Energy 35 (2010) 213–220

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Energy and exergy analysis of a micro-compressed air energy storage and air cycle heating and cooling system

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A R T I C L E I N F O

Article history:
Received 3 April 2009
Received in revised form
28 August 2009
Accepted 12 September 2009
Available online 28 October 2009

Keywords:
Compressed air energy storage (CAES)
Micro-CAES
Exergy
Second law
Air cycle heating and cooling

A B S T R A C T

Energy storage systems are becoming more important for load leveling, especially for widespread use of intermittent renewable energy. Compressed air energy storage (CAES) is a promising method for energy storage, but large scale CAES is dependent on suitable underground geology. Micro-CAES with man-made air vessels is a more adaptable solution for distributed future power networks. In this paper, energy and exergy analyses of a micro-CAES system are performed, and, to improve the efficiency of the system, some innovative ideas are introduced. The results show that a micro-CAES system could be a very effective system for distributed power networks as a combination that provides energy storage, generation with various heat sources, and an air-cycle heating and cooling system, with a energy density feasible for distributed energy storage and a good efficiency due to the multipurpose system. Especially, quasi-isothermal compression and expansion concepts result in the best exergy efficiencies.

1. Introduction

Interest in energy storage is now increasing, especially for matching intermittent renewable energy with customer demand, as well as for storing excess nuclear or thermal power during the daily cycle. Compressed air energy storage (CAES) is a promising method for energy storage, with high efficiency and environmental friendliness. However, large-scale CAES is dependent on the right combination of sites for air storage. Micro-CAES with man-made air vessels is a more adaptable solution, especially for distributed generation that could be widely applicable to future power networks [1,7,8,9].

In the case of the micro-CAES, it is possible to use the dissipated heat of compression for residential heating, which can contribute to improvements in energy efficiencies. In addition, compressed air systems can be used for both power generation and cooling load.

Energy and exergy analyses are performed to investigate performance of several types of micro-CAES systems. In addition, to increase efficiency of the systems, some innovative ideas, including a new means of constant-pressure air storage, are introduced [10].

2. System description

2.1. Constant pressure air storage

In general, both charging and discharging of a high- pressure vessel are unsteady state processes, where the pressure ratios are changing. These varying conditions can result in low efficiencies of compression and expansion, owing to deviation from design points. In the case of a large-scale CAES plant, it is necessary either to increase the volume of the cavern to limit pressure variations, or, as shown in Fig. 1, to utilize a water column to maintain a constant pressure in the cavern, where water from a surface reservoir displaces compressed air.

In the case of a micro-CAES with an air vessel of shallow depth, it is impossible to produce the required large pressure difference by means of a water column. Therefore, an urban CAES that provides constant air pressure by pump instead of by water column has previously been proposed. However, a disadvantage of such a system is that the pump consumes about 15% of the generated power. In this paper, we propose a new constant-pressure air storage system to overcome the power demand of the pump. Our system combines constant-pressure air storage and hydraulic energy storage, as shown in Fig. 2. In the following analyses of micro-CAES systems, we assume that pressure ratios of compression and expansion are not changing because of constant-pressure air storage.

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0360-5442/$ – see front matter
doi:10.1016/j.energy.2009.09.011

Nomenclature

k	specific heat ratio
k^*	effective ratio of specific heat
m	mass (kg)
c	specific heat [kJ/(kg.K)]
T	temperature (K)
P	pressure (kPa)
w	specific work (kJ/kg)
$\dot{W}$	rate of total work (kW)
η	efficiency (dimensionless)
Q	heat transfer (kJ)
E_{in}, E_{out}	electric power input, output (kJ)
$\dot{E}^+$	rate of exergy to the system (kW)
$\dot{E}^-$	rate of exergy from the system (kW)
$\dot{L}$	rate of exergy destruction (kW)
$\dot{M}$	mass flow rate (kg/s)
k	specific flow exergy (kJ/kg)
h	specific enthalpy (kJ/kg)
s	specific entropy (kJ/(kg.K))
ρ	density (kg/m^3)

Subscripts

g	gas
l	liquid
i	inlet
o	outlet
s	storage
H	heating performance
hc	heat of compression
c	compression
ac	after compression or after-cooler
e	expansion
ae	after expansion
a	air
reg	regeneration
h	heater
f	fuel or secondary fluid
0	dead state
II	exergy (Second Law)
q	heat exergy
y	transformation exergy
C	cooling performance
ce	cooling by expanding air

2.2. Configuration of the studied system

It is possible to build several different types of micro-CAES systems based on compression and expansion processes. In the case of large-scale CAES plants, in order to increase the overall efficiency of the system, it is customary to perform multistage compression with intercooling and multistage expansion with reheating. However, in the case of a micro-CAES system, it is very important to simplify the structure as much as possible while achieving a system with high efficiency.

In order to increase the efficiency of the system, isothermal compression/expansion (Ericsson cycle) is more desirable than an adiabatic process (Brayton cycle). To achieve quasi-isothermal compression, a large amount of atomized water is injected during the compression stroke to absorb the heat in the Isoengine developed by Linnemann and Coney [2]. Hugenroth et al. [3] proposed a liquid-flooded compressor and expander in an Ericsson cycle cooler. Water (or liquid) is discharged together with compressed air, and is then separated, cooled, and recirculated. The energy of the pressurized water can be recovered through a hydraulic motor to reduce energy consumption.

Compressed air is cooled to ambient temperature by water circulated through a cooler, and it is then stored in vessels. Hot water separated after compression and hot water from the cooler can be used to satisfy the heating load.

Although a heater (or combustor) is often employed in the expansion process of a CAES system, to heat compressed air in order to obtain increased power, it is not indispensable. If there is no heater in place before the expander, expanding air can be used to supply a cooling load, as in an air-cycle cooling system [5]. In that case, to achieve quasi-isothermal expansion, as with a compression process, liquid can be injected into the expander, separated, used to supply a cooling load, and pressurized by a pump for injection.

In the case of systems with a heater to preheat the expanding air, external heating of the expander or injection of hot liquid, such

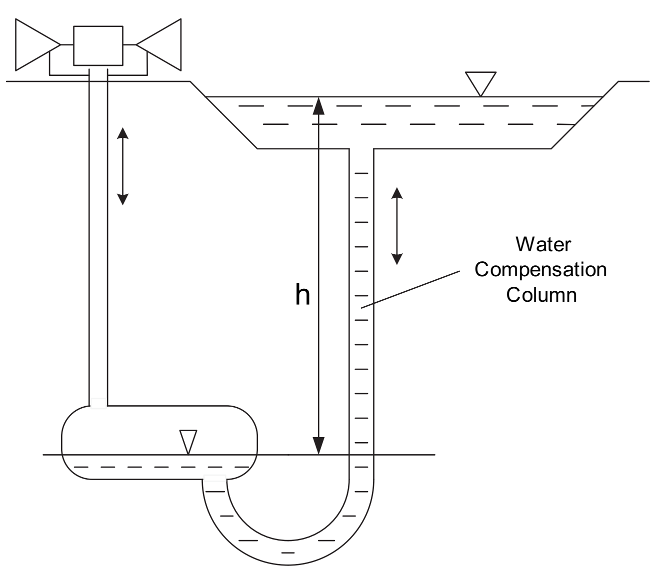

Fig. 1. Constant-pressure air storage cavern with water column.

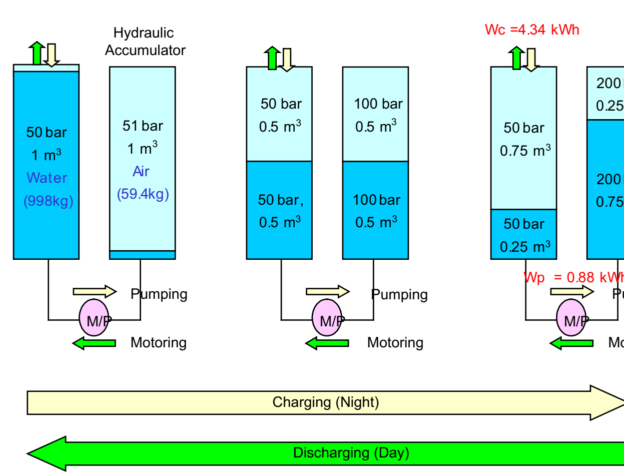

Fig. 2. Constant-pressure air storage combined with hydraulic energy storage for micro-CAES system.