Efficiency Improvement Techniques For Liquid Piston based Ocean Compressed Air Energy Storage

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ABSTRACT

Renewable energy resources require energy storage system for their optimal utilization. Ocean compressed air energy storage (OCAES) is a promising storage system for a utility-scale energy storage. An energy-efficient OCAES system can be built using isothermal liquid piston compressor/expander. Effect of various heat transfer enhancement techniques in the liquid piston on the end-to-end efficiency of OCAES is analyzed in this study. Heat transfer enhancement techniques like optimal trajectories, use of hollow spheres, spray cooling and porous media inserts are considered. It is observed that optimal trajectories can improve the efficiency of liquid piston based OCAES by about 5% over the base liquid piston based OCAES. Use of hollow spheres can improve by about 9%. Spray cooling and porous media indicate about 17% increase in end-to-end efficiency. This analysis indicates that liquid piston based OCAES can achieve significantly higher end-to-end efficiency over existing compressed air energy storage plants with the use of heat transfer enhancement technique in the liquid piston.

Keywords: Ocean energy, Underwater energy storage, Compressed air, Heat transfer enhancement, Energy efficiency.

1 INTRODUCTION

The variability of power from the renewable energy sources makes it hard to integrate with the electric grid. Renewable energy sources can be coupled with an energy storage system for their optimal utilization and improved reliability in the electricity grid. Ocean compressed air energy storage (OCAES) is a promising large-scale energy storage system [1]. Ocean energy resources like wind, waves, tidal etc. can be easily integrated with an OCAES system. In OCAES, energy is stored in the form of compressed air in an underwater energy storage device. This storage can be a receiver vessel, vented to sea water, mounted on the sea floor and connected to the compressed air source by pipeline [2]. Alternatively, flexible fabric energy bags can be used for underwater air storage [3]. OCAES uses hydrostatic pressure in the deep ocean to store compressed air at a constant high pressure. The constant air pressure in the OCAES results in significant improvement in the useful isothermal energy of compressed air over a land-based compressed air energy storage. In energy storage mode, excess energy is used to run the compressor and compressed air is passed to the underwater storage system. In energy recovery mode, compressed air is passed through the expander to generate electricity.

An OCAES system should have high efficiency to leverage the investments. OCAES with quasi-isothermal compression and expansion cycle shows high efficiency [4]. Liquid piston compressor has shown the near-isothermal operation of compressing and expanding a gas [5]. Liquid piston compressor uses a column of liquid to directly compress the gas in a fixed volume chamber. A liquid piston eliminates gas leakage and replaces sliding seal friction with viscous friction. Also, as a liquid can conform to an irregular chamber volume, the surface area to volume ratio in the gas chamber can be maximized. Such a design minimizes compression work and maximizes expansion work by mean of effective heat transfer to the surrounding. This results in near-isothermal operation which minimizes energy lost to heat generation.

A schematic of liquid piston based OCAES system with major components is shown in figure 1. Excess electric energy is used to operate electric motor which drives a hydraulic motor. The high-pressure liquid from the hydraulic motor is used to compress atmospheric air to high pressure. The compressed air then can be passed through the pipelines to the underwater storage system. Whenever electricity is required, the compressed air can be passed through the same liquid pistons. In this case, liquid pistons act as expanders and output high-pressure hydraulic liquid. The high-pressure liquid can be passed through the hydraulic motor coupled to the electric generator to generate electricity.

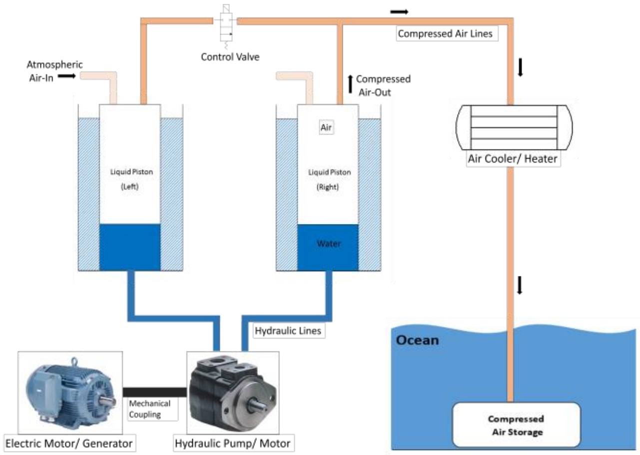

Figure 1 Schematic of liquid piston based OCAES

In our earlier study, the end-to-end efficiency of liquid piston based OCAES has shown liquid piston compression and expansion efficiency has a substantial influence on the end-to-end efficiency [6]. End-to-end efficiency based on the experimentally evaluated polytropic index and pressure ratio of 10 is observed to 45%. It is also observed that heat transfer enhancement techniques in liquid piston have the potential to show improved efficiency. Various heat transfer enhancement techniques have been proposed in the literature for the liquid piston compressor. Few of those are- optimal trajectories [7], use of hollow spheres [8], spray cooling [9] and porous media inserts [10]. These heat transfer enhancement techniques have shown improvement in liquid piston compression/expansion efficiency. The end-to-end efficiency of liquid piston based OCAES can be improved with the use of these heat transfer enhancement techniques.

In this study, the end-to-end efficiency of a liquid piston based OCAES system with different heat transfer enhancement techniques is analyzed. Various heat transfer enhancement techniques for liquid piston are discussed in section 2. An analytical model used for the efficiency evaluation of liquid piston based OCAES system is presented in section 3. Various numerical considerations are discussed in section 4. Results of the simulations are presented and discussed in section 5. Finally, section 6 concludes the paper.

2 EFFICIENCY IMPROVEMENT TECHNIQUES

2.1 Optimal Trajectories

The Pareto optimal trajectories for the liquid piston compressor/expander that maximizes efficiency for a given power have been found by Saadat et al [7]. They considered general heat transfer models, the viscous friction, and system constraints in the optimization process. These optimal trajectories were experimentally tested by Shirazi et al [11]. It was observed that optimal profiles show up to 4% higher efficiency for the same power density or 30% higher power density for the same efficiency compared to ad-hoc constant flow rate profiles.

2.2 Use of hollow spheres

Hollow spheres floating at the liquid-air interface in the liquid piston have been observed to be effective in reducing the temperature of the compressed air in the liquid piston compressor. Hollow spheres made of Silicon Carbide (SiC), High-Density Polyethylene (HDPE), and Polypropylene (PP) were tested by Kishore et al. in a liquid piston compressor [8]. It was observed that those hollow spheres are effectiveness in bringing down the temperature of compressed gas and hence enhances heat transfer in the system. The polytropic index of compression with use of hollow spheres reduces to 1.08 from 1.15 which corresponds to increase in compression efficiency from 79% to 87% for a compression ratio of 10.

2.3 Spray Cooling

In the spray cooling concept, small water droplets and high mass loading create a large interfacial surface area for heat transfer. The droplet spray heat transfer in the liquid piston compressor has been investigated by Qin et.al [9]. They developed a detailed multiphase thermodynamic model and validated with experimental data. It was observed that the total surface area of aloft droplets is critical to achieving high performance in a liquid piston and the best can be achieved with small droplets and high mass loading combined with direct injection. It is shown that compression efficiency could be increased from 71% for adiabatic compression to as high as 98% with spray injection for a compression ratio of 10. The mass loading, droplet diameters, direct vs premixed injection influence effectiveness of spray cooling and hence compression efficiency. For a compression ratio of 10 and mass loading of 1, the compression efficiency of 93% is shown with spray cooling in the liquid piston.

2.4 Porous Media Inserts

The porous media inserts increase heat transfer surface area significantly, hence their addition to the liquid piston compression/expander increases the compression efficiency at a fixed power density. Experimental investigations on heat transfer with porous media in a liquid piston during compression and expansion have been carried out by Yan et. al. [10]. A baseline case without inserts and five cases with different porous inserts were tested in a compression experiment. It was found that, in compression, porous inserts increase power density by 39-fold at 95% efficiency and increase efficiency by 18% at 100 kW/m^3. Similarly, in the expansion, porous media inserts increase power-density three-fold at 89% efficiency and increase efficiency by 7% at 150 kW/m^3.

3 ANALYTICAL MODEL

Inefficiencies in various components of the OCAES (shown in figure 1) contribute to loss of energy in the storage system. The end-to-end efficiency of the OCAES system is calculated by considering the efficiency of each of the components using equation (1).

$$\eta_{ETE} = \eta_{M/G}^2 \times \eta_{HP/HM}^2 \times \eta_C^2 \times \eta_E^2 \times \eta_P^2 \times \eta_{CV}^2 \times \eta_S \quad (1)$$

With the use of heat transfer enhancement techniques, the efficiency of liquid piston compressor/expander can be increased. Liquid piston compressor efficiency for OCAES is defined as the ratio of storage energy to work input. Storage energy is the amount of work extracted from the isothermal expansion of compressed air to the atmospheric pressure. Work input consists of compression work, cooling work and friction work. Liquid piston compressor efficiency (η_C) after neglecting viscous friction is given by (2).

$$\eta_C = \frac{\overbrace{\ln(P_r) + \frac{1}{\mathrm{P}_r} - 1}^{E_{Storage}}}{\underbrace{\frac{P_r^{\frac{n-1}{n}} - 1}{n - 1} + P_r^{\frac{-1}{n}} - 1}_{W_{compression}} + \underbrace{(P_r - 1)\left(\mathrm{P}_\mathrm{r}^{\frac{-1}{n}} - \frac{1}{P_r}\right)}_{W_{Cooling}}} \qquad (2)$$

where P_r is the pressure ratio (Ratio of storage pressure to the atmospheric pressure) and n is polytropic index of compression. Storage pressure (hence P_r) depends on the underwater air storage depth and n depends on the magnitude of heat transfer in liquid piston compressor.

In expansion process, liquid piston expansion efficiency (η_E) for polytropic expansion index n is given by (3).

$$\eta_E = \frac{\overbrace{\frac{1 - \left(\frac{1}{P_r}\right)^{\frac{n-1}{n}}}{n - 1} - \left(\frac{1}{P_r}\right)^{\frac{n-1}{n}} + \frac{1}{P_r}}^{W_{Expansion}}}{\underbrace{\ln(P_r) + \frac{1}{\mathrm{P}_r} - 1}_{E_{Storage}}} \qquad (3)$$

Efficiencies of other components are modeled as given in [6].

4 NUMERICAL SIMULATIONS

Numerical simulations for end-to-end efficiency are performed based on the analytical model of an individual component in the liquid piston based OCAES system. Efficiencies of electric motor/generator and hydraulic pump/motor are considered from industry standards. Storage pressure of 10 bar gauge (100 m of ocean depth) is considered for the analysis. Various components specifications designed for maximum power capacity of 0.5 MW with 2 MWh energy storage were used. Length and diameters of pipelines connecting various components, various constants for control values and storage system are considered as given in [6]. Monte Carlo simulations (10000 runs) are performed for uncertainty quantification. Stochastic assignments are done to assess variation in end-to-end efficiency due to the uncertainties for efficiencies of various components. Stochastic assumptions considered for efficiencies of various components are shown in Table-1.

Variable	**Mean / Max Value [µ] (%)**	**Standard Deviation[a] or Max/Min value (%)**	**Distribution**
$\eta_{M/G}$	96	0.5	Normal
$\eta_{HP/HM}$	93	1	Normal
η_C	Using (2)	Max=µ, Min=µ-2	Triangular
η_E	Using (3)	Max=µ, Min=µ - 2	Triangular
η_P	$\frac{P_{in} - \Delta P}{P_{in}}$	Max= µ, Min= µ-0.5	Triangular
η_{CV}	$\frac{P_{in} - (\Delta P)_{Loss}}{P_{in}}$	Max= µ + 0.5 Min= µ - 0.5	Triangular
η_S	99	Max= µ + 0.5 Min= µ - 0.5	Triangular

Table 1. Stochastic assignments in Monte Carlo simulation

5 RESULTS

The end-to-end efficiency of liquid piston based OCAES system with various heat transfer enhancement techniques in liquid piston are shown in Figure 2. The base liquid piston without any heat transfer enhancement technique considers experimental observed liquid piston compressor/expander efficiency. The isothermal OCAES is one in which compression and expansion happen isothermally which indicates 100% compression and expansion efficiency. Uncertainty bars represent 95% confidence interval valves.

It can be observed that estimated mean value of end-to-end efficiency is consistently higher with the use of heat transfer enhancement technique over the base liquid piston. The optimal trajectories can improve OCAES efficiency by about 5%. Although this improvement is comparatively a small value, this improvement happens without introducing any other media in the liquid piston. Therefore, optimal trajectory technique can be considered as an efficiency improvement technique without affecting other performance of the liquid piston like volumetric efficiency, power density, long term reliability etc. The use of hollow spheres has potential to improve the efficiency of OCAES system by about 9%. The addition of a layer of floating spheres in liquid piston increases heat transfer area and helps in temperature abatement in the liquid piston during compression. This results in improved efficiency of compression and similarly for expansion.

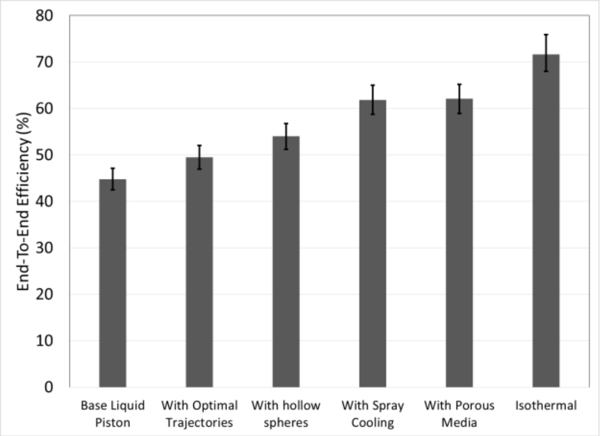

Figure 2 End-to-end efficiency of liquid piston based OCAES with various heat transfer enhancement techniques

Further, spray cooling and porous media inserts can show about 17% improvement in the OCAES efficiency achieving end-to-end efficiency of about 62%. Both these methods increase heat transfer media inside the liquid piston and hence help to curtail the temperature rise in the liquid piston during compression and temperature fall during expansion. The high surface area and high specific heat of the water spray help in heat transfer enhancement and hence improving compression/expansion efficiency of liquid piston. In porous media inserts, higher heat transfer surface area with the use of metallic foam as a porous media helps in absorbing the thermal energy from the air during compression and dissipate fast to the liquid. In expansion mode, the same porous media transfers thermal energy from the liquid to the air. Although spray cooling and porous media improves the efficiency of OCAES significantly, these heat transfer enhancement techniques require other media to be introduced in the liquid piston. This results in reduced volumetric efficiency of compression/expansion. Also, spray cooling and porous media inserts might require special care for continuous reliable heat transfer performance. This is because of the change in spray characteristics and porous media characteristics over time due to their degradation.

An isothermal liquid piston compressor would define an upper limit for end-to-end efficiency, which is about 72% for the given system considerations. This indicates that inefficiencies in the motor/generator, hydraulic pump/motor, pipelines, control values, and storage result in about 28% of energy loss. End-to-end efficiencies of existing compressed air energy storage (CAES) plants in Huntorf (Germany) and McIntosh AL (USA) are 42% and 54% respectively [6]. Clearly, liquid piston based OCAES with the use of heat transfer enhancement technique such as spray cooling or porous media inserts in liquid piston can show significantly higher end-to-end efficiency over existing CAES plants.

6 CONCLUSIONS

Effect of various heat transfer enhancement techniques on the end-to-end efficiency of liquid piston based OCAES is analyzed using numerical simulations. The analytical models for the efficiency of individual components are used to model end-to-end efficiency of a liquid piston based OCAES system. Uncertainty in input data is analyzed using stochastic assignments for component efficiencies and running Monte Carlo simulations. It is observed that spray cooling and porous media techniques indicate a significant improvement in the end-to-end efficiency. The liquid piston based OCAES with the use of heat transfer enhancement techniques such as spray cooling and porous media can result in a storage system with a significantly higher efficiency than existing compressed air storage systems. However, these methods introduce external media in the liquid piston reducing volumetric efficiency. Further investigations in their use for reliable long term use is needed to validate their performance.

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