compression/expansion [16]. To obtain an a quasi-isothermal compression a big amount of water finely atomized is mixed with the air and inserted into the compressor. The heat recovered during both phases can be sent to a storage necessary to supply a thermal load [16]. The following hypothesis were adopted during the model development: constant specific heat of the gas and liquid, ideal gas, incompressible and non-volatile liquid, insignificant pressure drop, adiabatic behavior of the components (heat exchangers not included), perfect separation/mixing of the phases. Hence it can be said that the compression/expansion process of an ideal gas, with a specific heat ratio of k ($c_p/c_v$) and in a thermal balance with a liquid, with a constant specific heat ($c_l$) and a behavior similar to the one characterizing the gas, can be examined through a ratio between specific heats concerning the mixture, whose value is k*.

$$k^* = \frac{{c_{p,g}}^*}{{c_{v,g}}^*} = \frac{m_g\, c_{p,g} + m_l c_l}{m_g\, c_{v,g} + m_l c_l} \qquad (1)$$

The compression process can be considered as isentropic where k will be substituted with k*. But first here is the list of the hypothesis adopted: the compression process was assumed to occur in a stationary condition, potential and kinetic energy are minimum and chemical or nuclear reactions are absent, the quasi-isothermal process a liquid finely pulverized will be injected, the compression and expansion isentropic efficiency is 80%, the electrical generator and engine efficiency is 90%, the process is divided into two phases with the same compression ratio for a $\beta_{TOT} = 50$.

### 3.2. Thermal storage

To be more specific the thermal storage systems used for the model are a heat-sensitive storage type, where the thermodynamic and energy relations regulating heating and cooling processes are basically the same. The only difference can be found in the heat transfer liquid that when the temperature is high is water, whereas with low temperature it will be mixed to an anti-freeze substance that tends to decrease the freezing point. As a matter of fact an aqueous solution at 56% of 1,2-etandiol presents a freezing point of – 50 °C [2]. This is possible because “heat” and “cold” are separated, hence two different fluids can be used. The thermal energy stored is the result of the algebraic addition of the contributions of positive energy in input and the negative one in output. Assuming that the latter is ignored, there is no connected load and the tank is considered adiabatic (dQ=0). The last hypothesis considers the energy amount stored in a short time period and then directly used. What follows are the different hypothesis: Incompressible fluid model; Uninterrupted, insulated, open system; minimum kinetic and potential energy variations; While considering the afore mentioned hypothesis and applying the first law thermodynamics to an open system, the energy stored is as follows [17]. Where m is the mass contained by the tank, $C_p$ the specific heat at constant pressure of the fluid, $T_1$ the initial storage temperature and $T_2$ the final storage temperature.

$$E_{sto} = m \int_{T_1}^{T_2} C_p dT \tag{2}$$

## 4. Energy analysis

The system examined, during the charging phase, uses electric energy to compress air, hence the total amount of the energy absorbed by the system to perform this phase can be represented as follows [13]:

$$E_c^+ = \int_{t_{in}}^{t_{fin}} \dot{P}_{el,c}(t)dt \tag{3}$$

Where $\dot{P}_{el,c}(t)$ is the electric power absorbed by the compressor and $t_{in}$ and $t_{fin}$ are respectively the initial and final states of the charging phase, that is $dt_{carica}$. During the discharging phase the energy pressure is transformed into electrical energy, the energy transferred from the system is expressed as follows:

$$E_e^- = \int_{t_{in}}^{t_{fin}} \dot{P}_{el,e}(t)dt \tag{4}$$

Where $\dot{P}_{el,e}(t)$ is the electric power absorbed by the compressor and $t_{in}$ and $t_{fin}$are respectively the initial and final states of the discharging phase, that is $dt_{scarica}$. Hence the electric efficiency of the total storage will be expressed as follows:

$$\eta_{I,CAES} = \frac{E_e^-}{E_c^+} \tag{5}$$

Finally it can be expressed a polygenerative efficiency that takes into consideration the useful effect determined by the thermal storages added to the one caused by the energy transferred from the turbine. Such condition can be obtained by comparing the energy present in thermal storages with the electric energy required by a heat pump to produce them, as the following relations [25]:

$$E_{el,H} = \frac{E_{sto,H}}{COP} \tag{6}$$

$$E_{el,C} = \frac{E_{sto,C}}{COP} \tag{7}$$

$$\eta_{pol,CAES} = \frac{E_e^- + E_{el,H} + E_{el,C}}{E_c^+} \tag{8}$$

## 5. Model validation

The model implemented in this paper has been validated by bibliographic data [16, 18]. Both systems present the same plant engineering configuration, two micro-CAES systems where compression and expansion processes are meant to reach a quasi-isothermal condition. All the illustrated validation tabs that are showed below report simulation results compared with those reported in the work previously mentioned. The simulation results concern the model.

Tab.1 Comparison of the energy components of the system

| | β | $T_c$ [°C] | $E^+_c$ (kWh) | $T_e$ [°C] | $E^-_e$ (kWh) | $\eta_{I,CAES}$ (%) | $E_{sto,H}$ (kWh) | $E_{sto,C}$ (kWh) |
|---|---|---|---|---|---|---|---|---|
| Simulation | 50 (7,1&7,1) | 90 | 5,34 | -8 | 2,81 | 52% | 1,83 | 1,39 |
| Results comparison (Young K.) | 50 (7,1&7,1) | 80 | 5 | -6 | 2,85 | 57% | 1,85 | 1,4 |

Tab. 1 shows the entire compression ratio (β) and the one of both phases, the final temperature of the compression phase ($T_c$) and the one of the expansion phase ($T_e$); the electric energy absorbed by the compressor ($E_c^+$) and the one transferred from the turbine ($E_e^-$) whose ratio determines the system efficiency ($\eta_{I,CAES}$); the thermal energy stored during the first phase ($E_{sto,H}$) and the refrigeration energy stored during the expansion phase ($E_{sto,C}$). It can be noticed the connection among the results that lead to consider the model realized to be valid. The output temperatures difference characterizing the two phases is determined by a different ratio between the liquid and gas of the mixture.

## 5. Result and discussion

In this paper a mathematical model of a small storage system (3 kW), with a storage capacity of $1 m^3$ and a pressure storage of 50 bar was created. The physical system modelled is a quasi-isothermal micro-CAES, which in a trigeneration system, enables the production of electric, thermal and refrigeration energies. The innovation of this system is the use of a quasi - isothermal compression phase. This phase were characterized by the injection of a mixture of liquid which, thanks to a higher thermal capacity, allowed the gas to be subject to lower temperature variations and perform a recovery of the thermal energy necessary to the cooling and heating demands of a residential unit.

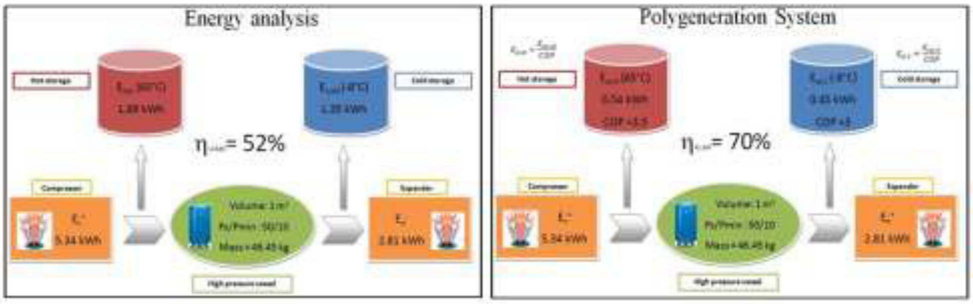

Fig. 2 Summary of the model simulations results

The reliability of the mathematical model was verified by comparing it with the few data provided by the bibliography concerning similar systems. The result of such validation was more than satisfying. The system was examined in an operating period of a whole day during which a charge/discharge cycle was performed in 1,88 h for the storage phase and 1,08 h to perform the full discharge of the system. Moreover the system absorbed 5,34 kWh to execute the charge phase, the energy required by this process was provided almost entirely by the renewable energy source. During the discharge phase there was a release of 2,81 kWh for a round-trip efficiency of 52%. The thermal storage determined by the heat subtracted during the compression phase was of 1,89 kWh, whereas the refrigeration energy stored during the expansion phase was of 1,39 kWh. However compression air systems can offer some advantages respect to conventional electrochemical tanks which require precious and expensive materials (characterized by a short service life), an efficiency affected by the operating conditions and high dissipation costs.

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## Biography

Andrea Vallati was born in Roma, Italy, on October 16, 1970. He received the M.S. degree in Mechanical Engineering, and the Ph.D. degree in Applied Physics, from University of Ancona (Italy) in 1997 and 2001, respectively. From 2006 he served as Assistant Professor at the Department of "Fisica Tecnica " of the same University. Since 2005 he is Professor of Energy and Applied Physics at the Faculty Engineering of “'Sapienza” University of Rome. He is author or co-author of about 40 scientific works, published in prominent international journals and conferences on heat transfer, thermodynamics and acoustics