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Thermal analysis of a compressor for application to Compressed Air Energy Storage

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HIGHLIGHTS

- We analyze heat transfer enhancement in a liquid-piston compressor for CAES.
- Hydrothermal characterizations of the inserted heat exchanger media are obtained.
- CFD simulations are done combining the VOF and porous media modeling methods.
- The heat exchangers can effectively suppress temperature rise and secondary flows.
- Results indicate optimization on the shape of the heat exchanger could be done.

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ABSTRACT

In this paper, the topic of Compressed Air Energy Storage (CAES) is discussed and a program in which it is being applied to a wind turbine system for leveling power supplied to the grid is described. Noted is the importance of heat transfer in the design of the compressor and its effect on performance. Presented is a design for minimizing the temperature rise in the compressor during compression. The design requires modeling regenerative heat transfer from the compressed air to solid material inserted in the compression space. Modeling requires characterizing pressure drop through the porous insert, interfacial heat transfer between solid and fluid in the matrix, and thermal dispersion within the porous regions. Computation and experimentation are applied for developing correlations for such terms. Two types of porous media are applied: interrupted plates and open-cell metal foams. Cases with foam inserts are computed and the results are discussed. Discovered in the results are some complex secondary flow features in spaces above the porous inserts.

1. Introduction

This paper presents thermal analyses on a liquid piston driven compressor used for Compressed Air Energy Storage (CAES). The CAES system stores energy as high-pressure air, to retrieve it later in a liquid piston expander. Compression leads to a tendency for temperature rise in a compressible gas. Absorbing heat from air during compression to reduce its temperature rise is important for improving compression efficiency. As the air temperature rises, part of the input work is being converted into internal energy rise that is wasted during the storage period as the compressed air cools toward the ambient temperature. This paper discusses techniques for minimizing that temperature rise.

Our desire is that the CAES system is integrated into a wind power field. The benefit of integrating energy storage into a wind power array is that fluctuations in wind power input can be smoothed over time and electric power generation equipment can be sized commensurate with a supply power that is nearer the average wind power of the day. The alternative is sizing for peak power or “throttling back” the wind turbine when the wind is strong.

Use of storage techniques for wind power is discussed in Ref. [1]. Various scenarios with and without storage were considered. In one, wind generation capacity in 2050 was 302 GW without storage and 351 GW with storage. Another study, which is modeled using CAES and wind energy to supply 20% of the total power generation in Texas concluded that the addition of CAES to wind energy reduces the impact of wind fluctuations on the electricity grid [2]. From a report written by the US Offshore Wind Collaborative [3], we read that the total amount of U.S. offshore wind energy capacity

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Nomenclature

a_V	surface area per unit volume of porous medium (1/m)
A	cross-sectional area (m^2)
b	half plate distance (m)
$\mathscr{C}$	coefficient for the Forchheimer term (1/m)
c_p	constant-pressure specific heat (J/kg K)
c_s	specific heat for solid (J/kg K)
c_v	constant-volume specific heat (J/kg K)
Dh	hydraulic diameter (m)
D	characteristic diameter (m)
d	characteristic length based on filament dia. (m)
d_f	filament diameter (m)
d_m	mean pore diameter (m)
E_s	storage energy (J)
$\vec{g}$	gravitational acceleration (m/s^2)
h_{sf}	surface heat transfer coefficient (W/m^2 K)
h_V	volumetric heat transfer coefficient (W/m^3 K)
K	permeability (m^2)
k	thermal conductivity (W/m K)
k_{dis}	dispersion conductivity (W/m K)
L	chamber length (m)
L_1	length of the upper region without insert (m)
L_{ins}	length of the insert region (m)
l	plate length (m)
m	total mass of air (kg)
n	polytropic exponent
Nu	Nusselt number
P	bulk pressure (Pa)
P_{tot}	supplied hydraulic pressure (Pa)
Pe	Peclet number
$\bar{q}$	area averaged wall heat flux
p	local pressure (Pa)
P_f	final air pressure (Pa)
Pr	Prandtl number
R	radius of chamber (m)
Re_l	Reynolds number based on l
r	radial coordinate
$\mathfrak{R}$	ideal gas constant (J/kg K)
Re	Reynolds number based on characteristic length d
$\vec{S}_m$	momentum source term (Pa/m)
T	local air temperature (K)
T_0	initial temperature; wall temperature (K)
T_a	average air temperature in the chamber (K)
T_s	local solid temperature (K)
T_{solid}	average temperature of solid in the chamber (K)
T_f	final averaged air temperature (K)
t	plate thickness (m)
$\mathscr{t}$	time (s)
U_{in}	liquid piston velocity (m/s)
V	instantaneous volume of chamber (m^3)
W_{in}	work input (J)
x	axial coordinate

Greek symbols

α	volume fraction
ε	porosity
η	compression efficiency
μ	dynamic viscosity (Ns/m^2)
ρ	density (kg/m^3)
ζ	final pressure compression ratio

Subscripts

0	initial value of variable
1	air phase
2	water phase
D	based on filament diameter
Da	Darcian
f	fluid phase
REV	averaged on the REV
s	solid
XX	local streamwise direction
YY	local cross-stream direction

Superscripts

*	dimensionless variable

is almost equal to the current total installed capacity. Noting that most electricity-demanding regions are on the coasts, the report highlights the significant potential for offshore wind generation. Traditional CAES systems store the compressed air in underground caverns and often marry this with combustion plants by using compressed air as oxidant for burning in combustion turbines [4]. More recent advancements include using multi-stage compressors with inter-cooling between stages and multi-stage expansion turbines, with reheat [5]. A small-scale wind turbine system with CAES was constructed and tested [6]. Although the study showed beneficial prospects of using combined CAES with the wind turbine system for home applications, the efficiency of the system tested was very low, mainly due to a lack of cooling during compression. Herein, near-isothermal compression and expansion are by using regenerative heat exchange with elements *within* the compressor/expander volumes.

In the present system, we employ the “open accumulator” concept proposed in Ref. [7]. In this system, gas is exhausted to the atmosphere during expansion, reversing during compression. Compression is with pumped liquid and air and expansion is with a liquid motor and an air expander. It is operated at a constant accumulator pressure; the maximum design pressure. Thus, with the open accumulator, the energy storage density per unit volume of air is always high since the low-power, low-accumulator-pressure situation in the closed accumulator is avoided. An added benefit is a dramatic reduction in accumulator pressure oscillation cycles and improved fatigue performance.

Though not necessary for the open accumulator CAES to be successful, our design is proposed to be used in a fluid power wind turbine system. In such as system, we use hydraulic equipment for power conversion and transmission, as shown in Fig. 1. It employs hydraulic circuits, a hydraulic drive pump, hydraulic pumps and motors, open accumulators, and liquid-piston air compressors [8]. Advantages include having a hydraulic pump in the nacelle at the top of the tower rather than a heavy transmission and generator assembly and having much of the equipment, including the generator, at ground (or sea) level, allowing easier access for assembly and maintenance. When electricity demand is small, the system operates in storage mode in which the excess shaft power from the wind turbine is transferred to hydraulic power in the drive pump and the hydraulic power is transmitted through the hydraulic circuit to the hydraulic transformers, which are a series of