Energy Conversion and Management 97 (2015) 340–350

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Thermodynamic impact of aquifer permeability on the performance of a compressed air energy storage plant

Peng Pei [a,*], Scott F. Korom [b], Kegang Ling [c], Jun He [c], Andres Gil [d]

[a] Institute for Energy Studies, University of North Dakota, 243 Centennial Dr., Upson II Room 366, Grand Forks, ND 58203, USA
[b] Barr Engineering Co., 234 West Century Avenue, Bismarck, ND 58503, USA
[c] Department of Petroleum Engineering, University of North Dakota, 243 Centennial Dr., Upson II Room 366, Grand Forks, ND 58203, USA
[d] Universidad Nacional de Colombia – Sede Medellín, Carrera 80 No. 65-223, Bloque M3, Medellín, Colombia

ARTICLE INFO

Article history:
Received 10 February 2015
Accepted 19 March 2015
Available online 5 April 2015

Keywords:
Compressed air energy storage
Aquifer
Permeability
Exergy analysis
Plant performance

ABSTRACT

Economic, large-scale energy storage technology plays a key role in enabling the utility industry to integrate more renewable energy sources into the grid. Compressed air energy storage in porous geological formations has the potential to become one of the principal energy storage technologies in the future. Storing pressurized air in aquifers has several advantages, including large storage capacity, geologically widespread availability, relatively constant pressure, and relatively low construction cost. The performance of a compressed air energy storage plant is influenced by the subsurface reservoir properties. In this paper, the design criteria, calculation procedure, and exergy analysis approach to quantify the influence of aquifer permeability on compressed air energy storage plants are proposed. A case-study model was built to simulate a compressed air energy storage plant using aquifers with porosities of 30% and different permeabilities (0.01–1.0 darcies). The exergy destruction rates and exergy and thermal efficiencies were calculated. The results indicated that as the permeability increased, the exergy destruction due to a pressure drop of working fluid in an aquifer decreased; as the permeability increased, both thermal and exergy efficiencies increased, and the net output of the plant increased. The benefits are more obvious when the permeability increased from low ($\leqslant$0.05 darcies) to medium–high values ($\geqslant$0.25 darcies).

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1. Introduction

Compressed air energy storage (CAES) is a modification of the basic gas turbine technology [1] and involves storing compressed air for subsequent use in power generation [2]. This technology is one of the primary technologies for bulk storage of electric energy (hundreds of MW-hours) [3], and provides an economical and efficient energy storage approach for the grid [4]. CAES may enable the utility industry to integrate more renewable energy sources into the grid [5] and defer the expansion of transmission and distribution assets [6]. During off-peak times, compressors use surplus low-cost electricity that cannot be consumed by the grid to pressurize air and store it in a tank or a geological formation [7]. In such cases, electricity is essentially stored as potential energy contained in the compressed air [8]. During peak times, the high-pressure air is released to drive a gas turbine to generate electricity that may be returned back to the grid at a higher price [9]. There is no need to compress the air again as in a typical Brayton cycle. The working fluid (pressurized air) may be heated with additional fuel before entering the gas turbine. In a Brayton cycle, since the largest share of the energy generated by a gas turbine is consumed by the compressor, the CAES actually boosts the output of a gas turbine by saving the load normally used to drive the compressor [10]. The motor driving the compressor during off-peak times can also be used as a generator by switching the clutch connected to the turbine (Fig. 1).

Large scale CAES usually employs underground geological formations for storage. Underground CAES has a smaller footprint and lower capital cost compared to pumping reservoir storage [11]. The underground storage reservoir can be either a constant-volume type (e.g., a salt dome cavern), or with pressure compensation (e.g., an aquifer, a depleted gas reservoir, or a hard rock cavern where water is used to compensate the pressure) [12]. Fixed-volume reservoirs have a limited storage capacity and air stored in them is subjected to pressure variations with cycling. The availability of salt domes in the U.S. is constrained in the Gulf Coast region. Solution mining of salt and excavating additional cavern volume from hard rock increases cost [7]. Therefore, CAES

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* Corresponding author at: 243 Centennial Dr., Upson II Room 366, Grand Forks, ND 52802, USA. Tel.: +1 (701)777 2533.

E-mail address: peng.pei@und.edu (P. Pei).

http://dx.doi.org/10.1016/j.enconman.2015.03.072
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Nomenclature

Symbols

E	exergy (kJ)
$\dot{E}$	exergy flow rate (kW)
e	specific exergy (kJ/kg)
h	aquifer thickness
k	permeability (D)
$\dot{m}$	mass flow rate (kg/s)
$\overline{M}$	molecular weight (kg/kmol)
n	specific heat ratio
n.s.	number of stages in compression
P	pressure (Pa or psi)
$\dot{q}$	volumetric flow rate, m^3/s or MSCF/d
Q	heat (kJ)
$\dot{Q}$	heat transfer rate (kW)
r_c	compression ratio
R	universal gas constant (kmol K)
R_g	relative gas constant (kJ/(kg K)
s	specific entropy (kJ/kg K)
T	temperature (K)
t	time (s)
V	volume (m^3)
W	work (kJ)
$\dot{W}$	power or work transfer rate (MW)
w_C	specific energy requirement (kJ/kg)
$\overline{Z}$	compressibility
ρ	density (kg/m^3)
η	efficiency
$\bar{\mu}$	viscosity (cp)

Subscripts

a	boundary of air bubble
AQ	aquifer
b	boundary
comp	compressor
comp_in	compressor inlet
comp_out	compressor outlet
CV	control volume
d	destruction
dis	discharge
dis_well	discharge wellbore
e	constant-pressure at the out boundary of the aquifer
exy	exergy
f	fuel
i	component *i* in the system
in	flow in
inj	injection
out	flow out
R	degree Rankine
th	thermal
TI	turbine inlet
w	well
0	environment temperature condition

Acronyms

CAES	compressed air energy storage
IEP	Iowa Energy Park
T–s	temperature–entropy

Units

°C	degree Celsius
cp	centipoise
D	Darcy
ft	feet
K	Kelvin
kg	kilogram
kmol	kilomole
kW	kilowatt
m	meter
mD	millidarcy
MSCF/d	thousand standard cubic feet per day
m^3	cubic meter
MPa	mega Pascal
MW	mega watt
P	Pascal
psi	pounds per square inch
°R	degree Rankine
s	second

technology that uses porous media, such as aquifers and depleted gas reservoirs, was proposed because these reservoirs have greater geological availability and may offer increased storage capacities and lower construction costs [13]. This technology stores pressurized air in porous formations with high permeability. The injected air displaces the water away from the injection well, forming a giant air bubble [14]. In reservoirs with high permeability, the pressure of stored air is relatively constant because of the movement of the air–groundwater interface; such a condition is favorable for the operation of turbines and compressors.

The performance of CAES is controlled by the aquifer characteristics and the efficiency of surface equipment, including the compressor, combustor, turbine and generator. Efficiencies of surface infrastructures are difficult to improve in the short term due to the constraint of currently-available technologies, but site selection and reservoir characterization can be used to choose aquifers that favor CAES operation. Target aquifers must have enough static water pressure for effective turbine operation [14]. The aquifer must have adequate porosity and permeability to move air in and out at the speeds required for CAES [15]. Some of the major concerns associated with an aquifer-based reservoir include: water encroachment, matching reservoir air pressure cycle to turbomachinery requirements, and air bubble deliverability [16]. It was suggested that the aquifer porosity needs to be above 10%, and that the permeability should be above 0.2 darcy (D) [7].

According to Darcy's Law, a pressure gradient is required to drive fluid flow through porous media. The pressure gradient and permeability of the porous media together determine the flow rate. Therefore, permeability determines rates of water displacement and air deliverability. High permeabilities enhance the economics of porous medium CAES reservoirs [14]. The injection pressure has to be higher than the formation pressure, depending on the required injection rate and formation permeability. Similarly, the discharge pressure should be lower than the storage pressure to facilitate the flow. But in practical operation the reservoir cannot be discharged below a minimum pressure and charged beyond a maximum pressure limit. The difference between the injection and discharge pressures represents a pressure loss, or a loss of available work.

The proposed Iowa Energy Park (IEP) highlights the importance of aquifer permeability on CAES projects. IEP was planned as a 270 Megawatt (MW) CAES project coupling wind power and air

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