Applied Energy Symposium 2019: Low carbon cities and urban energy systems
October 16-18, 2019, Xiamen, China
Paper ID: 0146

THERMODYNAMIC ANALYSIS OF AN ADIABATIC COMPRESSED AIR ENERGY STORAGE (A-CAES) SYSTEM FOR COGENERATION OF POWER AND COOLING ON THE BASE OF VOLATILE FLUID

Long-Xiang Chen [1], Mei-Na Xie [2], Feng-Xiang Wang [1,*]

1 Quanzhou Institute of Equipment Manufacturing, Haixi Institutes, Chinese Academy of Sciences, Jinjiang 362000, China

2 School of Energy Research, Xiamen University, Xiamen 361005, China

ABSTRACT

In our previous work, a novel isobaric adiabatic compressed air energy storage (IA-CAES) system has been proposed on the base of volatile fluid, while large amount of waste heat should be employed to offer the energy required in the evaporation, which may restrict its applications. In this work, a novel adiabatic compressed air energy storage (A-CAES) system is proposed which is also based on the volatile fluid while without using waste heat. Carbon dioxide (CO_2) is selected as the volatile fluid. The stead-state mathematical model and thermodynamic laws are employed to evaluate proposed system. The calculation results show that our proposed A-CAES system has the same round trip efficiency (RTE) with conventional one, while more than 30% additional cooling energy can be obtained and the total exergy efficiency (TEE) improves more than 2%. For a given total power generation (4 MW·h), the total volume of air storage unit in proposed A-CAES is only accounts for 60.97% of that in conventional A-CAES.

Keywords: Adiabatic Compressed air energy storage; Cogeneration; Carbon dioxide; Volatile fluid; Thermodynamic analysis.

NONMENCLATURE

Symbols

T	temperature, K
P	pressure, kPa
h	specific enthalpy, kJ/kg
$\dot{W}$	work input rate, kW
$\dot{m}$	mass flow rate, kg/s
W	work, kJ
n	number
Q	heat flow, kJ

Subscripts

in	inlet
out	outlet
c	compression process
e	expansion process
0	ambient conditions
com	compressor
exp	expander
v	volatile fluid
L	liquid
gen	generation
char	charge
disc	discharge
elec	electricity

Acronyms

ASU	air storage unit
ASV	air storage vessel
VSV	volatile fluid storage vessel
AC	after-cooler
IC	Inter-cooler
LC	low pressure compressor
HC	high pressure compressor
LT	low pressure turbine
HT	high pressure turbine
HE	heat exchanger
PH	pre-heater
IH	inlet-heater
TV	throttling valve
M	motor
G	generator
RTE	round trip efficiency
COP	coefficient of performance
TEE	total exergy efficiency

Greek letters

π	pressure ratio
η	isentropic efficiency

1. INTRODUCTION

Using renewable energy is an efficient way to address the environmental problems caused by growing fossil fuels consumption [1]. Integration of renewable energy into existing electricity grids directly may cause grids unstable due to unpredictable and intermittent characteristics of renewable energy [2]. The introducing of energy storage system (ESS) system can give a relevant contribution in solving above problems.

Compressed air energy storage (CAES) is a promising storage technology with high energy storage capacity and power rating [3]. In CAES, ambient air is compressed using surplus or intermittent electricity, then stored in underground hard-rock or salt caverns or artificial storage vessels during low demand period. During high demand period, compressed air releases out from the storage vessels, heated and expands in turbines to generate power [4].

In conventional CAES, air is heated in a combustion chamber burning conventional fossil fuels before expansion, resulting in CO_2 emissions. Moreover, it suffers from low round trip efficiency (~40 to 50%) due to exergy losses in gas compressors and turbines [5]. To address above problems adiabatic CAES (A-CAES) has been proposed. In A-CAES, an additional thermal energy storage (TES) unit is introduced to absorb the heat of compression in charging process. In discharging process the air is heated by TES unit instead of combustion chamber before flows into turbines to generate power. Hence fuel consumption is avoided and the round trip efficiency in the range 60-70% can be achieved [6].

More recently, the development of A-CAES is ongoing, many technologies are introduced in A-CAES for different applications, such as tri-generation CAES [7], low-temperature adiabatic CAES [8] and isobaric A-CAES [9].

In our previous work [10], a novel IA-CAES was proposed based on the volatile fluid (condensable gas). The main differences between IA-CAES and conventional A-CAES system are in the air storage vessels. In IA-CAES, the air storage vessels are divided into two parts by the pistons, one part for air storage and the other part filled with a suitable volatile fluid. CO_2 is selected as volatile fluid. In charging process, CO_2 is compressed by piston then liquefied, while waste heat is utilized to support the energy required in gasification of CO_2 in discharging process. Although, the IA-CAES shows a high total exergy efficiency, while the RTE is lower than 40% due to large amount of waste heat should be required, which may restrict its applications.

In this work, a modified A-CAES is proposed also based on the volatile fluid while without using the waste heat. Pistons in previous work are replaced by bladders, which greatly reduce the cost of manufacturing process of air storage vessels due to seal between the vessel wall and piston needn't be considered. Moreover, proposed A-CAES has the ability to cogenerate electricity and cooling energy. The thermodynamic analysis are evaluated by using steady-state mathematical model and thermodynamic laws.

2. SYSTEM DESCRIPTION

Fig. 1 and Fig. 2 demonstrate the schematic diagrams of charging and discharging process of conventional A-CAES systems, respectively. The operating principles of conventional A-CAES is fairly simple.

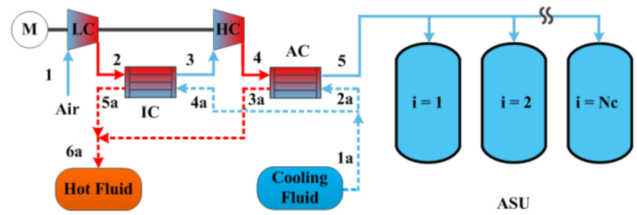

Fig. 1. Schematic diagram of conventional A-CAES system in charging process.

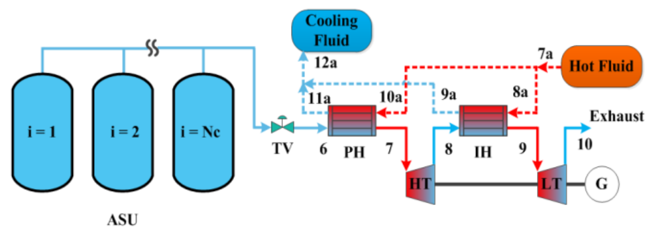

Fig. 2. Schematic diagram of conventional A-CAES system in discharging process.

In the charging process, renewable energy or surplus electricity is used to drive a 2-stage compression train (LC and HC). Air from the ambient is compressed to a high pressure and stored in a serious of artificial air storage vessels. After each compressions, the heat from compressed air is absorbed by the thermal fluid and stored in the thermal energy storage (TES) unit for later use.

In discharging process, compressed air in the storage vessels is throttled to a given pressure through a throttling valve (TV). The heat from the TES unit is employed to heat the compressed air to a high temperature in the pre-heater (PH), then it flows into the high pressure turbine (HT) and expands to generate electricity. Finally, the compressed air is reheated in inter-heater (IH) and expands in low pressure turbine (LT) to generate power.

The operating principles of proposed A-CAES system are almost the same with conventional A-CAES system, except for that in air storage unit (ASU). In conventional A-CAES, the ASU is consisted with a series

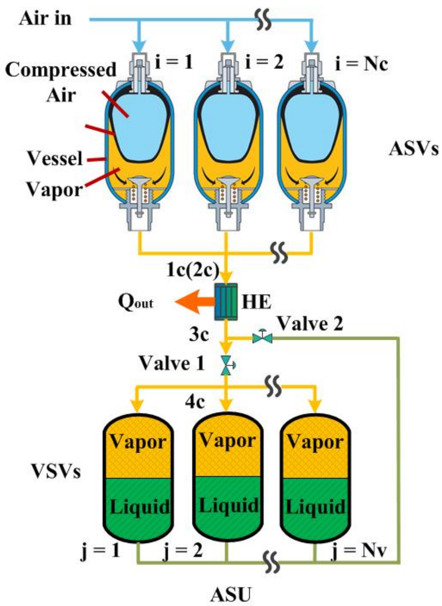

Fig. 3. Schematic diagram of ASU for proposed A-CAES in charging process.

of normal air storage vessels (ASVs) which are made by steel only. However, as seen in Fig. 3, both normal storage vessels and modified vessels are used. The modified storage vessels have been divided into two parts by the bladders, one part for air storage and the other part is charged with amount of volatile fluid and connected to the normal storage vessels. Carbon dioxide (CO_2) is proposed as volatile fluid in this work, due to its environmentally properties and high saturation pressure at ambient temperature.

Fig. 4 shows the T-s diagram of CO_2 in ASU in both charging and discharging process. In charging process, firstly, both valve 1 and valve 2 are switched off. When the compressed air is charged into ASVs, the bladder is pushed by the compressed air then it compresses the CO_2 from ambient temperature (state 1c) to a high temperature (state 2c). The compression process of CO_2 is regarded as isentropic process. Then the high pressure and high temperature CO_2 is cooled to near ambient temperature and liquefied (state 3c) in the heat exchanger (HE). After that, valve 1 is switched on and the liquid CO_2 is throttled to a lower pressure. At this moment, the CO_2 is at the two phase region (state 4c) and stored in volatile fluid storage vessels (VSVs), which are a serious of normal vessels without bladders. When the ASVs are full filled with compressed air, the charging process end.

In discharging process, firstly both valve 1 and valve 2 are switched off, the compressed air in the ASVs is released from high pressure (7.4 MPa) to a suitable pressure (4.2 MPa). Then the valve 2 is switched on and the liquid CO_2 (state 1d) is throttled to 4.2 MPa which aims to push the compressed air out of the storage vessels

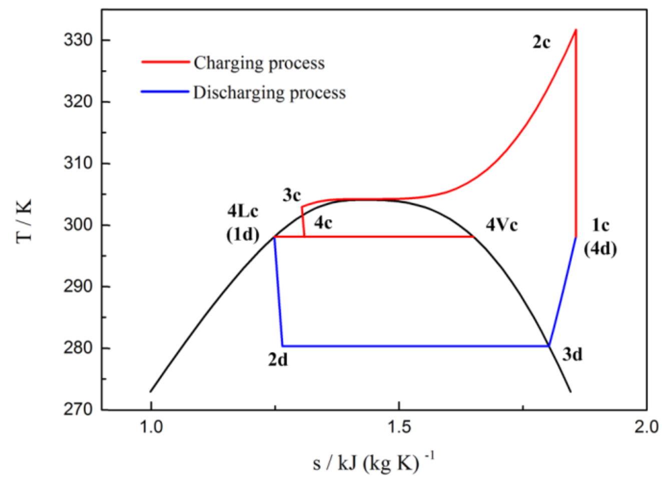

Fig. 4. T-s diagram for volatile fluid in ASU.

at its operating pressure. After that, the CO_2 evaporates at the temperature 280.37 K (about 7 ℃, state 2d to state 3d), in this way partial of cooling energy can be obtained. The discharging process end when the compressed air is fully replaced by the CO_2. Finally, the CO_2 in the ASVs is heated to ambient temperature (state 1c/4d) in the idle time.

3. THERMODYNAMIC ANALYSES

The following assumptions are made to simplify the analysis of conventional A-CAES and proposed A-CAES systems.

(1) The composition of air in two CAES systems consist of 77% N_2 and 23% O_2 (mass fraction).
(2) The heat and pressure loss in the pipes connecting all the components can be negligible.
(3) The systems in any operation mode reach steady state.
(4) Outlet temperature of the AC and IC are always 20K higher than ambient temperature.
(5) The throttling process is isenthalpic.
(6) All the kinetic and potential effects are ignored.
(7) The storage tank is adiabatic during changing and discharging process.
(8) The electric efficiency of the compressor motor and of the expander generator is equal to one.

3.1 Energy analysis and exergy analysis

Energy analysis is associated with the first law of thermodynamics through energy balances and energy efficiencies. Energy analysis method alone is not enough to express all the aspects of energy utilization processes of a system. Exergy analysis is based on the second law of thermodynamics and it can present more meaningful and useful information than energy analysis. Hence, in this work both energy analysis and exergy analysis are evaluated. The calculation models of both energy and exergy for main components of A-CAES are shown in Table 1.

Table 1 Calculation models for A-CAES

Main components	Energy and exergy equation
Compressor	$P_{out,c} = \pi_c P_{in,c}$
	$\dot{W}_{com} = \dot{m}_{c,in}\left(h_{c,out} - h_{c,in}\right)$
	$\eta_{com} = (h_{c,out,is} - h_{c,in})/(h_{c,out} - h_{c,in})$
	$\dot{Ex}_{com} = \dot{W}_{com}$
Expander	$P_{out,e} = P_{in,e}/\pi_e$
	$\dot{W}_{exp} = \dot{m}_{e,in}\left(h_{e,in} - h_{e,out}\right)$
	$\eta_{exp} = (h_{e,out} - h_{e,in})/(h_{e,out,is} - h_{e,in})$
	$\dot{Ex}_{exp} = \dot{W}_{exp}$
Heat exchanger	$\dot{m}_{HE,hot}(h_{HE,hot,in} - h_{HE,hot,out}) = \dot{m}_{HE,cold}(h_{HE,cold,out} - h_{HE,cold,in})$
	$\dot{Ex}_{fluid} = \dot{m}_{fluid}\left[\left(h_{fluid,in} - h_{fluid,out}\right) - T_0\left(s_{fluid,in} - s_{fluid,out}\right)\right]$

3.2 System evaluation

Round trip efficiency (RTE) is defined as the ratio between the discharge energy and the charge energy in a cycle period. As the heating energy and cold energy are not considered in the reference, RTE can be calculated as follows:

$$RTE = \frac{W_{elec,out}}{W_{elec,in}} = \frac{W_{gen}}{W_{com}} \tag{1}$$

where the $W_{elec,out}$ is the electricity out, $W_{elec,in}$ is the electricity in, W_{gen} is the electricity generation for expanders, W_{com} is the electricity consumption for compressor train.

Total exergy efficiency (TEE) is defined as the ratio of total net exergy output Ex_{out} in discharging process to total net exergy input Ex_{in} in charging process. As the heating exergy is not considered in the reference, TEE can be presented as:

$$TEE = \frac{Ex_{discharge}}{Ex_{charge}} = \frac{Ex_{exp} + Ex_{HE,out}}{Ex_{com}} \tag{2}$$

where the Ex_{exp} is the total exergy of expanders, Ex_{com} is the total exergy of compressors, $Ex_{HE,out}$ is the total cold exergy of volatile fluid.

Table 2 Parameters setting in A-CAES systems.

Term	Unit	Value
Ambient pressure	kPa	101.32
Ambient temperature	K	298.15
Specific heat capacity of thermal oil	kJ/(kg K)	2.1
Minimum pressure in storage vessels	kPa	4200
Maximum pressure in storage vessels	kPa	7400
Discharge time	h	4.0
Isentropic efficiency of compressors	-	0.87
Isentropic efficiency of turbines	-	0.88
Isentropic efficiency of RC	-	0.80
Outlet temperature of the IC and AC	K	318.15
Evaporating temperature of CO_2 in HE exchanger	K	280.37
Pressure loss of heat exchanger	-	3%
Rated power of compression train	kW	1000
Rated power of expansion train	kW	1000

Table 3 Thermodynamic data for air in A-CAES systems.

State point	Conventional and proposed A-CAES			
	T(K)	*P*(kPa)	*h*(kJ/kg)	*m*(kg/s)
1	298.15	101.32	300.47	1.616
2	587.29	892.67	598.06	1.616
3	318.15	865.89	319.23	1.616
4	626.92	7628.87	640.41	1.616
5	318.15	7400.00	307.28	1.616
6	298.15	4200.00	291.37	2.482
7	552.14	4074.00	560.27	2.482
8	354.99	643.84	357.32	2.482
9	552.14	624.52	561.06	2.482
10	357.95	101.32	361.16	2.482

Coefficient of performance (COP) of cooling is defined as the ratio of the cold energy to the charge energy, which is defined as,

$$COP = \frac{Q_{cold}}{W_{com}} \tag{3}$$

where the Q_{cold} is the total cold energy generated in HE exchanger in discharging process.

4. RESULTS AND DISCUSSION

A novel A-CAES system is proposed to cogenerate power and cooling energy based on the volatile fluid. The thermodynamic analysis including the energy analysis, exergy analysis and the parametric analysis of two A-CAES systems are carried out in this section. The thermodynamic properties of air and CO_2 were calculated by the REFPROP 9.1 developed by the National Institute of Standards and Technology of the United States (NIST) [29].

Table 4 Thermodynamic data for therminol 66 in A-CAES systems.

State point	T(K)	h(kJ/kg)	m(kg/s)
1a	298.15	626.12	0.828
2a	557.29	1170.32	0.828
3a	298.15	626.12	0.858
4a	596.92	1253.54	0.858
5a	572.14	1201.50	1.686
6a	572.14	1201.50	2.544
7a	572.14	1201.50	1.241
8a	378.08	793.96	1.241
9a	572.14	1201.50	1.303
10a	328.15	689.12	1.303
11a	352.51	740.27	2.544

Table 5 Thermodynamic data for air in A-CAES systems.

State point	T(K)	P(kPa)	h(kJ/kg)	m(kg/s)
1c	298.15	6434.24	274.78	3.518
2c	280.37	4200.00	274.78	3.518
3c	280.37	4200.00	425.61	3.518
4c	298.15	4813.88	446.24	2.291
2d	331.73	7400.00	463.87	2.291
3d	303.15	7400.00	294.24	2.291
4d	298.15	6434.24	294.24	2.291

Air is selected as the working fluid for the compressor train and turbine train and therminol 66 is selected as the heat transfer fluid for TES in both two A-CAES systems. All basic conditions and assumptions of the simulated of A-CAES systems are shown in Table 2 (any missing parameter not included for brevity can be deduced from the results given in Table 3 - 5).

Table 6 Comparison of simulation results of A-CAES systems.

	A-CAES	Proposed A-CAES
LC power	481.0 kW	481.0 kW
HC power	519.0 kW	519.0 kW
LT power	496.2 kW	496.2 kW
HT power	503.8 kW	503.8 kW
Charge time	6.14 h	6.14 h
Volume of ASVs	949.1 m^3	578.7 m^3
RTE	65.11%	65.11%
COP	0.0000	0.3455
TEE	65.11%	67.30%

The thermodynamic data obtained from the simulation are listed in Table 3, Table 4 and Table 5 for air, therminol 66 and CO_2 in A-CAES systems, respectively. Moreover, from Table 3 and Table 4, we can find that the thermodynamic data of air and therminol 66 in the proposed A-CAES are completely identical to that in conventional A-CAES.

The comparison of simulation results of both A-CAES systems are shown in Table 6. It can be seen that the RTE of both A-CAES systems are the same. However, 34.55% additional cooling energy can be obtained in the proposed A-CAES. This is the reason that the TEE of proposed A-CAES improves more than 2% compares with the conventional one. Although the volume of ASU in conventional A-CAES is fully used for air storage, and 28.96% of total volume of ASU in proposed A-CAES is used for volatile fluid storage, while for a given total power generation (4 MW·h), the total volume of 578.7 m^3 for ASU is required in proposed A-CAES, which is only accounts for 60.97% of that in conventional A-CAES (949.1 m^3). It is because that large amount of compressed air remains in the air storage vessels in the conventional A-CAES at the end of discharging process, while all of the compressed air is pushed out by the volatile fluid in the proposed A-CAES. In this way, more compressed air can be utilized in the proposed A-CAES.

The comparison results show that the proposed A-CAES has larger storage capacity and is more efficient than conventional A-CAES.

5. CONCLUSION

In this work, a volatile fluid based A-CAES is proposed, which can cogenerate power and cooling energy. The air storage vessels (ASVs) are divided into two parts by bladder, and one for air storage and the other is filled with volatile fluid. CO_2 is proposed as volatile fluid due to its environmentally properties and high saturation pressure. Thermodynamic analyses of proposed A-CAES and conventional A-CAES systems are carried out, and a comparative research of three systems is conducted. The comparison results show that the proposed A-CAES has the same RTE with the conventional one, while more than 30% additional cooling energy can be got in the proposed A-CAES. Moreover, the total volume of air storage unit in proposed A-CAES only accounts for 60.97% of that in conventional A-CAES, hence it has larger storage capacity than the conventional one.

ACKNOWLEDGEMENT

This work is supported by the National Natural Science Foundation of China (Grant No.: 51706221), Natural Science Foundation of Fujian (Grant No.: 2017J05143)

REFERENCE

[1] Sadreddini A, Fani M, Ashjari Aghdam M, Mohammadi A. Exergy analysis and optimization of a CCHP system composed of compressed air energy storage system and ORC cycle. Energy Convers Manag 2018;157:111–22.

[2] Krawczyk P, Szabłowski Ł, Karellas S, Kakaras E, Badyda K. Comparative thermodynamic analysis of compressed air and liquid air energy storage systems. Energy 2018;142:46–54.

[3] Chen LX, Hu P, Zhao PP, Xie MN, Wang FX. Thermodynamic analysis of a High Temperature Pumped Thermal Electricity Storage (HT-PTES) integrated with a parallel organic Rankine cycle (ORC). Energy Convers Manag 2018;177:150–60.

[4] Cheayb M, Marin M, Tazerout M, Poncet S. Modelling and experimental validation of a small-scale trigenerative compressed air energy storage system. Appl Energy 2019;239:1371–84.

[5] Zakeri B, Syri S. Electrical energy storage systems: a comparative life cycle cost analysis. Renew Sustain Energy Rev 2015;42:569–96.

[6] Sciacovelli A, Li Y, Chen H, Wu Y, Wang J, Garvey S, et al. Dynamic simulation of Adiabatic Compressed Air Energy Storage (A-CAES) plant with integrated thermal storage – Link between components performance and plant performance. Appl Energy 2017;185:16–28.

[7] Yan Y, Zhang C, Li K, Wang Z. An integrated design for hybrid combined cooling, heating and power system with compressed air energy storage. Appl Energy 2018;210:1151–66.

[8] Wolf D, Budt M. LTA-CAES – a low-temperature approach to Adiabatic Compressed Air Energy Storage. Appl Energy 2014;125:158–64.

[9] Nielsen L, Leithner R. Dynamic Simulation of an Innovative Compressed Air Energy Storage Plant - Detailed Modelling of the Storage Cavern. WSEAS Trans Power Syst 2009;4:253–63.

[10] Chen LX, Xie MN, Zhao PP, Wang FX, Hu P, Wang DX. A novel isobaric adiabatic compressed air energy storage (IA-CAES) system on the base of volatile fluid. Appl Energy 2018;210:198–210.

[11] NIST Standard Reference Database 23. NIST thermodynamic and transport properties of refrigerants and refrigerant mixture REFPROP, version 9.1; 2013.