Evaluating Plant Configurations for Adiabatic Compressed Air Energy Storage by Dynamic Simulation

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ABSTRACT

Adiabatic Compressed Air Energy Storage (A-CAES) represents a zero emission electrical storage technology together with acceptably high cycle efficiency. Therefore the application of internal heat storage becomes necessary. One main characteristic of such A-CAES is that the heat generated during compression exceeds the amount of usable heat for the expansion process afterwards. In real life cycling mode this could lead to a heat storage overload. For heat storage management four possible solutions are proposed and discussed. To assess these solutions and to obtain a well suited overall plant configuration a dynamic model of the whole A-CAES process was developed with the focus on the stratified high-temperature heat storage. After an introduction to basic mechanisms relevant for the understanding of heat management in an A-CAES context, a brief explanation of the model structure is given and two heat management solutions are discussed more in detail.

Introduction

Compressed air energy storage (CAES) is a promising candidate for large scale electricity storage. It allows for greater siting flexibility as compared to pumped hydro at acceptable costs. CAES is particularly appealing when considering the storage of large amounts of fluctuating wind energy output in daily to weekly cycles [1]. Within the last years considerable efforts have been undertaken to develop CAES processes that omit any fuel use [2]. Therefore it is necessary to store the heat generated during compression in a thermal energy storage device and transfer it to the expansion process so the compressed air can be reheated before flowing to the expander (see Figure 1).

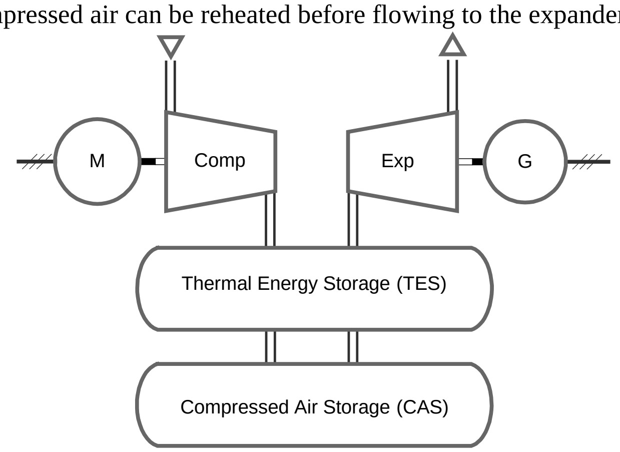

Figure 1: Simplified A-CAES process scheme

Challenges of thermal energy storage in an A-CAES plant

A-CAES is the only electricity storage technology so far where two storage processes – compressed air storage (CAS) and thermal energy storage (TES) - in parallel account for the stored energy content. These two processes have to be synchronized all the time during operation. Having this in mind one main challenge for design and operation of thermal energy storage within an A-CAES plant is the fact that the heat generated in the compression process exceeds the amount of usable heat for the expansion process afterwards.
The driving forces for this excess heat phenomenon can be explained by the two following principle effects:

- Frictional losses during compression and expansion
- Humidity of ambient air

Frictional losses due to non isentropic compression and expansion cause additional heat to the airstream. Figure 2 shows an adiabatic compression in a T,s-plot for different isentropic efficiencies. One can see that the compression outlet temperature rises with a decrease in isentropic efficiency going in line with a rise in entropy generation. While compression 1-2a is a theoretical case with no entropy production at all (isentropic efficiency = 1), the temperature rise in a real compressor at design point is higher (1-2b).

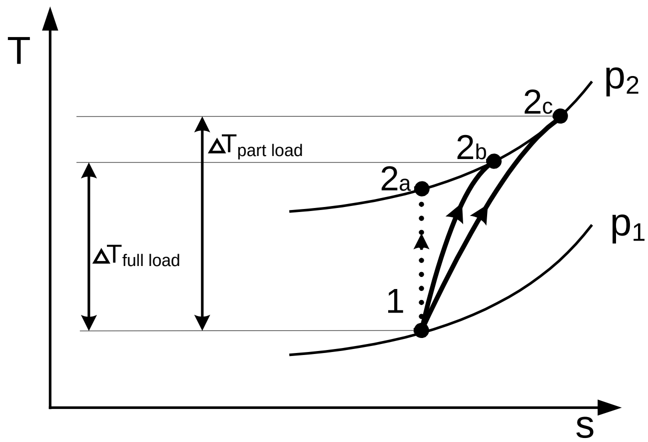

Figure 2: Compression from pressure p_1 to p_2 in T,s-diagram for different isentropic efficiencies

In most compressors isentropic efficiencies decrease in part load operation (1-2c), which goes along with a higher compressor outlet temperature and thus with a rise in the specific amount of heat produced during compression.. Within an A-CAES process this has to be considered in order to avoid the accumulation of excess heat in the TES.

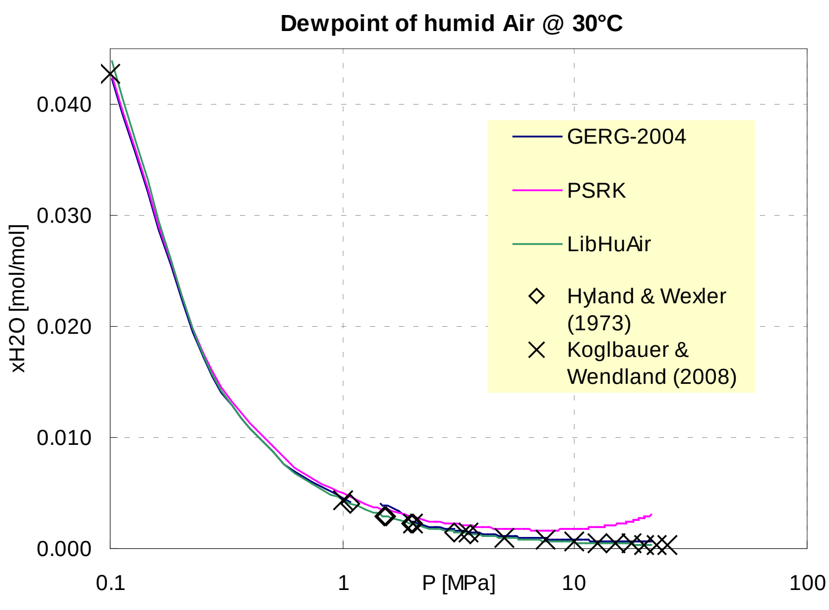

Figure 3: Saturation concentration for humid air at 30°C

The second effect that might lead to excess heat is based on the ability of ambient air to carry a certain amount of vaporised water [3]. This ability rises with temperature and falls with pressure. When the humidity of air rises beyond saturation concentration water starts to condense. Figure 3 shows the saturation concentration according to different real gas property models (lines) and measurement data (◇/ X) for isothermal conditions at 30°C over pressure [4,5,6]. Considering now an A-CAES process air enters at ambient conditions with around 0.1 MPa and is compressed up to 7 to 10 MPa, where the saturation concentration is drastically lower (compare Figure 3) and water tends to condense. The condensed water, also called free water then has to be separated from the air mass flow before entering the CAS. Separating the free water decreases the heat capacity flow of the air in comparison to the sucked ambient air volume flow. As a consequence of this decrease in heat capacity flow, the air isn't able to extract the same amount of heat during expansion mode as it was introduced to the TES during compression mode, again leading to excess heat inside the TES.

Within several charging and discharging cycles excess heat can lead to an overload of the TES. As a consequence the air cannot be cooled down enough in the TES during the charging phase and in an intercooled process higher compressor stages suffer greater thermal stresses. Furthermore the overall efficiency of the system decreases, and the storage temperature inside the compressed air tank reaches safety relevant values. When designing an A-CAES plant this phenomenon must be addressed, calling for a suitable overall plant configuration and heat management system.

Dynamic A-CAES plant model

When setting up A-CAES plant configurations together with a well balanced heat management system, it is necessary to understand the thermal behaviour of stratified TES as proposed for A-CAES. Figure 4 shows such a stratified TES with molten salt as heat storage media at laboratory scale. A dynamic computer model based on a one dimensional finite element approach was developed and validated by measured data from the laboratory TES (see Figure 4). Using real gas property models for humid air, heat and mass balance are set up individually for each element. This way the developed model is able to reproduce adequately the stratified temperature field inside the TES, considering its time dependant thermal losses a as well as the phase equilibrium of humid air. With this model it is now possible to grasp the time dependent thermal behaviour of a stratified TES within an A-CAES environment.

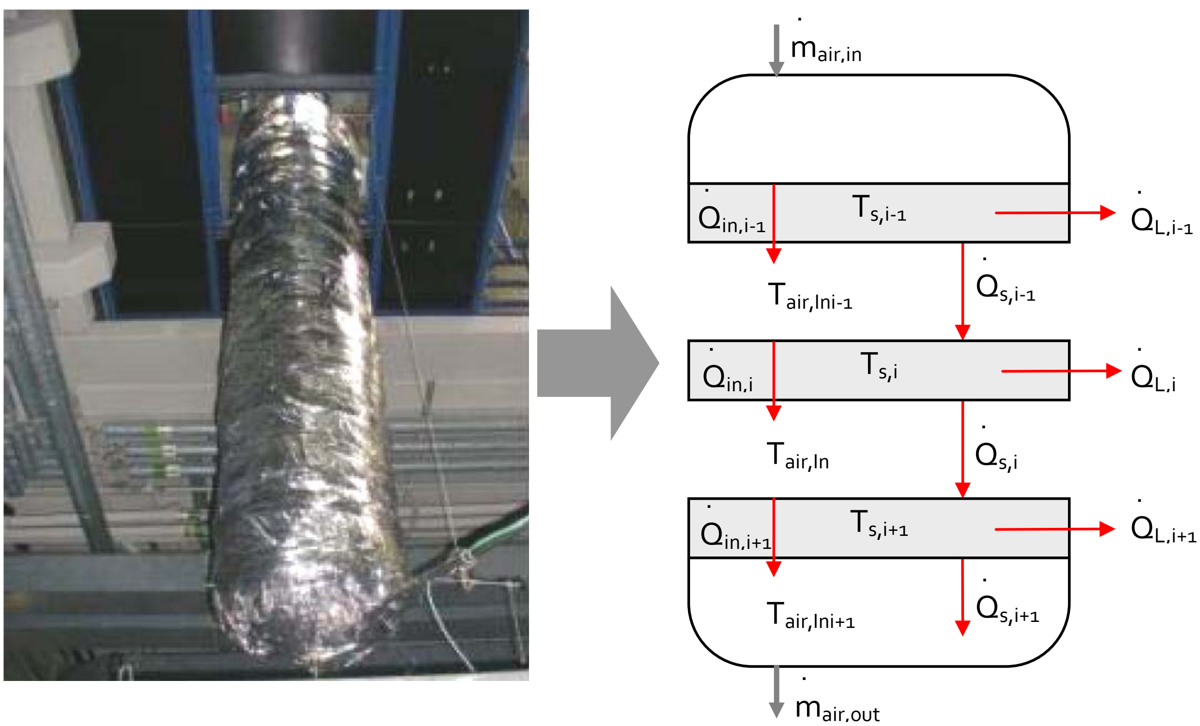

Figure 4: Left: CAES-TES on a molten salt basis at laboratory scale (Ruhr-University Bochum); Right: 1-dimensional finite element approach depicted for the charging mode

The developed TES model can be incorporated into an overall plant model of an A-CAES system allowing flexible modification of the plant configuration. Doing so different A-CAES plant configurations can be easily set up and evaluated individually. Figure 5 shows one promising plant layout of an A-CAES with a 2-stage TES (left side). On the right hand side one can observe the thermocline behaviour for a cyclic operation of the A-CAES plant. The principle aim of this particular plant layout was to limit the maximum storage temperature to 420°C in view to reduce thermal stresses of the compressing equipment. Doing so, the development effort for new high temperature adiabatic compressors can be minimized.

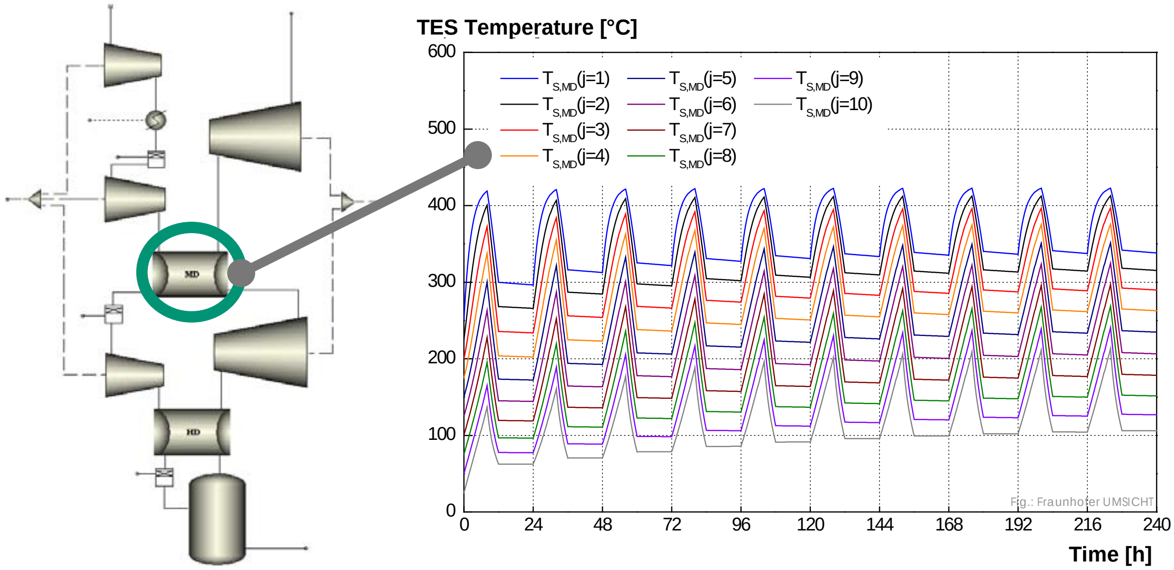

Figure 5: Left: Graphical view of the A-CAES dynamic plant model for certain plant configuration
Right: Time dependent thermocline behaviour of the mid pressure TES in cyclic operation

Heat management solutions

On the right side of Figure 5 the stratified temperature field inside the mid-pressure TES under cyclic operation can be observed. It is visible that especially in the lower and thus colder regions of the TES temperature tends to rise cycle by cycle due to the accumulation of excess heat. This demands for further heat management solutions being implemented. Several solutions for balancing the TES are viable:

- Controlled re-cooling of the TES or the air flow directly (1)
- Passive adaptation of the thermal losses to the excess heat (2)
  (modifying insulation of TES)
- Injection of water to the airflow during expansion before reheating inside the TES (3)
  (in order to adjust heat capacity flow during expansion)
- Controlled re-cooling of the TES with a combined use of excess heat (4)
  (e.g. for an ORC-process, district heating)

Main goal of such heat management solutions is to balance the TES in a way that it is perfectly synchronized with the charging status of the CAS at any time during operation. The implemented heat management solution then has to ensure sufficient operational flexibility together with a high cycling efficiency at minimal additional investment cost. All of the three targets demand contradictory measures. High efficiency in case of A-CAES can be reached by reusing as much compression heat as possible via TES. On the other hand besides higher investment cost this leads to a decrease of operational flexibility particularly because of the excess heat phenomenon. Table 1 indicates the different characteristics of each solution regarding financial and technical efforts, operational flexibility and plant efficiency.

	Financial effort	**Technical effort**	**Operational Flexibility**	**Plant Efficiency**
(1) Re-cooling of TES	--	O	++	--
(2) Adaptation of thermal losses	++	++	-	--
(3) Water injection	-	--	+	++
(4) Combined use of excess heat	O	-	O	+

Table 1: Assessment of possible heat management solutions for adiabatic compressed air storage plants ranging from highly favourable (++) to highly unfavourable (--)

Obviously there is no single solution that satisfies all needs. Adaptation of thermal losses for example performs well regarding financial and technical effort but a decrease in plant efficiency has to be accepted as well as a lack of operational flexibility. On the other hand water injection to the expanding airflow and combined use of excess heat is favourable regarding plant efficiency but technically and financially more demanding. Since excess heat could be harvested on a relatively high temperature level the deployment of solution 3 or 4 are promising and should be investigated in detail. Therefore the TES model was extended by a re-cooling option of the lower and thus colder areas inside the TES. Furthermore the process of humidifying the airstream in expansion mode was modelled as well. Both models were integrated to the TES model as depicted in Figure 6.

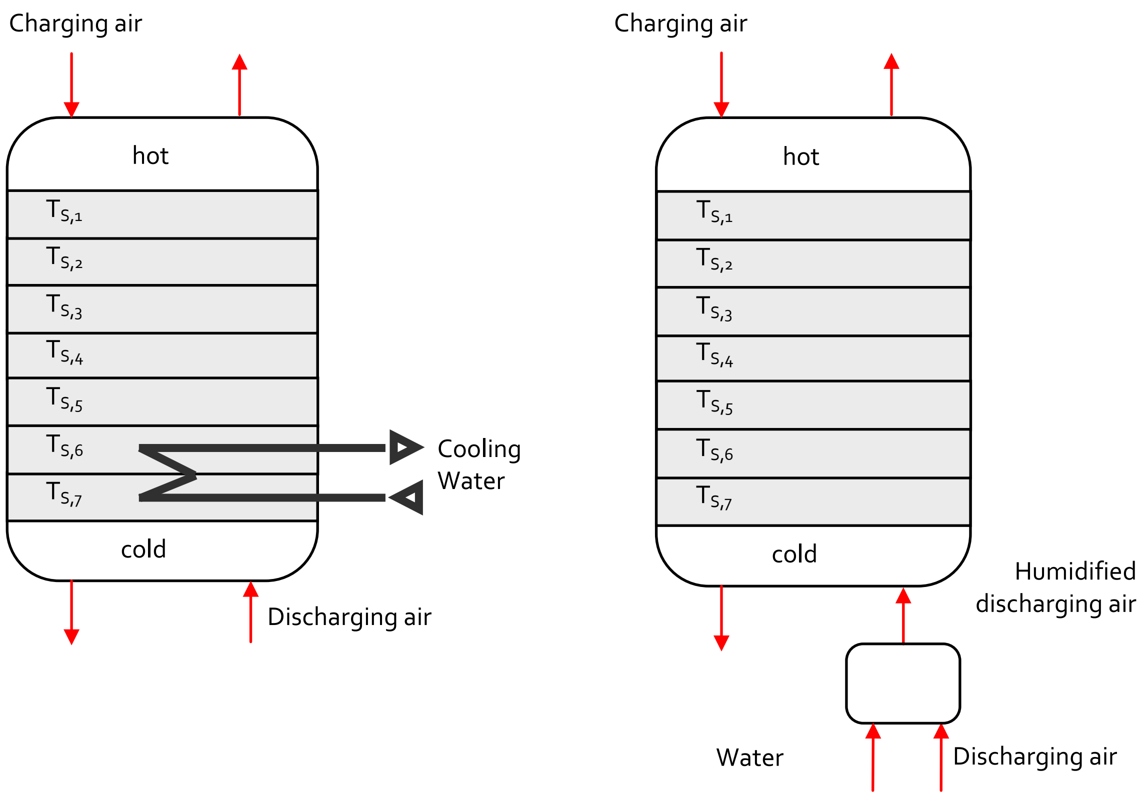

Figure 6: Left: Process scheme of re-cooling of the TES with a combined use of excess heat (4); Right: Process scheme of water injection to the airflow during expansion before reheating inside the TES (3)

To carry out a proof of concept a simple 1-stage TES A-CAES plant configuration with a turbine power of 200 MW_{el} at a storage capacity of 5 full load hours was chosen. The maximum storage temperature for the one-stage TES was set to be 520°C together with a pressure variation of 40-60 bar inside the CAS.

For the re-cooling circuit (compare Figure 6 left) the cooling water outlet temperature was adjusted to 110 °C cooling down just the lower part of the TES. Under these conditions a compensation of the excess heat could be proven. When additionally the extracted heat will be reused in e.g. an Organic Rankine Cycle (ORC) [7] around 500 kW_{el} can be generated given an efficiency of 0.1 of the ORC. Altogether this would account for a rise in overall efficiency of the A-CAES storage plant in average of 1 percentage points.
The second concept of water injection aims at a rise of the specific heat capacity of the airstream during expansion. This way it is possible to extract more heat out of the TES than with the dryer air stored in the CAS. By adjusting the water flow the amount of heat to be additionally extracted can be controlled. For the examined plant configuration the water flow was set to 5,5 kg/s at a temperature range of 30-40°C in case of full load conditions. Doing so, a rise in turbine power output of up to 5 MW_{el} could be observed accounting for a rise in cycle efficiency of around 1.5 percentage points.

Finally it can be concluded that both heat management concepts examined using the dynamic plant model are generally feasible and lead to the desired heat balancing of the TES. Which concept to prefer has to be decided individually taking into account that the re-cooling solution can operate almost constantly thanks to the TES. Coupling the extracted heat flow with an ORC thus generates baseload power or backup power to enhance blackstart capability of the storage plant. On the other side water injection just has an effect to the turbine output power when the A-CAES plant works in expansion mode, but then results in an even higher rise of overall cycle efficiency.

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