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# Thermal analysis of near-isothermal compressed gas energy storage system ☆

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## HIGHLIGHTS

- A novel, high-efficiency, scalable, near-isothermal, energy storage system is introduced.
- A comprehensive analytical physics-based model for the system is presented.
- Efficiency improvement is achieved via heat transfer enhancement and use of waste heat.
- Energy storage roundtrip efficiency (RTE) of 82% and energy density of 3.59 MJ/m$^3$ is shown.

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## ABSTRACT

Due to the increasing generation capacity of intermittent renewable electricity sources and an electrical grid ill-equipped to handle the mismatch between electricity generation and use, the need for advanced energy storage technologies will continue to grow. Currently, pumped-storage hydroelectricity and compressed air energy storage are used for grid-scale energy storage, and batteries are used at smaller scales. However, prospects for expansion of these technologies suffer from geographic limitations (pumped-storage hydroelectricity and compressed air energy storage), low roundtrip efficiency (compressed air energy storage), and high cost (batteries). Furthermore, pumped-storage hydroelectricity and compressed air energy storage are challenging to scale-down, while batteries are challenging to scale-up. In 2015, a novel compressed gas energy storage prototype system was developed at Oak Ridge National Laboratory. In this paper, a near-isothermal modification to the system is proposed. In common with compressed air energy storage, the novel storage technology described in this paper is based on air compression/expansion. However, several novel features lead to near-isothermal processes, higher efficiency, greater system scalability, and the ability to site a system anywhere. The enabling features are utilization of hydraulic machines for expansion/compression, above-ground pressure vessels as the storage medium, spray cooling/heating, and waste-heat utilization. The base configuration of the novel storage system was introduced in a previous paper. This paper describes the results obtained from a transient, analytical, physics-based thermodynamic system model used for the system design and evaluation of three design configurations (including base configuration). The system model captures real gas effects and all loss mechanisms. The model demonstrates an energy storage roundtrip efficiency of 82% and energy density of 3.59 MJ/m$^3$. Experimental evaluation of system performance and detailed cost-analysis will be presented in future publications.



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**Nomenclature**

*Symbols*

| | |
|---|---|
| $ED$ | energy density [MJ/m$^3$] |
| $m$ | mass [kg] |
| $c$ | specific heat capacity [J/kg K] |
| $T$ | temperature [K] |
| $h$ | heat transfer coefficient [W/m$^2$ K] |
| $A$ | heat transfer area [m$^2$] |
| $UA$ | overall heat transfer coefficient [W/K] |
| $p$ | pressure [Pa] |
| $V$ | volume [m$^3$] |
| $\dot{m}$ | mass flow rate [kg/s] |
| $t_T$ | wall thickness [m] |
| $k$ | thermal conductivity [W/m K] |
| $v$ | velocity [m/s] |
| $D$ | diameter [m] |
| $g$ | acceleration due to gravity [m/s$^2$] |
| $C_D$ | drag coefficient [−] |
| $t$ | time [s] |
| $L$ | length [m] |
| $N$ | number [−] |
| $\dot{N}$ | number of droplets per unit time [s$^{-1}$] |
| $\dot{V}$ | volumetric flow rate [m$^3$/s] |
| $Nu$ | Nusselt number [−] |
| $Re$ | Reynolds number [−] |
| $Pr$ | Prandtl number [−] |
| $\dot{Q}$ | rate of heat transfer [W] |
| $W$ | work [J] |
| $Q$ | heat [J] |
| $num$ | number of (used to define number of Pelton turbine jets) [−] |
| $jet$ | Pelton turbine jets (used to quantify number of) [−] |
| $pause$ | standby period between charging and discharging [s] |

*Indices*

| | |
|---|---|
| $v$ | at constant volume |
| $G$ | of gas |
| $L$ | of liquid |
| $amb$ | of ambient air |
| $T$ | of tank walls |
| $i$ | inner |
| $o$ | outer |
| $ave$ | average (of inner and outer) |
| $min$ | minimum |
| $dr$ | of the drop(s) |
| $ini$ | initial (beginning of time period) |
| $spr$ | of the spray |
| $in$ | inlet or input |
| $term$ | terminal (velocity) |
| $trav$ | travel (residence) |
| $S$ | surface |
| $out$ | outlet or output |
| $max$ | maximum |
| $mixed$ | mixture of bulk and spray liquid |
| $WH$ | waste heat |
| $ind$ | indicated (after expansion/compression losses) |
| $elec$ | electrical (after all component losses) |
| $Carnot$ | Carnot (efficiency) |

*Greek letters*

| | |
|---|---|
| $\Delta T$ | temperature difference |
| $\eta_{elec}$ | electric round-trip efficiency [−] (after all component losses) |
| $\eta_{ind}$ | indicated efficiency [−] (after expansion/compression losses) |
| $\eta_{Ex}$ | exergetic efficiency [−] |
| $\rho$ | density [kg/m$^3$] |
| $\tau$ | thermal time constant [s] |
| $\varepsilon$ | heat exchanger effectiveness [−] |

*Abbreviations*

| | |
|---|---|
| AA-CAES | advanced-adiabatic compressed air energy storage |
| CAES | compressed air energy storage |
| ED | energy density |
| GLIDES | Ground-Level Integrated Diverse Energy Storage |
| HVAC | Heating Ventilation and Air Conditioning |
| LAES | liquid air energy storage |
| LTA-CAES | low temperature adiabatic compressed air energy storage |
| ORNL | Oak Ridge National Laboratory |
| PD | positive displacement (pump) |
| PHES | pumped heat electricity storage |
| PSH | pumped storage hydroelectricity |
| RTE | round trip efficiency |
| RK | Redlich-Kwong |
| T-CAES | trigenerative compressed air energy storage |

## 1. Introduction

To increase the penetration of renewable energy technologies, low-cost, high roundtrip efficiency (RTE) energy storage solutions are necessary to avoid grid instability resulting from the intermittent nature of renewable sources [1,2]. About 99% of currently installed electrical energy storage capacity worldwide consists of pumped-storage hydroelectricity (PSH) [3,4], which is a large-scale/capacity (MW-GW), high RTE (65–87%), technologically mature solution [4,5], costing up to $100/kW h [4–6]. PSH operates via a simple principle: during charging, water is pumped from a lower reservoir to an upper reservoir and during discharging, or energy extraction, the water flows from the upper reservoir down to the lower reservoir, through a turbine which dispatches electricity via an electrical generator. Site selection for PSH has been difficult because it is geographically limited to sites where a large head of water can be developed by large differences in height (>500 m ideally) [7]. Additionally, market conditions for large-scale storage systems vary and are unfavorable in some countries, which hinders the development of new projects.

Compressed air energy storage (CAES) is another large-scale/capacity storage technology that has been considered where PSH is not feasible. With CAES, off-peak electricity is used to compress atmospheric air into underground hard-rock or salt caverns using reversible motors/generators turning a chain of gas compressors. An above-ground system of vessels or pipes can also be used instead of underground caverns, for smaller scale CAES systems [5,8]. For electricity extraction, the compressed air is released and mixed with natural gas as it expands and is burned through a gas turbine. Similarly to PSH, large-scale CAES is limited to suitable geographical locations, in this case, locations where the topography allows for naturally occurring underground caverns [9]. So far, there are only two commercial CAES plants in operation; they are located in Huntorf, Germany, and MacIntosh, Alabama [10].

Conventional CAES suffers from low roundtrip efficiency (~40 to 50%) because of the significant energy losses in gas compressors