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Stanisław Sałyga, Łukasz Szabłowski*, Krzysztof Badyda

Energy analysis of underwater energy storage system based on compressed air

Institute of Heat Engineering, Warsaw University of Technology,
21/25 Nowowiejska, 00–665 Warsaw, Poland

Abstract

Due to the very intensive development of renewable energy sources, producing electricity in irregular and unpredictable way, storage plays an increasingly important role in the current energy system. Currently used systems for storing electricity on a large scale include only pumped storage and compressed air energy storage. The paper presents energy analysis of three underwater energy storage systems based on compressed air without recuperation, and with recuperation and adiabatic. Balance calculations for selected configuration of the system was performed. The efficiency of storage of electricity was calculated using four different definitions.

Keywords: UWCAES; CAES; Compressed air energy storage

1 Introduction

Currently there are only two methods of energy storage used on a large scale: pumped storage and compressed air energy storage(CAES). In the case of CAES power plant a huge volume tank is needed to store compressed air. CAES technology is relatively well known. Currently in the world there are two large objects of this type: Huntorf in Germany (290 MW) and McIntosh in the USA (110 MW). The first one was launched in 1978, while the second in 1991. Overview of the state of knowledge about the CAES technology was presented in [11–13,16,21].

In the [4] a hybrid systems using CAES in combination with renewable technologies (RT), e.g., wind turbines, was shown and possibility of CAES-RT loca-

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[*] Corresponding Author. Email address: lszablow@itc.pw.edu.pl

tion in Poland was presented. Dynamic mathematical model of CAES was also introduced [4,6].

An interesting alternative for the above mentioned systems is underwater compressed air energy storage (UWCAES), where the air is stored in underwater bags. The storage pressure in this case is constant and it depends only on the depth at which the compressed air storage were located.

In [8] the design parameters of the UWCAES in order to study their impact on the efficiency and exergy losses was analyzed. The greatest losses of exergy were generated in the process of compression and expansion of air. The system showed the greatest sensitivity to the efficiency of the above processes and to the depth of compressed air bags location. In turn, the authors of [7] have simulated numerically UWCAES system of 4 MWh capacity and analyzed it in terms of energy, exergy and exergoeconomics. For this purpose, multiobjective optimization method using a genetic algorithm was applied.

In [15], tests of specifically designed balloons for the underwater storage of compressed air were conducted. In the first experiment the balloons with a diameter of 1.8 m immersed in tanks of fresh water were examined. They were subjected to 400 cycles of charging and discharging proving adequate strength of the balloons. In the second trial balloons with a diameter of 5 m were immersed in sea water at a depth of 25 m. The test results showed that with the use of appropriate materials they can safely be used even in the sea water.

However, the authors of [18] dealt with the numerical simulation of flow around the underwater storage of compressed air using the methods of computer fluid dynamics.

The paper [19] presents a hybrid system to produce and store the electricity consisting of the underwater CAES (UWCAES), whose tanks were mounted in such a way that they can simultaneously produce electricity from sea waves (VIVACE – vortex induced vibration aquatic clean energy).

In turn, the work [20] simulate hydrodynamic loads acting on tanks for underwater storage of compressed air. In this paper energy analysis of three underwater energy storage systems (without recuperation, with recuperation and adiabatic) based on compressed air was presented.

2 Methods and materials

The calculations shown in the following paragraph were done in commercial software [2,10]. The model of the working medium relied on Peng-Robinson equation of state [14]:

$$p = \frac{RT}{v-b} - \frac{a\,(T)}{v\,(v+b) + b\,(v-b)}\ , \tag{1}$$

where: p – pressure, R – gas constant, T – absolute temperature, v – molar volume, a – attraction parameter, b – van der Waals covolume.

There are several ways to describe the efficiency of compressed air energy storage systems the following describes four of them [4–6]:

$$\eta_{CAES\,I} = \frac{E_{el\,g}}{E_{el\,c} + Q_f}\ , \tag{2}$$

$$\eta_{CAES\,II} = \frac{E_{el\,g} - E_{el\,c}}{Q_f}\ , \tag{3}$$

$$\eta_{CAES\,III} = \frac{E_{el\,g}}{\frac{E_{el\,c}}{\eta_{el\,R}\cdot\eta_{tr}} + Q_f}\ , \tag{4}$$

$$\eta_{CAES\,IV} = \frac{1 - HR\,\eta_{gas}}{ER_{net}}\ , \tag{5}$$

where: $E_{el\,g}$ – energy from electric generator, $E_{el\,c}$ – energy consumed by compressor, Q_f – chemical energy of fuel (0 in adiabatic systems), $\eta_{el\,R}$ – efficiency of reference power plant (for purposes of this article 42% was assumed), η_{tr} – efficiency of power transmission to the CAES power plant (90% was assumed), HR – heat rate for gas turbine only ($Q_f/E_{el\,g}$), η_{gas} – the efficiency of conversion of chemical energy into electrical energy (36.9% – for heat rate of simple cycle of gas turbine equal to 9743 kJ/kWh [9]), $ER_{net} = E_{el\,c}/E_{el\,g}$.

Equation (5) is less used – more on this can be found in [9]. More about modeling of CAES systems can be found in [17].

3 Description of model

The model was built using commercial Aspen HYSYS software [2,10]. Air composition were shown in Tab. 1. The energy storage system is charged during the valleys of load of the power system and discharged at peaks. As a working medium in a heat store Therminol 55 oil was used. It is a synthetic oil used in the heat storage system [3] and its operating range is -28 °C–15 °C [1]. Fuel used in the simulation (excluding adiabatic system) was methane with a lower heating value of 50035 kJ/kg.

Table 1: Mass composition of air

Component	%wt
Oxygen	23.052
Nitrogen	74.990
Carbon dioxide	0.046
Argon	1.276
Water	0.636

3.1 UWCAES without recuperation

Loading part of the system (Fig. 1) consists of three parts of compressor with a total capacity of 45 MW. Behind the first and the second parts of the compressor are intercoolers (Cooler_1, Cooler_2), which cool the compressed air to temperature of 25 °C. Behind the last part of the compressor is aftercooler, which lowers the temperature of the air being directed to the underwater tank to 4 °C (in this way was also included the process of cooling compressed air through the wall of the balloon to the temperature of the surrounding water). The heat received in the cooler is dissipated to the environment. After coolers moisture separators (Moisture separator_1, Moisture separator_2, Moisture separator_3) are installed to collect water from compressed air. This prevents condensation of water in the next stage of the compressor and in underwater balloons.

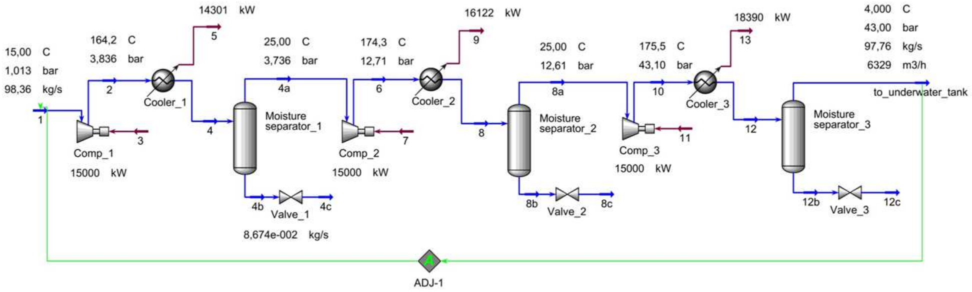

Figure 1: Loading of UWCAES system.

Polytropic efficiencies of compressors are: 90% (Comp_1) and 85% (Comp_2 and Comp_3). Pressure drop of each heat exchanger is 0.001 MPa. Pressure drops on pipelines and moisture separators have been omitted in the calculations.

As a compressed air storage tanks of constant pressure were used. In real life, this is realized with the help of underwater balloons. It was assumed that the working pressure compressed air storage was 4.3 MPa. It means that the tank would have to be located at a depth of less than 400 m. The temperature at this depth is approx. 4 °C, because of that it was assumed that the air directed to balloons was cooled to that temperature.

Unloading part (Fig. 2) consists of high pressure turbine (Turbine_1) and low pressure turbine (Turbine_2) of polytropic efficiencies of 80% and two combustion chambers (Combustion chamber_1, Combustion chamber_2). The combustion chambers are fulled with methane of a temperature of 15 °C. The high pressure gas turbine part operates at a constant pressure of 4.3 MPa at the inlet and 1.1 MPa at the outlet. At the outlet of low pressure part of gas turbine is ambient pressure.

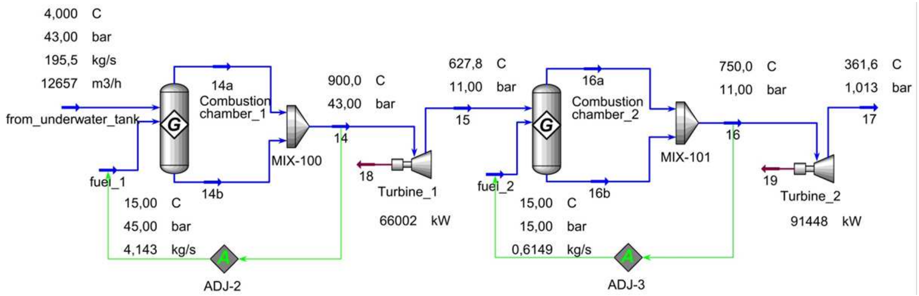

Figure 2: Unloading of UWCAES without recuperation (combustion chamber modeled as Gibbs reactor (G) and mixer (MIX); the temperatures after combustion chambers were adjusted using ADJ tool in HYSYS by changing fuel flow).

The main assumptions for the gas turbine:

- air pressure from the storage – 4.3 MPa
- inlet temperature to high pressure turbine (Turbine_1) – 900 °C
- outlet pressure of high pressure turbine – 1.1 MPa
- polytropic efficiency of turbines – 80%
- inlet temperature to low pressure turbine (Turbine_2) – 750 °C
- outlet pressure of low pressure turbine – ambient pressure – 0.1013 MPa.

In order to determine the mass flow of air fed to the turbine and the volume of the underwater vessel it was assumed that the system is charged in 6 h and discharged in 3 h. In such a case, the volume of the compressed air tank is 37 974 m^3 and during the process of charging the reservoir receives 2 112 Mg of air. During unloading process underwater tank releases 195.5 kg/s of air of a pressure of 4.3 MPa. In order to achieve the appropriate temperatures of the working medium before each of the turbine part the combustion chambers consume 4.76 kg/s of fuel, which means a chemical power equal to 238 MW. The power of gas turbine in the same time is 157.5 MW.

3.2 UWCAES with recuperation

Based on the model presented in subsection 3.1 a model of UWCAES system with a recuperative heat exchanger was built. Assumptions about the ambient parameters, work cycle, compressor power and polytropic efficiencies of turbines and compressors have been adopted as outlined in the above mentioned subsection. Recuperative heat exchanger was modeled using the concept of the degree of regeneration of gas turbine $\sigma = 0.6$ ($\sigma = (T_{13} - T_{from\_underwater\_tank})/(T_{19a} - T_{from\_underwater\_tank})$, where symbols T are temperatures in K according to Fig. 3).

The unloading part of the system was shown in Fig. 3. The results presented there reflects the state of the system during the process of discharging the compressed air storage.

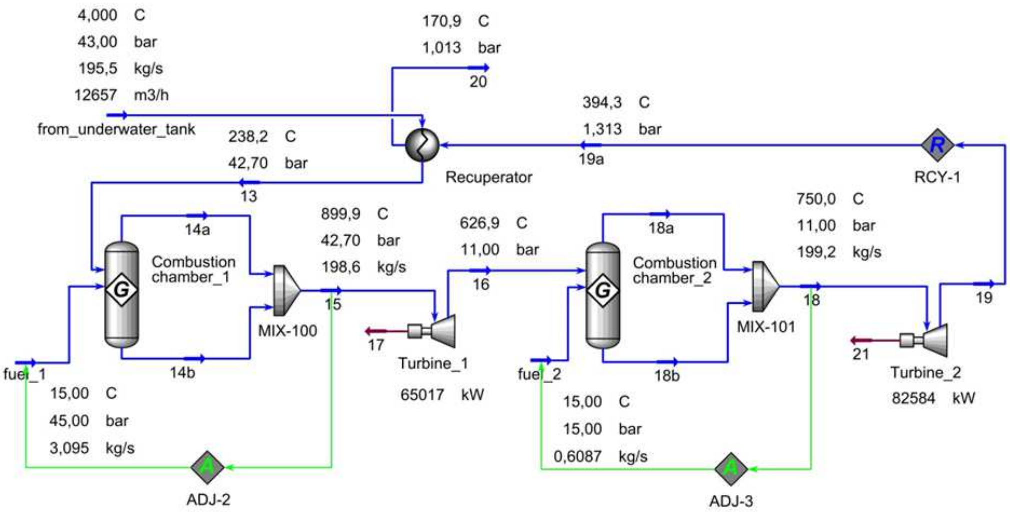

Figure 3: Unloading of UWCAES with recuperation (recycle (R, RCY) is a tool in HYSYS which allows to calculate using iterations).

The use of recuperative heat exchanger required introduction of pressure loss on flows of air and exhaust gases. It was assumed that the pressure loss is 0.003 MPa. This resulted in some modifications of turbine operation. In particular, the exhaust gas pressure directed to the turbine was 4.27 MPa, and the pressure after expansion on last part of the turbine was 0.1313 MPa.

Charging and discharging time was the same as for the previous case. In the process of discharging the compressed air storage system consumes 3.7 kg/s of fuel (185 MW of chemical power) and the gas turbine generate 147.6 MW.

3.3 Adiabatic UWCAES

Scheme of loading part was illustrated in Fig. 4, while unloading part – in Fig. 5. The volume of compressed air tanks is here the same as for previous two cases. Charging and discharging times are 6 and 3 h, respectively. The principle of operation of the adiabatic system differs from previous cases in that the heat from the compression process is stored here. In the case of this model thermal oil Therminol 55 was used. Polytropic efficiency of compressors is 90% (Comp_1) and 85% (Comp_2).

Heat storage consist of two parts: high temperature and low temperature part. Each of them has two tanks of oil: cold and hot. In high temperature storage the oil has a temperature of 280 °C and 40 °C, while in the low temperature part 67 °C and 15°C. During loading the compressed air reservoir oil is pumped from cold to a hot tanks to cool the air. During emptying underwater balloons from the compressed air the oil is pumped from hot to cold tanks to heat the air before turbines. In high temperature storage is 1576.8 Mg of oil, while in low temperature storage 1296 Mg of the same thermal oil.

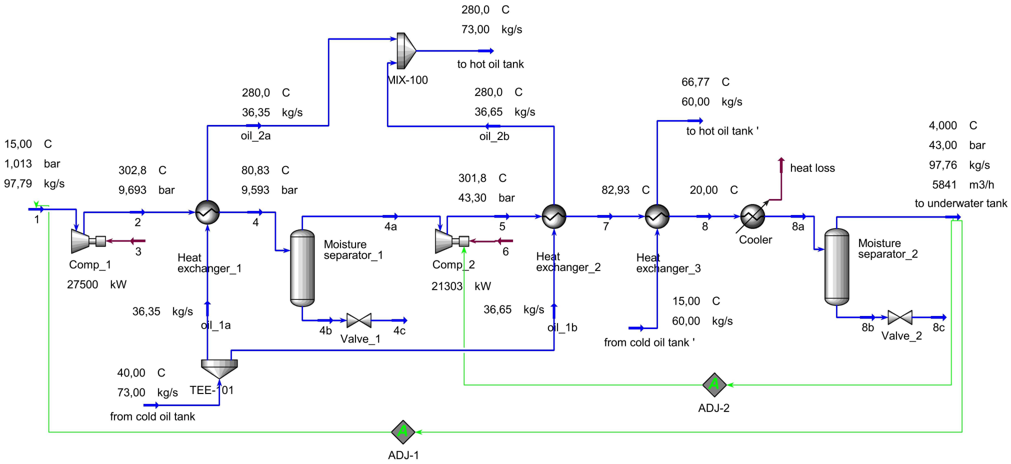

Figure 4: Loading of adiabatic UWCAES system.

Polytropic efficiency of each turbine is 80% and pressure drop on every heat exchanger is 0.001 MPa at air side.

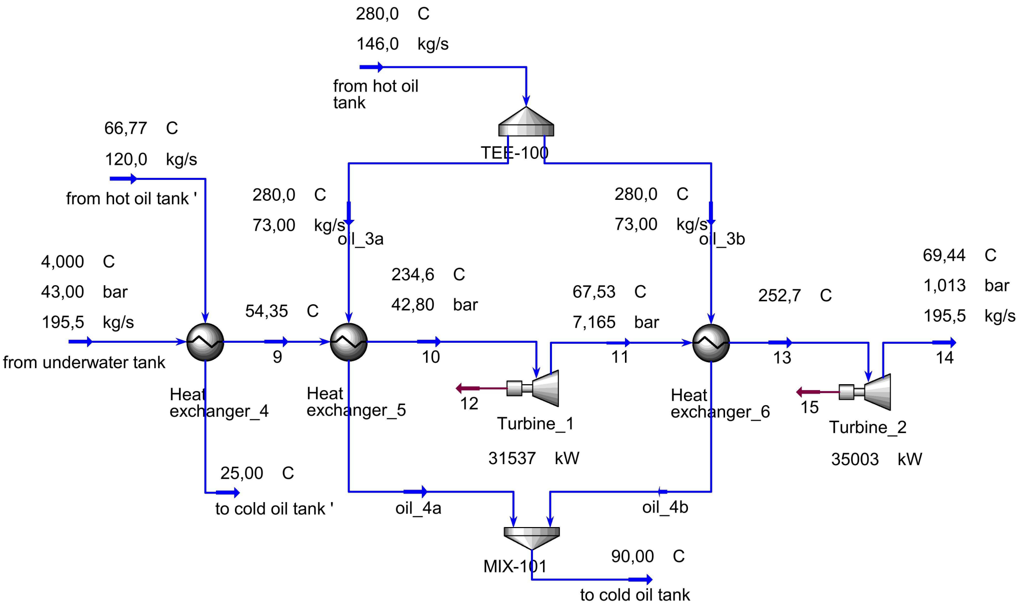

Figure 5: Unloading of adiabatic UWCAES system.

4 Results

The results of the simulation are shown in Tabs. 2 and 3.

Table 2: Energy consumption/generation for UWCAES: without recuperation – I, with recuperation – II, adiabatic – III

Energy	I	II	III
$E_{el\,c}$, MWh	270.0	270.0	292.82
$E_{el\,g}$, MWh	472.5	442.8	199.619
Q_f, MWh	714.2	555.9	0

Due to the weaker cooling of air during the compression process for the case III (in comparison to cases I and II) compressing the same amount the medium requires more energy. It should be also emphasized that during discharging the adiabatic system a smaller amount of energy is generated, but due to the lack of chemical energy, Q_f, the efficiency (according to Eq. (2)) is better (see Tab. 3). As a result of the recuperation fuel flow for the case II is considerably lower than for the case I, which increased the efficiency of the system II in relation to the I (by all the definitions).

Table 3: Gross efficiency of UWCAES: without recuperation – I, with recuperation – II, adiabatic – III

Gross efficiency	I	II	III
$\eta_{CAES\,I}$, %	48.0	53.6	68.17
$\eta_{CAES\,II}$, %	33.1	34.9	N/A
$\eta_{CAES\,III}$, %	28.4	31.1	25.77
$\eta_{CAES\,IV}$, %	77.5	87.7	68.17

Due to the lack of Q_f, in the case of an adiabatic system, result from formula (5) is the same as from Eq. (2). Definition (3) is not applicable for adiabatic CAES (dividing by zero). Result from formula (4) is worse than for conventional CAES system (with Q_f) – this means that definition 4 should not be used for adiabatic CAES.

5 Conclusions

In order to compare all three systems the same volume of compressed air reservoir was used. During unloading the biggest amount of energy was generated in the system I. For the case II it was slightly smaller (due to the pressure drop across the recuperative heat exchanger). In the case of adiabatic system we have the smallest amount of energy during discharging, but the greatest efficiency (according do definition 2). The efficiency of the system with recuperation was bigger than the same parameter for the classic system I. As a result of a very good cooling of air in cases I and II, the amount of energy taken during the compression is lower than for the adiabatic system.

The use of system I is recommended when the reliability, high power and also quick start is required. Other systems are better from the point of view of efficiency.

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