MaimAir: A Flexible and Modular Energy Storage System for Tomorrow Energy Banks

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ABSTRACT

The diffusion of non-contrallable electric power generation systems imposes the use of energy storage systems that would give a flexibility to energy users in order to fit power availability. In the present paper, a novel energy storage system based on the compression of air through pumped water is presented. Differently from CAES on trial, the proposed sepration of energy transfer, in water, from energy storage, in air, leaves the opportunity to adjust the kind of compression from adiabatic to isothermal.
The energy storage process, charge and supply, could be both fast or slow leading to different configuration and applications. The novel proposed storage system is modular and could be applied in different scales for different locations. The system may offer an ideal energy buffer for wind and solar storage with no (or negligible) environment hazard. We call it MaimAir.
Thermodynamic aspects of the storage systems are discussed, highlighting the optimal operating conditions. Efficiency of the proposed system is discussed aswell.

Keywords: Compressed air energy storage (CAES); Adiabatic CAES; Isothermal CAES; Liquid piston; Gas compression

1 INTRODUCTION

Energy storage systems are of paramount interest at present, as they are mandatory in order to rise electricity production from uncontrollable renewable sources (e.g. solar energy, wind energy) [1-4]. Moreover, they can provide a better exploitation of existing power plants avoiding the construction of new power plants just to respond to growth in peak power demand, that is especially valuable in European countries where environmental impact is critical as best suitable sites has already been exploited.
There are a lot of different systems proposed for energy storage, right now the ones with commercial development are just hydrodynamic storage, for large systems, and lead based batteries for medium to small ones. Alternatives for mechanical storage are given by compressed air energy storage (CAES) that are under demonstrating operation from long time, in some sites like Huntorf in Germany (operating since 1978) and McIntosh, Alabama, USA (operating since 1991). These systems are quite promising as they don't have the geographical limits of hydrodynamic storage, thus being of wider use. Nonetheless they need to provide heat to air before turbine expansion, leading to a delay in activation, and fuel consumption. Moreover this requires many ancillary services for the storage plant. These systems have low energy efficiency, rated 40% - 75% [2], partly due to thermal issues and partly to mechanical issues related to air compression and air expansion with a variable pressure gap.
Some evolutions of CAES systems have been proposed, trying to overcome the need for heating of air before expansion. Actually, air has to be cooled after compression, too, in order to reduce its specific volume so to increase stored mass of high pressure air in the vessel. Thus, heat storage has been proposed in, so called, adiabatic CAES to avoid fuel consumption for heating [3 - 7]. This will improve energy and exergy efficiency of systems but it won't be useful to avoid activation delay that limits the kind of service CAES systems could provide to power grid.
Moreover, usual compressors and turbines are hardly suitable to operate with variable back pressure. So during charging phase, air is compressed up to the highest storage pressure. While before introduction in turbine, air is expanded in a compensation valve, lowering its pressure to the lower storage pressure.
Thus, despite CAES technology has already started being exploited, a lot of improvement is possible.

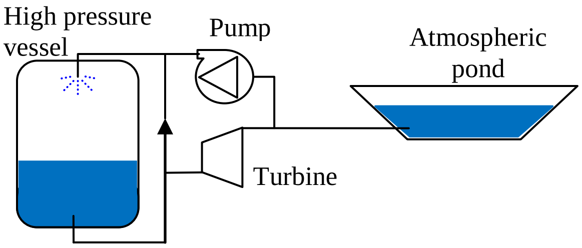

Fig. 1 – sketch of proposed system

In traditional CAES, compression of air takes place in the compressor, then it is moved to the storage vessel.

Similarly, air is taken from the vessel and introduced in turbine for expansion. In the proposed system, air is compressed and expands directly in the storage vessel. This is done through a water piston that modifies the volume available to air, reducing it during charge and increasing it during discharge. The water piston is used as heat storage, too, so to absorb heat during compression and reject it during expansion.

The new system is thus a hydraulic compressed air energy storage, that we would like to call MAIMAIR (other authors have called it HYCAES, but we would prefer this term that is the union of maim, that is water in hebrew, with air). As sketched in fig. 1, it is composed of high pressure storage vessel, almost full of air when fully out of power, an atmospheric pond for water storage, a water pump and a hydraulic turbine and connecting pipes. It is not ever-new, as there are some papers illustrating similar systems [7 - 10]. In present paper, thermodynamic aspects of proposed systems will be analyzed to prove its energy feasibility.

2 POLYTROPIC TRANSFORMATION

Reversible compression of air by water piston can be done through different polytropic transformations, according to heat exchange of air. Rapid compression and high volume to surface ratios provides an almost adiabatic transformation. In order to avoid limiting power to energy ratio in the system, a rapid phenomenon will be assumed, so that heat exchange through vessel is negligible. Nonetheless, a perfect mixing of water to air is assumed, so to have an almost infinite contact surface that lets any heat exchange rate be provided to air. Air and water will be assumed at same temperature. This transformation will have the lowest possible polytropic index.

A reversible polytropic transformation is described by equation (1):

$$p_0 \cdot {V_0}^m = p_f \cdot {V_f}^m \tag{1}$$

We remind that m=1 for an isotherm and $m=\gamma=c_P/c_V$ for a reversible adiabatic transformation. Introducing $\mu=m-1$ and $\beta=V_0/V_f$ as well as perfect gas state equation, it becomes:

$$\frac{T_f}{T_0} = \beta^\mu \tag{2}$$

Assuming temperature independent specific heat, while specific heat of liquid water is almost independent of transformation, energy balance for a perfectly mixed adiabatic vessel is:

$$M_a \cdot c_V \cdot (T_f - T_0) + M_w \cdot c_w \cdot (T_f - T_0) = -W \tag{3}$$

Work can be calculated straightly from polytropic equation:

$$W = \int_{V_0}^{V_f} p \cdot dV = \frac{p_0 \cdot V_0^m}{m-1}\left(V_0^{1-m} - V_f^{1-m}\right) \tag{4}$$

Mass of air is related to initial state through equation of state:

$$M_a = \frac{p_0 \cdot V_0}{R_a \cdot T_0} \tag{5}$$

Mass of water is related to its density:

$$M_w = \rho_w \cdot (V_0 - V_f) \tag{6}$$

Substituting and simplifying, eq. (3) becomes, as in [12]:

$$\frac{T_f}{T_0} - 1 = \frac{1}{\mu} \cdot \frac{(\beta^\mu - 1)}{\frac{c_V}{R_a} + \frac{\rho_w \cdot c_w}{p_0} \cdot \frac{T_0}{\beta}(\beta - 1)} \tag{7}$$

Substituting (3) in (7) it comes:

$$\mu = \frac{1}{\frac{c_V}{R_a} + \frac{\rho_w \cdot c_w}{p_0} \cdot \frac{T_0}{\beta}(\beta - 1)} \tag{8}$$

that, by defining air initial density from (5) becomes:

$$\mu = \frac{R_a}{c_V} \cdot \frac{1}{1 + \frac{\rho_w \cdot c_w}{\rho_{a,0} \cdot c_v} \cdot \left(1 - \frac{1}{\beta}\right)} \tag{9}$$

So, recalling Mayer's relation, the polytropic index with respect to adiabatic index is so expressed:

$$m = 1 + \frac{\gamma - 1}{1 + C \cdot \left(1 - \frac{1}{\beta}\right)} \tag{10}$$

where C is the ratio of heat capacity per unit volume between water and air at initial state.

At low compression ratios (β → 1) polytropic is close to adiabatic. At high compression ratios it depends on C that depends on initial state on behalf. Even at high initial pressure, like 100 bar, C is quite big, around 40. Thus even at that pressure, a compression ratios of 2 (close to the limit given by the critical pressure of water) lead to an *m* of 1.019, as shown in fig. 2. This means that it is possible to reach an almost isothermal transformation through a thin spraying of water during compression, as shown .

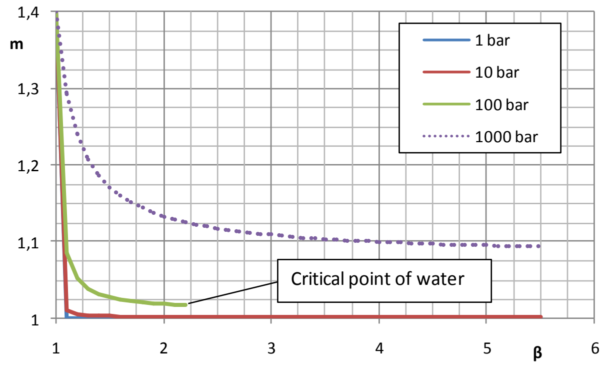

Fig. 2 - lower value of polytropic index vs. compression ratio for different initial values of air pressure

Usually, storage vessels should be as small as possible, thus implying a high final pressure. Yet, in order to have separated phases in the vessel pressure should not exceed critical pressure of water, around 220 bar. Therefore initial one should not exceed 80 bar. Moreover, if compression is done without spraying, it will be mostly adiabatic.

3 OPTIMAL COMPRESSION RATIO

Final pressure of storage system is limited by its mechanical stability. On the contrary, even though lower initial pressure means more storable energy per unit mass, it means lower initial mass, too, as stated by eq. (5).

Assuming a reversible isothermal compression during energy storage specific storable energy per unit volume is given by:

$$\mathrm{E} = -\frac{W}{V_0} = -\frac{1}{V_0}\int_{V_0}^{V_f} p_0 \cdot V_0 \frac{dV}{V} = p_0 \cdot ln\frac{p_f}{P_0} \qquad (11)$$

Differentiating with respect to initial pressure, a maximum for storable energy per unit volume is found at:

$$p_0 = \frac{P_f}{e} \qquad (12)$$

This means that optimal compression ratio β is *e*.

This value is higher than pressure rate between initial and final pressure in operating CAES [11], even though this optimal value is not relevant for them.

Numerical solution of equations for almost isothermal reversible storage transformations has shown that at higher intial pressure the optimal compression ratio increases slightly, as shown in fig. 3.

Assuming the final pressure to be equal to the critical pressure of water, the highest storable energy per unit volume is $8\text{x}10^6$ J/m^3, being the initial pressure p_0 equal 80 bar.

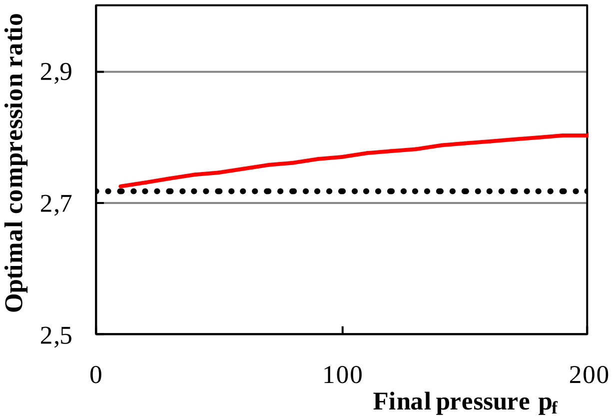

Fig. 3 – optimal compression ratio vs. storage final pressure

4 EFFICIENCY

CAES has been proved to be cost effective with efficiency comparable to hydrodynamic storage. It should be highlighted that in the proposed system the fully charged storage vessel is mainly filled of water rather than air. As energy is stored in air compression, this means that energy storage cost per unit volume is higher than in conventional CAES.

Nonetheless, in existing systems, compressed air has to be cooled prior to being stored, losing a lot of energy, and it has to be reheated after then, before expansion in turbine. These lead to a large amount of thermal energy loss in conventional CAES.

Conventional compressed air storage are almost isothermal, as air is cooled after compression that occurs outside of the vessel. Actually, temperature increases during storage and decreases during air extraction, thus reducing energy efficiency, but for present calculations this will be neglected. Stored energy per unit volume is thus given by the difference in air mass as specific internal energy is almost constant. Thus, neglecting the dependence of specific heat on temperature (limited to 7% in the relevant thermodynamic states of air), stored energy per unit volume refered to the initial pressure in air storage $p_{0'}$, could be expressed as:

$$E = \left(M_f - M_{0'}\right) \cdot c_V \cdot \frac{T_{0'}}{V} = \frac{1}{\gamma - 1} \cdot (p_f - p_{0'}) \qquad (13)$$

Thus, vessel usage ratio is given by the ratio of eq. (11) to eq. (13):

$$\varepsilon = \frac{p_0 \cdot \ln\frac{p_f}{p_0}}{\frac{1}{\gamma-1} \cdot (p_f - p_{0'})} \qquad (14)$$

Final to initial pressure ratio of these systems is rather different. Thus, comparison of the vessel usage ratio of these systems should be between the newly proposed, at optimal pressure ratio, to conventional at its operation ratio. Introducing eq. (12) in eq. (14) it becomes:

$$\varepsilon = \frac{\gamma - 1}{e} \cdot \frac{1}{1 - \frac{p_{0'}}{p_f}} \qquad (15)$$

Huntorf plant has a 1.57 compression ratio that corresponds to a 40.5% usage ratio according to (15). This means that air storage vessel for proposed MAIMAIR system should be 2.5 times larger than in a traditional CAES that works just like Huntorf plant, being more expensive. Nonetheless, thermodynamic analysis for Huntorf plant, based on available data [11], shows that only 31% of compression work is actually gathered in energy storage, even neglecting compressor efficiency.

This means, for example, that a storage vessel in which 100 units of energy are gathered with a MAIMAIR system, would be filled to 40,5%, if used for a traditional CAES, but it would need 323 units of energy. So the newly proposed system is more expensive to be built but is much more efficient during operation.

According to [9], the investment cost for the newly proposed MAIMAIR can be estimated to be in between of 1÷1.5 times conventional CAES. But, its operation will be 3.3 times more efficient. Thus break-even will be obtained nearly in half the time needed for conventional CAES.

5 CONCLUSIONS

Thermodynamic analysis of proposed system has shown that isothermal compression of air through a water piston is possible.

The proposed MAIMAIR system is suitable for energy storage with the main advantage of no fuel nor heat storage system. Efficiency analysis has shown that loss in vessel usage due to water piston displacement is well compensated by the reduction of thermal energy loss after compression and of heat demand before expansion. The proposed system is thus an alternative to available large scale energy storage.

In conclusion the energy buffer is based on the combination of the huge thermal buffer due to the heat capacity of water to compressibility of air with the separation of energy transfer from actual energy storage. This act as a thermodynamic reserve that avoids most of the energy dispersion of common CAES.

NOMENCLATURE

c	[J/kg K]	specific heat
c_v	[J/kg K]	specific heat for constant volume transformation for air
c_p	[J/kg K]	specific heat for constant pressure transformation for air
C	$=\frac{\rho_w \cdot c_w \cdot R_a \cdot T_0}{p_0 \cdot c_V}$	capacity per unit volume ratio between water and air at initial state
E	[J/m^3]	storable energy per unit volume
m	[-]	general polytropic index
M	[kg]	mass
p	[Pa]	pressure
t	[-]	vessel usage ratio
R	[J/kg K]	specific gas constant
T	[K]	temperature
V	[m^3]	volume
W	[J]	work

Greek symbols

β	$= V_0/V_f$	compression ratio
γ	$= c_P/c_V$	polytropic index of isoentropic transformation
ε	$=\frac{E_{CAES}}{E_{MAIMAIR}}$	vessel usage ratio
μ	$= m - 1$	modified polytropic index
ρ	[m^3/kg]	density

subscripts

a	related to air
f	final state, full vessel
w	related to water
0	initial state, empty vessel
0'	initial state, empty vessel, conventional CAES

REFERENCES

[1] Electric Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits. EPRI, Palo Alto, CA, 2010

[2] Leading the Energy Transition, Factbook, Electricity Storage, SBC Energy Institute, Gravenhage, Netherlands, 2013

[3] E. Fertig, J. Apt, Economics of compressed air energy storage to integrate wind power: A case study in ERCOT, Energy Policy, 3 9, 2330–2342, 2011

[4] H.L. Ferreira, R. Garde, G. Fulli, W. Kling, J.P. Lopes, Characterisation of electrical energy storage technologies, Energy 53, 288–298, 2013

[5] C. Bullough, C. Gatzen, C. Jakiel, M. Koller, A. Nowi, S. Zunft, Advanced Adiabatic Compressed Air Energy Storage for the Integration of Wind Energy, Proceedings of the European Wind Energy Conference, London UKEWEC, 2004

[6] N. Hartmann, O. Vöhringer, C. Kruck, L. Eltrop, Simulation and analysis of different adiabatic Compressed Air Energy Storage plant configurations, Applied Energy 93, 541–548, 2012

[7] Y.M. Kim, J.H. Lee, S.J. Kim, D. Favrat, Potential and Evolution of Compressed Air Energy Storage: Energy and Exergy Analyses, Entropy 14, 1501–1521, 2012

[8] Y.M. Kim, D.G. Shin, D. Favrat, Operating characteristics of constant-pressure compressed air energy storage (CAES) system combined with pumped hydro storage based on energy and exergy analysis, Energy 36, 6220–6233, 2011

[9] H. Wang, L. Wang, X. Wang, E. Yao, A Novel Pumped Hydro Combined with Compressed Air Energy Storage System, Energies 6, 1554–1567, 2013

[10] C. Qin, E. Loth, Liquid piston compression efficiency with droplet heat transfer, Applied Energy 114, 539–550, 2014

[11] M. Raju, S.K. Khaitan, Modeling and simulation of compressed air storage in caverns: A case study of the Huntorf plant, Applied Energy 89, 474–481, 2012

[12] D. Fargion, E. Habib, A novel flexible and modular energy storage system for near future Energy Banks, http://arxiv.org/abs/1601.03350.