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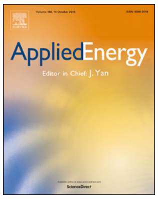

A near-isothermal expander for isothermal compressed air energy storage system

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HIGHLIGHTS

- A specific expander was analysed by theoretical and experimental methods.
- A quasi-isothermal expansion process was further improved by spraying water into the cylinder.
- Specific work generation was enhanced and the cylinder size was reduced.

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ABSTRACT

Compressed air energy storage technology is considered as a promising method to improve the reliability and efficiency of the electricity transmission and distribution, especially with high penetration of renewable energy. Being a vital component, the expander takes an important role in compressed air energy storage operation. The specific work of an expander can be improved through an isothermal expansion compared with the adiabatic expansion process due to a nearly constant temperature which enables the expander to operate with a high pressure ratio. In this study, a specific reciprocating expander with a high pressure ratio was developed and its adiabatic expansion characteristics were measured. Numerical modelling was performed to simulate adiabatic expansion. This model was also validated by experimental results. Based on these findings, we propose a quasi-isothermal expansion process using water injection into the expander cylinder. Modelling was also extended to simulate the quasi-isothermal process by introducing water–air direct heat transfer equations. Simulation results showed that when spraying tiny water droplets into the cylinder, the specific work generated was improved by 15.7% compared with that of the adiabatic expansion under the same air mass flowrate, whilst the temperature difference was only about 10% of that of the adiabatic process, and cylinder height was decreased by 8.7%. The influence of water/air mass flowrate ratio and the inlet temperature on the expander performance was also studied.

1. Introduction

As clean energy is vital to the mission of mitigating climate change and air pollution, the business case for clean energy is growing, and the trend toward a cleaner power sector is supported by beneficial relationships between economies and emissions, born out in relationship statistics (economies grow, emissions fall), private-sector emissions reductions, and market forces in the power sector and global momentum on emission-reducing technologies [1]. Renewable energy sources (e.g. solar and wind) are vitally important alternatives for clean, affordable, and reliable energy paradigms. The cost of electricity generated from renewables fell dramatically between 2008 and 2015: down 41% for wind, 54% for rooftop solar photovoltaic (PV) installations, and 64% for utility-scale PV [1]. Global capital investment in these clean energy resources was twice as much as that of fossil fuels in 2015 [1,2].

The mismatch between an intermittent electricity supply and demand over multiple time and energy scales necessitates energy storage to balance and optimize power flow and generation. Electrical energy storage can play an important role in decarbonizing the electricity

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Nomenclature

Symbols	**Concepts, Units**
A	open area of the inlet/outlet valve, m^2
BDC	bottom dead center
c_p	specific heat at constant pressure, kJ/(kgk)
c_v	specific heat at constant volume, kJ/(kgk)
$CAES$	compressed air energy storage
C_D	drag coefficient
d	water droplet diameter, m
D	cylinder diameter, m
g	acceleration, m/s^2
h	specific enthalpy, kJ/kg
$ICAES$	isothermal compressed air energy storage
m_a	mass of air, kg/s
m_w	mass of water, kg/s
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
Q	heat exchange through the cylinder walls, kJ
Q_c	transferred heat between water and air, kJ
S	stroke distance, m
S_w	water droplets surface area, m^2
T	temperature, K
TDC	top dead center
t	time, s
u	specific internal energy, kJ/kg
V	volume, m^3
v	velocity, m/s
w	velocity, m/s
W	mechanical energy, kJ
W_{adia}	Work generation of adiabatic expansion, kJ
W_{s_adia}	Ideal work generation of adiabatic expansion, kJ
W_{n_iso}	Work generation of near-isothermal expansion, kJ
W_{iso}	Ideal work generation of isothermal expansion, kJ
W_{pump}	Work consumption of water pump, kJ

Greek symbols

α	heat transfer coefficient
η_{adia}	Isentropic efficiency
η_{isoth}	isothermal efficiency
η_{isoth2}	isothermal efficiency considering pump power consumption
κ	specific heat ratio
λ_e	ratio of connected rod length to crank radius
λ	thermal conductivity, W/(m·K)
μ	gas flow coefficient
μ_a	dynamic viscosity of the air, Pa·s
ρ	density, kg/m^3
φ	crank angle, rad
ω	angular speed, rad/s
ψ	flow function

Subscripts

a	*air*
A	outlet for air phase, accumulated water on the piston for water phase
E	inlet
I	before the inlet/outlet valve
II	after the inlet/outlet valve
out	outlet
$pump$	pump
w	water

sector by offering a new, carbon-free source of operational flexibility, improving the utilization of generation assets and facilitating the integration of variable renewable energy sources [2,3]. Low-cost fabricated compressed air energy storage (CAES) will be a most promising method to store electricity for medium- and long-term periods [2]. When off-peak electricity is available it can be used to produce compressed air via a series of compressors. Compressed air is then stored in a reservoir. During peak periods the stored compressed air is released to drive expanders to generate electricity [4,5]. CAES technologies can help accommodate fluctuations in wind generation and decrease transmission line size rather than enlarging lines to match maximum power levels. The first patent for CAES technology was filed by Frazer W. Gay in 1948 [6]. This technology has been developed since the 1970s as a load-following and load-peaking power system. CAES system has an estimated efficiency of 70% with an expected lifetime of about 40 years [7]. Two commercial CAES plants have been constructed in Huntorf, Germany and McIntosh, USA [8]. Other countries such as the UK, Denmark, and the Netherlands have been keen to develop CAES plants as well [4].

Many types of CAES have been studied and developed, including conventional CAES, advanced-adiabatic CAES, liquid air energy storage, isothermal CAES, and so forth [4]. In the ideal isothermal CAES (ICAES) process, the temperature during compression is kept constant while related heat is released. The power required to run the compressor is correspondingly lower than that required to run an adiabatic compressor with the same pressure ratio. During expansion, related heat is supplied continuously to ensure expansion at a constant temperature. Thus, the electrical power used to run the compressor during charging can be completely recovered during discharging. The ideal cycle efficiency of ICAES systems can be as high as 100% [4,9]. In this study, a liquid piston based ICAES is proposed, which can yield a compressive efficiency of 89.0% according to the simulation results [8].

The compressor and expander are the pivotal components of the CAES system [10]. Generally, most gas power cycles perform work by expanding adiabatically and produce less specific work than their isothermal counterparts, which run at constant temperature. Isothermal expansion leads to a high pressure ratio and high power density, improving specific work generation. Meanwhile, lower inlet/outlet air temperature differences result in better performance in low-grade heat applications [11]. If heat is continuously transferred to the working fluid during the expansion process, this results in isothermal expansion or, more accurately, quasi-isothermal expansion, which may be somewhere between the adiabatic and ideal isothermal processes [12]. Compressing and expanding a gas nearly isothermally allows efficiency losses due to temperature deviations to be minimized or eliminated, which can in turn prevent heat transfer loss leading to improved efficiency [13]. An experimental system using condensable gas of R134a was built to investigate energy storage potential and compression/expansion characteristics. The experimental results showed a round trip efficiency of 95.8% was achievable [13]. Cicconardi et al. proposed using many super-heaters to make the expansion gradually approach isothermal conditions in a steam power plant and found that the thermal efficiency can be improved from 38.5% to 49.2% [14]. Kim et al. indicated that multi-stages compression with intercooling and multi-stages expansion with reheating could also transform the adiabatic process into a near-isothermal process. Thus, the exergy losses due to heat transfer were decreased by minimizing the temperature differences between heat exchangers. System efficiency was as high as 71.6% [15]. Woodland et al. [16] carried out theoretical study of the Organic Rankine Cycle (ORC) based on a liquid flooding expander. For