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System Modelling of a Combined Air and Hydro Energy Storage System

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Energy storage technologies are playing an essential role in recent decades due to the increased penetration of renewable power. Compressed air energy storage (CAES) is among the most promising energy storage technologies. However, conventional CAES system has two main drawbacks, i.e. the heat loss during air compressing and variable working condition during expansion caused by air pressure drop. In this paper, a combined air and hydro energy storage (CAHES) system is proposed and simulated. The system realizes isothermal compression during charging through enhanced heat transfer in an external heat exchanger, and reduces air pressure drop during expansion through heat compensation. Simulation results show that the exergy efficiency of a typical CAHES system reaches 65.3 %, which is significantly higher than a conventional CAES system. Two major influencing factors on system efficiency and energy density are compression volume ratio and allowed pressure drop during expansion.

1. Introduction

Renewable energy has been brought to the forefront in recent decades as one of the most promising technology pathways in reducing CO_2 emissions (Krajacic et al., 2010). According to predictions by (IEA, 2014), the share of global renewable electricity generation will increase from less than 10 % in 2010 to about 35 % in 2050. Despite of its environmental friendliness, some inherent disadvantages of renewable energy have restricted its application, one of which is its strong fluctuation, causing technological difficulties in grid connection.

Energy storage technologies provide solutions to this problem through stabilizing power generation and improving power qualities (Mohammad Rozali et al., 2013). They are regarded as indispensable components in the development and large-scale application of renewables. Compressed air energy storage (CAES) is one of the potential large-scale energy storage technologies because of its less stringent geographic requirement, high technological maturity as well as low capital cost (Yang et al., 2014).

However, a conventional CAES system has two major disadvantages: the heat loss during compressing and variable working condition, both leading to system efficiency reduction. To address the problem of heat loss, three types of measures have been proposed in literature, including AACAES system (Hartmann et al., 2012), isothermal compressing (Iglesias and Favrat, 2014) and air reheating using renewables (Beukes et al., 2008). However, these measures have not solved the problem perfectly. The problem of variable working condition is usually solved by water compensation (Kim et al., 2011), but problems also exist with these measures.

In this paper, a combined air and hydro energy storage (CAHES) system is proposed. The system realizes isothermal compression through enhanced heat transfer in an external heat exchanger, and avoids variable working condition through heat compensation. In the following sections, detailed operating procedures of the CAHES system are presented. Different performance indices of the system are defined, calculated and compared with a conventional CAES system. The influences of compression volume ratio and allowed pressure drop during expansion on the performance of the CAHES system are also investigated.

2. The combined air and hydro energy storage system

A CAHES system is composed of a base system and an additional heating/cooling system as shown in Figure 1. The base system consists of four main components: a vessel, a hydro turbine, a pump and a water sink. The additional heating/cooling system consists of three main components: a heat exchanger, a solar collector and a heating/cooling medium tank.

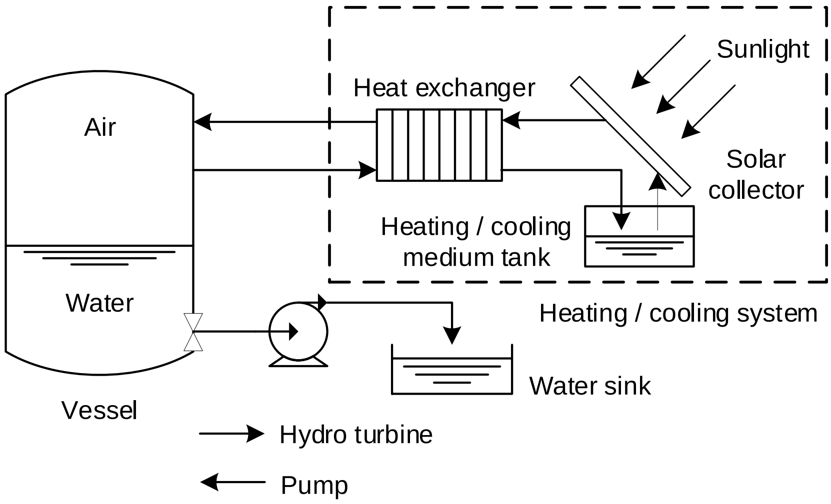

Figure 1: Schematic of a CAHES system

During charging, the surplus electricity drives the pump to extract water from the water sink into the vessel. The air within the vessel is compressed and electric power is by this means converted to pressure energy held by the pressurized air. Meanwhile, an external heat exchanger is adopted, where cooling medium at ambient temperature absorbs the compression heat and cools down the compressed air. The cooling process makes it possible to maintain the air compression process isothermal, leading to higher air density and thus higher energy density of the system.
During discharging, the compressed air in the vessel expands and drives the water through the hydro turbine to generate power. In this process, the external heat exchanger is used for heating up the expanded air by heat-transfer medium carrying the collected solar energy. The heat that the air absorbs would partly or fully compensate for the pressure decrease caused by expansion, and thus to enable a quasi-isobaric or isobaric generating process.

3. Case study

3.1 System performance indices

The proposed CAHES system has two types of energy inputs: electricity during charging process and solar radiation during discharging process. The efficiency of this multi-input system is more complicated to evaluate than those with a single energy input, owing to different grades of energy inputs. It’s difficult to describe the system efficiency via a universally applicable index.
In this paper, three different efficiency indices are adopted, including the simplest efficiency, charging electricity ratio (Succar and Williams, 2008) and the exergy efficiency. The simplest efficiency is defined as the ratio of total energy output to total energy input, disregarding the grades of different types of energy. The charging electricity ratio is defined as the ratio of the system electricity output to electricity input. The exergy efficiency is defined as the ratio of system exergy input to exergy output. For the proposed CAHES system, the simplest efficiency, charging electricity ratio and the exergy efficiency are defined in Eq(1) to Eq(3)

$$\eta_s = W_{hy\_tur} / (W_{pump} + Q_{solar}) \tag{1}$$

$$CER = W_{hy\_tur} / W_{pump} \tag{2}$$

$$\eta_{ex,CAHES} = W_{hy\_tur} / (W_{pump} + Q_{ex}) \quad (3)$$

Apart from efficiency, energy density is another paramount index for energy storage systems. For the proposed CAHES system, the output energy density is defined as the ratio of the hydro turbine power generation to the vessel volume.

3.2 Base case

First of all, a baseline model is established in Matlab-Simulink. Some important geometrical and thermal dynamic settings in the model are listed in Table 1. It can be deducted from the settings that the air compression volume ratio is 2, and allowed percentage of air pressure drop during discharging is 30 % in the baseline model.

Table 1: Geometrical and thermal dynamic settings in the model

State	Air volume [m³]	Temperature [°C]	Pressure [MPa]
1 (before charging)	1,000	25	5
2 (after charging/before discharging)	500	25	10
3 (after discharging)	1,000	133	7

In the model, the efficiency of pump and hydro turbine are represented by two quadratic curves.

$$\eta_{hy\_tur} = -3\theta^2 + 6\theta - 2.07 \quad (4)$$

$$\eta_{pump} = -2\theta^2 + 4\theta - 1.1 \quad (5)$$

where is the ratio of real head and design head.

The simulation results of the baseline CAHES system are presented in Table 2 in comparison to a conventional CAES system. The thermal efficiency of the solar collector is assumed to be 90 %. The performance indices of the traditional CAES system are calculated based on data given by (Kondoh et al., 2000). According to their study, a traditional CAES system requires 0.8 kWh electricity and 4,100 Btu (about 1.2 kWh) fuel to produce 1 kWh electricity, and the output power density is about 4 kWh/m³. The exergy of the fuel is about 93 % of the fuel's lower heating value.

Table 2: Simulation results of the CAHES system and comparison with CAES system

System performance	CAHES	CAES
Simplest efficiency	27.7 %	50 %
CER	90.7 %	125 %
Exergy efficiency	65.3 %	53.2 %
Energy density (kWh/m^3)	1.05	4

In the CAHES system, solar energy serves as an external heat source, featuring low temperature and energy density. Due to the low grade energy input, the CAHES system's simplest efficiency, CER and energy density are lower than those of the CAES system. However, in terms of exergy efficiency, which is considered to be a more reasonable index from the perspective of second law of thermodynamics, the CAHES system has a better performance than the CAES system.

3.3 Influencing factors

As discussed above, the two types of system performance indices are efficiency and energy density, and the main influencing factors are air compression volume ratio β and allowed percentage of pressure drop λ. The influence of β and λ on system exergy efficiency is shown in Figure 2 (left). For a given λ, when β increases, pump head varies more drastically during the charging process, causing the pump efficiency to drop. Therefore, the system exergy efficiency decreases. For a given β, the exergy efficiency increases with increasing λ at the beginning, but starts to decrease after reaching a peak value. The reason is that, increasing λ actually has both positive and negative effects on the system exergy efficiency, which mutually result in the peak value of the exergy efficiency. On the one hand, when λ increases, the required temperature as well as the amount of solar energy both diminish, causing significant decrease of the required solar energy exergy, so the system exergy efficiency increases. On the other hand, the increase of λ leads to larger hydro turbine head variation and lower the hydro turbine efficiency, thus the system exergy efficiency decreases.

The influence of β and λ on system energy density is shown in Figure 2 (right). For a given λ, increasing β means that a certain amount of compressed air expands to a larger volume and lower pressure, and thus releases more energy. For a given β, increasing λ means that the compressed air absorbs more solar energy to maintain the original high pressure and therefore generates more power.

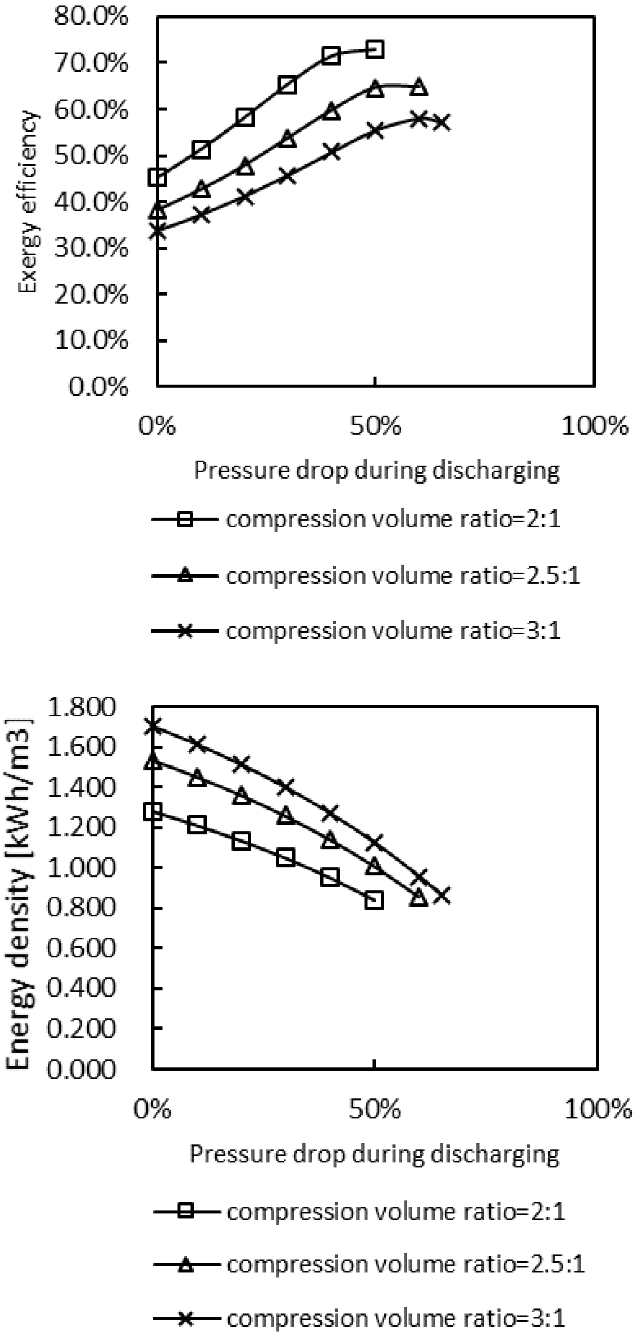

Figure 2: Influence of compression volume ratio and allowed percentage of pressure drop on exergy efficiency and energy efficiency

Based on the analysis above, it can be found out that the increase or decrease of β and λ generally have opposite impacts on system efficiency and energy density. In can be concluded that efficiency and energy density are two contradictory indices of the system performance. The relationship of exergy efficiency and energy density with different β and λ are shown in Figure 3.

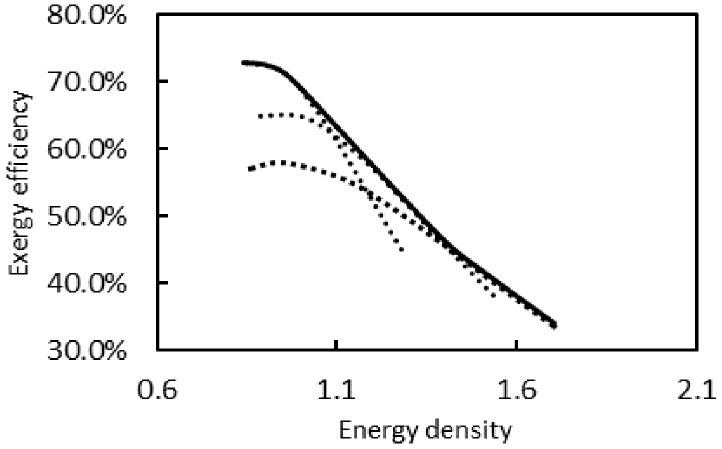

Figure 3: Relationship between exergy efficiency and energy density

In Figure 3, the dashed curves represent the relationship of exergy efficiency with energy density for three given β. The intersections indicate that the combinations of different λ and β can result in an exact same system performance. The solid curve is the envelope of the dashed curves and represent the optimal performance of the proposed CAHES system. For systems requiring high efficiency, systems with small compression volume ratio β and large pressure drop λ is recommended, while for systems requiring high energy density, the opposite is preferred.

4. Conclusions

In this paper, a novel combined air and hydro energy storage system (CAHES) is proposed. The system realizes an isothermal compressing process during charging through enhanced heat transfer in an external heat exchanger, and a quasi-isobaric expansion process during discharging through thermal compensation from solar radiation. The proposed CAHES system has two major advantages over the conventional CAES system:

(1) The exergy efficiency of a typical CAHES system reaches 65 %, which is more than 10 percentage higher than a conventional CAES system

(2) By utilizing the solar energy, the CAHES system eliminates the consumption of fossil fuels and thereby avoids emission of carbon dioxide

Two types of indices, efficiency and energy density have been used to evaluate the system performance, and the influence of compression volume ratio as well as allowed pressure drop on the system performance has been investigated. It’s found that the two indices are to some extent contradictory. For systems with different requirements on efficiency and energy density, different compression volume ratio and allowed pressure drop should be adopted.

References

Beukes J., Jacobs T., Derby J., Conlon R., Henshaw I., 2008, Suitability of compressed air energy storage technology for electricity utility standby power applications, IEEE 30th International. IEEE 2008, 1-4.

Hartmann N., Vöhringer O., Kruck C., Eltrop L., 2012, Simulation and analysis of different adiabatic compressed air energy storage plant configurations, Applied Energy, 93, 541-548.

IEA (International energy agency), 2012, <www.eia.gov/electricity/annual/html/epa_08_01.html> accessed 29.01.2015

Iglesias A., Favrat D., 2014, Innovative isothermal oil-free co-rotating scroll compressor–expander for energy storage with first expander tests, Energy Conversion and Management, 85, 565-572.

Kim Y.M., Shin D.G., Favrat D., 2011, Operating characteristics of constant-pressure compressed air energy storage (CAES) system combined with pumped hydro storage based on energy and exergy analysis, Energy 36(10), 6220-6233.

Kondoh J., Ishii I., Yamaguchi H., Murata A., 2000, Electrical energy storage systems for energy networks, Energy Conversion & Management, 41, 1863-1874.

Krajacic G., Duic N., Mathiesen B.V., Carvalho M.D.G., 2010, Smart Energy Storages for Integration of Renewables in 100% Independent Energy Systems, Chemical Engineering Transactions, 21, 391-396.

Mohammad Rozali N.E., Wan Alwi S.R., Manan Z.A., Klemeš J.J., Hassan M.Y., 2013, Optimisation of pumped-hydro storage system for hybrid power system using power pinch analysis, Chemical Engineering Transactions, 35, 85-90.

Succar S., Williams R.H., 2008, Compressed air energy storage: theory, resources, and applications for wind power, Princeton Environmental Institute, Princeton, NJ, USA.

Yang Z., Wang Z., Ran P., Li Z., Ni W., 2014, Thermodynamic analysis of a hybrid thermal-compressed air energy storage system for the integration of wind power, Applied Thermal Engineering 66, 519-527.