Journal of Energy Storage 18 (2018) 121–132

Contents lists available at ScienceDirect

Journal of Energy Storage

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

How moisture content affects the performance of a liquid piston air compressor/expander☆,☆☆

Anirudh Srivatsa, Perry Y. Li*

Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN 55455, USA

ARTICLE INFO

Keywords:
Compressed air energy storage (CAES)
Isothermal compressor/expander
Liquid piston
Heat transfer
Evaporation/condensation
Wet compression
Overspray fogging

ABSTRACT

For a compressed air energy storage (CAES) system to be competitive for the electrical grid, the air compressor/expander must be capable of high pressure, efficient and power dense. However, there is a trade-off between efficiency and power density mediated by heat transfer. This trade-off can be mitigated in a liquid (water) piston air-compressor/expander with enhanced heat transfer. However, in the past, dry air has been assumed in the design and analysis of the compression/expansion process. This paper investigates the effect of moisture on the compression efficiency and power. Evaporation and condensation of water play contradictory roles – while evaporation absorbs latent heat enhancing cooling, the tiny water droplets that form as water condenses also increase the apparent heat capacity. To investigate the effect of moisture, a 0-D numerical model that takes into account the water evaporation/condensation and water droplets has been developed, assuming equilibrium phase change. The 0-D model is also extended to a 1-D model to investigate the spatial effect. To increase computational efficiency, a uniform pressure in the 1-D deformable model is assumed. Results show that inclusion of moisture improves the efficiency-power trade-off minimally at lower flow rates, high efficiency cases, and more significantly at higher flow rates, lower efficiency cases. This effect is the same regardless of whether air is assumed to be an ideal gas or a real gas. The improvement is primarily attributed to the increase in apparent heat capacity due to the increased propensity of water to evaporate. While the 1-D model does capture the spatial effect, the 0-D model is found to be sufficiently accurate in predicting the efficiency and power density of the compressor.

1. Introduction

A grid scale energy storage that is economical and dispatchable is key to meeting the challenge of integrating more and more renewable energy in the electrical grid. Since renewable energy such as wind or solar are intermittent, variable and unpredictable, without energy storage, backup power plants are needed to compensate for the mismatch between power supply and demand. Currently, most of these backup power plants, known as “peaker” plants are natural gas turbine generators that use fossil fuels and are expensive to construct, maintain and operate. Compressed air energy storage (CAES) is widely believed to be a viable means for storing large amount of energy.

In recent years, an Open Accumulator Isothermal Compressed Air Energy Storage (OAICAES) system has been proposed [2] as a cost effective, scalable, fossil-fuel free, dispatchable approach for grid scale energy storage. Whereas a traditional CAES stores the compressed air in underground salt caverns and reuses the energy by mixing the compressed air with fuel in natural gas turbine, the OAICAES does not use any fossil fuel and stores and reuses energy by compressing and expanding the air using a near isothermal compressor/expander. This results in a much higher overall efficiency. In addition, with the open accumulator architecture, the energy storage density can be increased by 5–6 times[1] so that compressed air can be stored in pressure vessels without geographical restrictions on the availability of underground caverns. The system can also be directly integrated with a wind turbine.

A key element of the OAICAES is the near-isothermal air compressor/expander that compresses/expands air from/to atmospheric pressure to/from 200 bar. The compressor/expander would be most efficient if the compression/expansion processes are isothermal. However, this is often at the expense of power density as long cycle

☆ A portion of the results in this paper was presented in [1] in abbreviated form. The current paper contains more extensive results (such as derivation and results of the 1-D model) and expanded exposition and discussion.

☆☆ Research supported by the National Science Foundation under Grant EFRI-1038294.

* Corresponding author.
E-mail addresses: sriva047@umn.edu (A. Srivatsa), lixxx0999@umn.edu (P.Y. Li).

[1] This is due to the possibility of maintaining air pressure to be constant even as compressed air is depleted and to the use of higher pressure.

https://doi.org/10.1016/j.est.2018.04.017
Received 4 August 2017; Received in revised form 17 April 2018; Accepted 17 April 2018

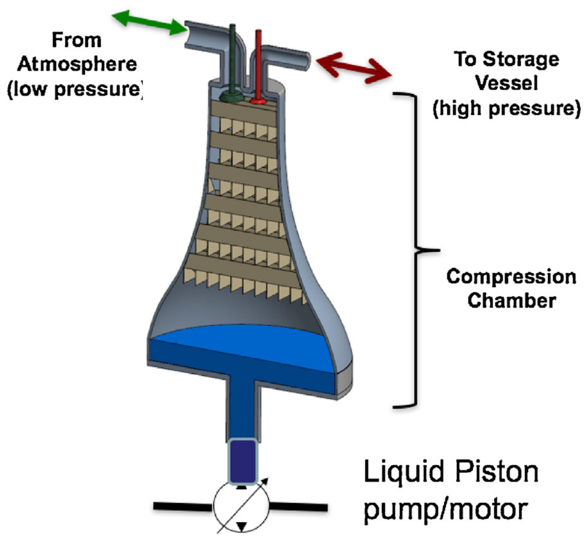

Fig. 1. A gourd shaped liquid piston compressor/expander with porous media. Note that the current study assumes a cylindrical compressor/expander.

times are needed to allow for heat transfer, so that large (and expensive) compressor/expanders are needed to satisfy the required power. To improve the trade-off between efficiency and power density, one approach is to spray tiny water droplets into the system to absorb the compression heat [3]. This is especially useful for low pressure stage of the compressor/expander. Another approach, better suited for high pressure stage, is a liquid (water) piston compressor/expander that uses the movement of the water column to compress and expand the air above it (Fig. 1) [4]. This allows the use of porous media to dramatically increase the heat transfer area [5–7]. The liquid also forms an excellent seal for the compressed air. By optimizing the liquid piston's trajectory, further improvement can be obtained [8–13,24]. Overall, two orders of magnitude increase in power density can be achieved without sacrificing efficiency [12].

The models used in our previous work for the design and analysis of the liquid piston near isothermal air compressor/expander have assumed that the air in the chamber is completely dry despite it being in contact with the water piston and the possible presence of water films on the porous media. This paper aims to study the effect of moisture in the air on the compressor/expander performance. The presence of moisture has two contradictory effects. On the one hand, evaporation absorbs latent heat that helps to keep the compressed air cool; on the other hand, condensation into tiny water droplets suspended in air increases the heat capacitance and heat transfer surface area. Evaporation and condensation are enhanced respectively by the increase in temperature and the increase in pressure. Which effect is more important is not clear a-priori. This is compounded by the fact that significant temperature and pressure variations, which affect evaporation/condensation, occur during the compression/expansion cycle.

To investigate the effect of moisture, a 0-D numerical model that considers phase change and heat transfer to/from water droplets is developed in this paper. The two phases of water are assumed to be in quasi-equilibrium at equal temperature with saturated vapor, and air is assumed to be either an ideal gas or a real gas. The 0-D model, (with air assumed to be an ideal-gas), is also extended to a 1-D spatially distributed model to capture the spatial variation. In order to increase computational efficiency, the 1-D model assumes that the pressure is uniform within the compression chamber, thus avoiding the need to solve the 2nd order full Navier–Stokes equation. This assumption was previously verified in detailed 2D CFD simulation using COMSOL software. The 0-D and 1-D models are exercised in the compression mode, with and without moisture, and for different liquid piston speeds. Results show that the presence of moisture improves the efficiency-power trade-off minimally at lower flow rates, high efficiency, lower temperature cases, and more significantly at higher flow rates, lower efficiency and higher temperatures cases. This effect is the same for both the ideal gas and real gas assumptions for air.

The beneficial effect of injecting water into the compression stage of a gas turbine (known as wet compression) has been studied and documented in the literature (e.g. [14–19]). The significant reduction in compression work has been attributed to the evaporative cooling (overspray fogging) effect. However, a key difference between the liquid piston CAES and the gas turbine applications is that the former has, by design, additional heat transfer intended to operate at lower temperature at near isothermal condition. In the latter, these additional heat transfer is often negligible and ignored in analysis [17].

The rest of the paper is organized as follows. In Section 2, the system description and the 0-D model is developed. The extension to a 1-D system model is presented in Section 3. Simulation results for different compression rates are presented in Section 4. Discussion and concluding remarks are given in Sections 5 and 6.

2. System description and the 0-D model

We consider the 2nd stage liquid piston compressor/expander for compressing and expanding air between 7 bar and 200 bar. The compression/expansion chamber is cylindrical with a diameter of 76 mm and length of 483 mm which corresponds to the experimental setup in [7]. The chamber is initially filled with air at 7 bar pressure. As water is pumped into the chamber from the bottom, the air volume decreases and the air pressure increases. The chamber can be empty or filled uniformly with porous media. In the latter case, the porous media increases the surface area for heat transfer. The air is assumed to be saturated with water vapor at all times such that the vapor pressure of water is the saturated vapor pressure. As chamber volume decreases, water is assumed to condense homogeneously into tiny droplets suspended in the air. The diameters of the water droplets are assumed to be small such that they are in thermal equilibrium with the air surrounding them. Hence, the suspended water droplets serve to increase the heat capacitance of the air.

As temperature increases, the saturated vapor pressure increases and there is an increased tendency for the water to evaporate, either from the droplets or from the liquid piston. Latent heat is absorbed or released by the water during evaporation and condensation respectively. Evaporation tends to keep the air cool but condensation tends to increase the air temperature.

In the 0-D model, the entire air and moisture in the compression/expansion chamber is assumed to be uniform. Let the decreasing chamber volume be $V(t)$, temperature be $T(t)$ and the air density be $\rho_a(t)$. The total pressure P is:

$$P = P_a(T, \rho_a) + P_s(T) \tag{1}$$

where $P_a(T, \rho_a)$ is the partial pressure of air satisfying the ideal gas or the real gas assumption,

$$P_a(T, \rho_a) = \rho_a R_a T \tag{2}$$

and $P_s(T)$ is the saturated vapor pressure for steam computed using the Antoine equation (with P_s expressed in mmHg and T expressed in deg C) [20]:

$$P_s(T) = 10^{A_s - \frac{B_s}{C_s + T}} \text{mmHg} \tag{3}$$

with $A_s = 8.07131$, $B_s = 1730.63$ deg C, and $C_s = 233.426$ deg C for temperature below 100 deg C and $A_s = 8.14079$, $B_s = 1810.97$ deg C, and $C_s = 244.485$ deg C for temperature above 100 deg C. Note that $P_s(T)$ increases with temperature (Fig. 2) so that water needs to evaporate to keep the air saturated as temperature increases.

Let $u_a(T, \rho_a)$ be the specific internal energy of air so that $C_{va} = \partial/\partial T u_a(T, \rho_a)$ is the constant volume specific heat capacity of air. If