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# Improvement of the Pumped Thermal System Technology for Large-scale Electricity Storage

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## 1. Introduction

### *1.1 South Korea and renewables energies*

Citizen awareness towards renewable energies has shown worldwide growing interest for the past twenty years [1]. Consequently, politicians can no longer ignore them, especially when running campaigns. During the last presidential elections in South Korean in 2017, the future president Moon Jae-In proposed a list of key elements to promote renewable energies and to curb the critical global warming. As an example, one of Pres. Moon's objectives is to produce 20% electricity from renewable energy sources by 2030, as described by the third key point. On a global scale, renewable energies appear as the solution to reduce pollution levels and the increasing Earth temperature while ensuring acceptable safety levels.

### *1.2 The importance of electricity storage*

However, renewable energies also face serious drawbacks, since they are by nature highly variable, uncontrollable and in a way unpredictable. This seems quite unsuitable with the grid fluctuations. Indeed, the network requires a certain level of flexibility linked to the customers' demand, as well as quick answers from the electricity production systems [2]. To face the challenge of producing more electricity from renewable energy sources, it has become a necessity to develop energy storage systems ESS. These systems usually combine two or more energy sources with a nuclear power plant producing a constant input of electricity, and additionally at least one source of renewable energy, e.g. solar panels [2]. Electricity is produced and then either transferred directly in the grid or stored as another form of energy (mechanical, chemical, electromagnetic or thermal) in order to be used later.

### *1.3 Pumped Thermal Electricity Storage*

ESS technologies have been under investigation for a long time. The dominant large-scale electricity storage systems are the Pumped Hydro Storage PHS (mechanical conversion), Compressed Air Energy Storage CAES (mechanical conversion), flow batteries (chemical conversion) and Pumped Thermal Energy Storage PTES (thermal conversion) [3]. Unlike the three firsts, PTES systems are free from geographical and geological constraints and do not make use of any dangerous material. Besides, this storage technology shows comparable capacity, efficiency and discharge time.

PTES technology is based either on a Brayton cycle [3] or on a Rankine cycle [4], depending if the working fluid remains a gas (Brayton cycle) or undergoes a change of phase (Rankine cycle). This enables to store electricity (anticlockwise flow ; heat pump cycle ; charge) as sensible (Brayton cycle) or latent heat (Rankine cycle) ; or to deliver electricity (clockwise flow ; heat engine cycle ; discharge). The working fluid flows between two reservoirs composed of refractory material, e.g. aluminium oxide spheres [3], or water [4]. The system proposed by Mercangöz et al. [4] is presented on Fig. 1.

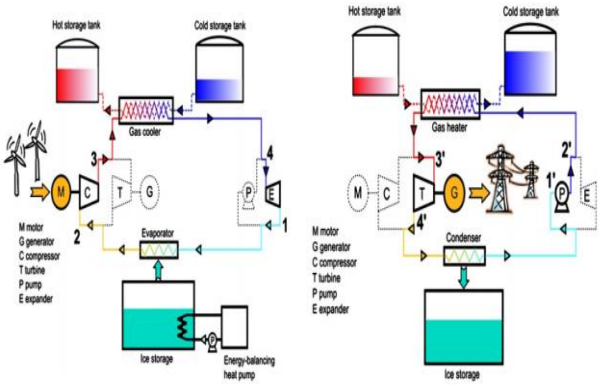


Fig. 1. Layout of the PTES system during charging (left) and discharging (right) mode [4]

Mercangöz et al. [4] suggested to use carbon dioxide as a transcritical fluid following a Rankine cycle with water for the storage medium. In addition, the authors proposed a thermodynamic cycle for a pilot plant. However, some of their results should be called into question.

### *1.4 Aim of the present study*

In this study, we aim at constructing a thermodynamic cycle for a small-scale pilot plant to produce 1MW with a round-trip efficiency of 53%. First, we explain why carbon dioxide is a promising candidate for a PTES system. Then, we show how to construct such a transcritical cycle with carbon dioxide as the working fluid.

## 2. Methods and Results

In this section, we first demonstrate why carbon dioxide is a promising fluid for this application. Following, we move on to the method applied to construct a transcritical cycle leading to a round-trip efficiency of 53% with a produced power of 1MW.

*2.1 Potential of supercritical $CO_2$*

Carbon dioxide in all its phases already has a number of applications in various areas. As a supercritical fluid, it is for instance used in the agribusiness, in the pharmaceutical field and in the cosmetic industry. This is due to its very unique physical properties.
The main properties of carbon dioxide are summarized as follows :

- ➔ Physical properties : high thermal conductivity, low dynamic viscosity, critical point (pressure : 73.8 bar, temperature : 304.25 K) among the lowest, low surface tension, high power density
- ➔ Environmental properties : zero ODP (Ozone Depletion Potential)
- ➔ Economics : approximately $15/m$^3$

Thermodynamic applications take advantage of its physical properties, as for compressions or expansions. Indeed, the required pressure ratio is then much lower when the transformation takes place in a vicinity of the critical point. This explains the extensive body of research that has been conducted on carbon dioxide.

*2.2 Thermodynamic cycle for 1MW pilot plant*

We construct our thermodynamic cycle in a T-s diagram, also called Hirn diagram, and we present the result on Fig. 2.

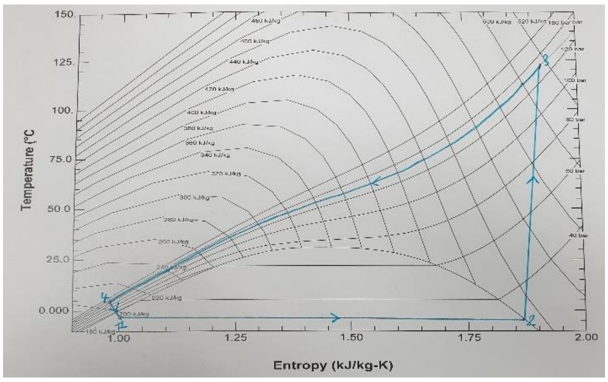


Fig. 2. Proposed Hirn diagram for a 1 MW pilot plant with a roundtrip efficiency of 53%

We explain the method for the charging phase, knowing that it is the same method when the system is used as a heat engine (discharging phase).
The states 1 to 4 and the corresponding transformations are introduced on Fig. 1. and recapped below :

- 1 -> 2 : $CO_2$ evaporation (ice generation ; isobaric transformation) ;
- 2 -> 3 : compression in the compressor (adiabatic and irreversible transformation) ;
- 3 -> 4 : $CO_2$ cooler (water heating ; isobaric transformation) ;
- 4 -> 1 : expansion in the expander (adiabatic and irreversible transformation)

The physical properties of the fluid (temperature, pressure, enthalpy, entropy, phase) at each state of the cycle are presented in Table I. The table is filled at each step following our method. The properties of each state are calculated thanks to the latest version of the database Refprop (REFerence fluid Properties) [5] provided by the National Institute of Standards and Technology NIST. This thermodynamic database was chosen because it belongs to the most accurate ones.

As mentioned in the Section 2.1, compressing or expanding supercritical $CO_2$ next to its critical point enables to reduce the work needed. Therefore, as a starting point to construct the cycle, we decide to set the states 1 and 2 under the saturation curve and close to the critical point (P=73.8 bar, T=31.1ºC). The physical properties of these two points are to be found in Table I. They are chosen based on the recommendations of Mercangöz et al. [4].

Table I. Physical properties at each state of the transcritical Rankine cycle

| State | Temperature (ºC) | Pressure (bar) | Enthalpy (kJ.kg$^{-1}$) | Entropy (kJ.kg$^{-1}$.K$^{-1}$) | Phase |
|---|---|---|---|---|---|
| 1 | -3 | 32.164 | 199.67 | 1 | two-phase |
| 2 | -2.8718 | 32.164 | 432.71 | 1.8626 | gas |
| 3is | 113.94 | 140 | 496.14 | 1.8626 | super-critical |
| 3 | 122.56 | 140 | 510.53 | 1.8994 | super-critical |
| 1is | -3.49 | 32.164 | 191.57 | 0.97 | liquid |
| 4 | 4.06 | 140 | 202.77 | 0.97 | liquid |

To access to the state 3, we start with the definition of the isentropic compressor efficiency introduced through (1) as :

$$\eta_{is,comp} = \frac{h_{3is} - h_2}{h_3 - h_2} = 0.815 \quad (1)$$

We use here the isentropic efficiency of the compressor and not the polytropic one because the first one only induces a little change in the final result, which can be neglected in a first approximation. The state 3is is achieved if the transformation 2 -> 3 were isentropic and not irreversible as it actually is. This means that the entropies of the states 2 and 3is are identical, an so are the pressure of the states 3 and 3is since the transformation 3 -> 4 is isobaric. For the pressure at these two states, we make the same choice as Mercangöz et al. [4], i.e. P=140 bar. Using the database Refprop [5] with the pressure and the enthalpy of the fluid at the state 3is, we can then obtain the missing properties at this state.

Finally, using an isentropic compressor efficiency of 0.815 as in [4], we find :

$$h_3 = h_2 + \frac{h_{3is} - h_2}{\eta_{is,comp}} = 432.71 + \frac{496.14 - 432.71}{0.815}$$

$$i.e.\ h_3 = 510.53\ kJ.kg^{-1}$$

Knowing the pressure and the enthalpy at the state 3, we infer the other physical properties of the fluid at this state. The last state is the state 4, which we can achieve through the expander isentropic efficiency, defined by (2) as :

$$\eta_{is,exp} = \frac{h_1 - h_4}{h_{1is} - h_4} = 0.86 \quad (2)$$

However, in order to find the enthalpy at the state 4, we must know the enthalpy at the state 1is, which is obtained if the transformation 4 -> 1 were isentropic. Consequently, the entropies of the states 4 and 1is are equal. To find the entropy at the state 1is, we take into account that the expander isentropic efficiency is quite high [4], meaning that the transformation 4 -> 1 is almost isentropic. It follows that the entropy at the state 1is is very close to the one at the state 1 and we take for this entropy the value 0.97 $\mathrm{kJ.kg^{-1}.K^{-1}}$. This enables us to find the enthalpy at the state 1is since the transformation 4 -> 1 is isobaric so the pressure at the state 1is is the one at the state 1. Calculating as before, we obtain the enthalpy at the state 4 and finally we know all the physical properties of the fluid at the state 4.

This approach gives a general idea on the cycle and its physical feasibility. However, the estimation of the entropy at the state 1is is not very accurate and can be improved by the use of an in-house made program. This will be achieve in future work.

Finally, we have to estimate the coefficient of performance of this heat pump. The coefficient is defined by (3) as follows :

$$COP = \frac{useful\ heat}{work\ required} = \frac{q_{34}}{w_{23}} = \frac{h_3 - h_4}{h_3 - h_2} \quad (3)$$

$$i.e.\ COP = \frac{510.53 - 202.77}{510.53 - 432.71} = 3.95$$

For a given mass flow rate, we can evaluate the duty linked to each transformation. The different duties are presented in Table II. We assumed a constant mass flow rate of 15 $\mathrm{kg.s^{-1}}$, which is a standard value for existing turbomachineries.

Table II. Duty associated to each transformation

| Transformation | Duty (MW) |
|---|---|
| 1 -> 2 | 3.50 |
| 2 -> 3 | 1.17 |
| 3 -> 4 | 4.62 |
| 4 -> 1 | 0.05 |

For the charging phase, we use a turbine with a nominal power of 1MW. To find the thermodynamic reverse cycle, we repeat the previous method and we finally obtain a thermal efficiency $\eta_C$ of 13%, which is quite low and could certainly be improved a lot.

The roundtrip efficiency is then given by the formula (4) :

$$\eta_{RT} = \frac{W_{out}}{W_{in}} = COP * \eta_C = 53\% \quad (4)$$

## 3. Conclusions

The Pumped Thermal Energy Storage system is a promising technology to increase the amount of energy produced from renewable sources by storing it for a latter use. This paper addresses the need of research on carbon dioxide used as a transcritical fluid in a Rankine cycle.

After presenting the main reasons for choosing carbon dioxide as a working fluid, we introduced the method used to obtain a basic and thermodynamic cycle, which is buildable with today's technologies. This cycle enables to produce 1MW of electricity with a roundtrip efficiency of 53%. This low efficiency can easily be improved by using more sophisticated turbomachineries with higher efficiencies.

Further work will first be dedicated to finding a cycle that would enable the PTES technology to compete even more with the Pumped Hydro Storage PHS technology. Namely, we will be seeking to construct a cycle producing at least 50 MW with a roundtrip efficiency of at least 65%. Furthermore, an exergo-analysis will be conducted to evaluate precisely the loss sources and evaluate the cost of 1MW produced by this system. Finally, this technology will be applied to a real case study since it has never been done before. This will enable to understand how useful this system can become in our world.

## REFERENCES

[1] Quaschning, Volker V. Renewable energy and climate change. Wiley, 2019.

[2] Chen H, Cong TN, Yang W, Tan C, Li Y, Ding Y. progress in electrical energy storage systems : a critical review. Prog Nat Sci 2009;19(3):291-312.

[3] Benato, Alberto. "Performance and cost evaluation of an innovative Pumped Thermal Electricity Storage power system." *Energy* 138 (2017): 419-436.

[4] Mercangöz, Mehmet, et al. "Electrothermal energy storage with transcritical CO2 cycles." *Energy* 45.1 (2012): 407-415.

[5] Lemmon, Eric W., Marcia L. Huber, and Mark O. McLinden. "NIST standard reference database 23." *NIST reference fluid thermodynamic and transport properties—REFPROP, Version*9 (2010): 55.