COMPRESSED-AIR ENERGY STORAGE SYSTEMS FOR STAND-ALONE OFF-GRID PHOTOVOLTAIC MODULES

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ABSTRACT

In this work, a low-cost, low-volume, low-maintenance, small-scale compressed-air energy storage system (SS-CAES) is proposed, which can be used in conjunction with off-grid stand-alone photo-voltaic panels, for powering appliances and residential units in order to minimize the dependency on centralized power system grids. As a first step towards achieving this objective, we have designed and examined the compression efficiency of a single-stage, isothermal compression system that utilizes a fluid piston. Preliminary results clearly establish that the prototype holds enormous promise as energy storage systems that are compatible with renewable energy sources such as solar.

INTRODUCTION

The ability to efficiently harness and utilize renewable but intermittent energy sources such as **solar**, wind and geothermal for electrical power production, is critically dependent on the availability of cost-effective, energy-storage technologies. Existing storage technologies include electrochemical batteries and fuel cells, supercapacitors, thermal-storage materials, flywheels, pumped hydro (PH), superconducting magnetic energy storage (SMES) and compressed air energy storage (CAES). Of particular interest to this project are the CAES systems. Large-scale CAES systems such as the ones in Huntdorf, Germany and McIntosh, Alabama are already operational and use underground caverns for compressed air storage. In such systems, typically, natural gas or other fuels are used during the operation of turbines corresponding to the expansion phase of the compressed air.

But, so far, to the best of our knowledge, excepting Lemofouet et al [1], there have been no concerted efforts to examine much smaller scale CAES systems as effective storage solutions for renewable energy sources, Specifically, SS-CAES can be effective energy storage solutions (a detailed discussion on the feasibility of various CAES systems can be found in Ref [1]), when used in conjunction with photovoltaic panels, where air-compression is powered by the PV panel(s) during the day and energy extraction (via appropriate pneumatic to electrical energy via turbines) occurs during PV inactivity. Thus, as an off-grid alternative to the large-scale compressed air energy storage systems we propose to examine the viability of a unique energy-efficient, small-scale, compressed-air energy storage system that can be specifically tailored to power household appliances, and the scalability of such systems to power individual household and commercial units. Specifically, the focus of this project will be the development of PV-CAES systems that can be operated at very low powers, to optimally utilize the output of individual PV panels.

Compressed Air Energy Storage

CAES involves compressing air and storing it either above-ground or below-ground. The ability to efficiently store and discharge energy of CAES systems depends critically on the initial and final storage volumes, operating thermodynamic conditions (pressure, temperature), as well as the rate of compression and discharge and heat-exchange capabilities. The workings of a CAES system comprise of a compression phase (charging) and a discharge phase. During the compression phase, the rate of compression and the quality of heat exchange determines the temperature of the system, and any heat irreversibly lost adversely affects the efficiency of the system. During discharge, the compressed air (or gas) is expanded, and usually external heat has to be provided to compensate for cooling of the air when expanded.

Traditional CAES are large-scale and rely on unique geological formations like underground caves for compressed air-storage. Such systems are capable of long-time energy storage. They are typically used in conjunction with commercial power plants for supplementing and matching peak demand as well as ensuring load balancing. Specifically, they involve compressing air during off-peak hours by pumping air underground. Later during peak energy consumption periods, the compressed air is discharged- it is heated (usually by means of natural gas), and expanded to drive turbines that generate electricity.

Large scale CAES systems are characterized by reasonable round-trip efficiencies (~ 60 %), and have high energy and power densities [2], and are therefore suited for the storage of large quantities of solar energy for widespread transmission and usage [3]. In underground CAES, approximately two-thirds of the power produced by a traditional gas turbine is used to compress the air prior to combustion.

While reliable data are available on large-scale CAES, in contrast, not much work has been carried out in examining

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the efficacy of small-scale CAES systems as energy storage systems. In particular, the ability to use SS-CAES as storage systems to supplement renewable energy sources has not been extensively studied. In the following sections we will discuss the advantages and the limitations of using SS-CAES as a viable storage system; specifically, we will examine different thermodynamic regimes under which the proposed SS-CAES system can be operated, to have optimal efficiencies when used in conjunction with PV panels.

Thermodynamics of CAES

In this section, we provide a brief background on the thermodynamics of CAES, while we refer the reader to Ref [1] for a more detailed and a comprehensive review on this subject. The energy storage capabilities of CAES systems can be easily understood in terms of the first law of thermodynamics, where the energy produced by an external source (n this case, a PV panel) is used in compressing air; if the work done in compressing air is given by *dW*, then the change in internal energy *dU* is related to *dW* by Eqn. 1.

$$dU = dQ + dW \qquad (1)$$

where *dQ* is the change in heat content of the compressed system. If we assume that air obeys the idal gas law (Eqn 2),

$$PV = nRT, \qquad (2)$$

where *P, V, n, and T r*epresent the pressure, volume, the number of moles, and the temperature of the system, while *R* is the Avogadro gas constant. then the change in internal energy of the compressed air only depends on the difference in the initial and final temperature (i.e. the interaction energy between constituent particles are zero, and the internal energy equals the kinetic energy of the gas), while the heat content depends on the ability of heat-exchange between the compressed air and its surroundings.

The compression process can occur under many different conditions: if the compression is isothermal, then the temperature of the system does not change, and dU =0; if on the other hand the compression is adiabatic, then dQ =0. Depending on the relative contributions of dU and dQ, one can use the polytropic index (γ) to characterize the nature of compression. γ varies between 1-1.4 for air, where 1 corresponds to isothermal, and 1.4 corresponds to adiabatic conditions. Further, for a given compression condition (i.e. for a given γ), the work done in compressing air from an initial state P_i, V_i, T_i to a final state P_f, V_f, T_f is given by Eqn 3, where $g = \dfrac{\gamma}{\gamma - 1}$.

$$\begin{aligned} W &= \int dW = -\int_i^f P dV \\ &= gnRT_i\left(\left[\frac{P_f}{P_i}\right]^{(1/g)} - 1\right), \end{aligned} \qquad (3)$$

Note that the work required to compress air isothermally for a given thermodynamic initial and final state is the lowest and therefore is the ideal mode of compression (Fig. 1). But, quasi-static compression (where the time between successive compression operations is long enough to ensure thermal equilibration) is required to ensure constant temperature conditions, and therefore typical industrial compressors work under non-isothermal conditions.

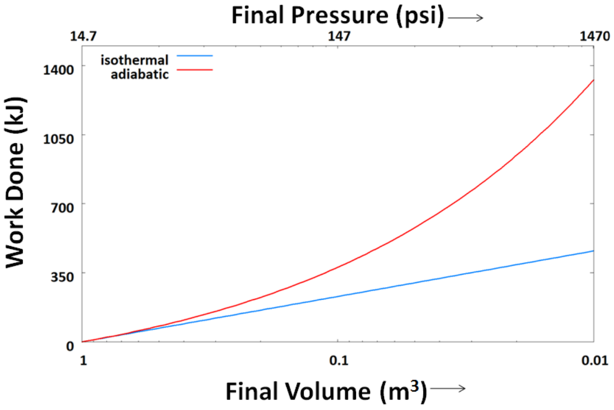

Figure 1: Work done to compress 1m^3 air under adiabatic and isothermal conditions; notice the relatively much lower values of work done for isothermal conditions

The above equations are specific to a closed-system compression, where the mass (or equivalently the number of moles) of air being compressed is constant. In order to characterize compression into an external storage tank (an open system), one can describe the process in terms of successive closed-system compression steps, where the pressure of the tank increases with every compression step. The storage volume, the final pressure as well the compression ratio (= P_f/P_i) of the storage tank, define the total energy available (E_a) for extraction once the compression stage is over. Using Eqn. 4, one can characterize E_a as follows:

$$E_a = gP_f V_{\tan k}\left(1 - \left(\tfrac{P_f}{P_i}\right)^{(-1/g)}\right) \qquad (4)$$

Since the discharge phase can be viewed as the reverse of the compression phase, the concepts described above can also be used to describe the thermodynamics of the discharge phase of a CAES system. The energy available for extraction given by Eqn. 4 represents a theoretical maximum for the conversion from pneumatic to mechanical/electrical energy. In typical PV-CAES systems, both phases can be operated under different thermodynamic conditions, based on need and available resources. The round-trip efficiencies of the different cycles (i.e. different polytropic indices), which can be calculated from Eqn 5 are shown in Fig. 1-the isothermal cycle has an ideal efficiency (*η=1*), but in principle, the realization of perfect isothermal conditions is experimentally very difficult.

$$\eta = \frac{1-(P_f / P_i)^{-1/g}}{(P_f / P_i)^{1/g} - 1} \qquad (5)$$

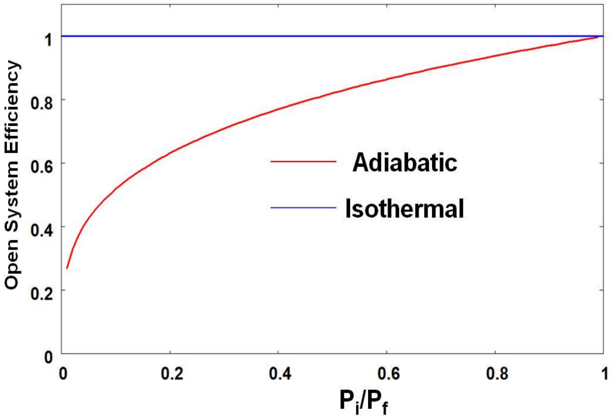

Figure 2: Round trip efficiency of an open-compression system as a function of compression ratio for the isothermal and adiabatic conditions

KEY FEATURES OF THE PROPOSED PROTOTYPE

The primary objective of this project is the development of a SS-CAES system capable of operating in tandem with individual PV panels. In particular, attention will be paid to CAES systems with high efficiencies that can fully utilize the entire range of the electrical output of standard residential PV panels, The power output of such panels typically range up to 160 W, which may not be conducive for operating commercial compressors. Towards this end, we propose a low-power, high efficiency CAES system, whose compression phase is capable of operating at the same range of powers that correspond to the output of PV panels. The fact that such systems can be run at low-power make them tailor-made to be operated at low compression rates and therefore suitable to be working under isothermal conditions.

As a first step in achieving the stated objective, we have designed and developed a single-stage, displacement-based, piston-driven, small-scale, low-cost, quasi-isothermal compressor that has the capabilities of functioning at low compression rates (rpm = 10-60).Typical compressors use multi-stage compression to attain higher pressures, but in the current prototype, we have initially opted to have a single-stage system with minimum moving parts. Also, it should be noted that CAES systems capable of storing the excess heat produced during compression and re-using it during the expansion phase such as the advanced-adiabatic CAES system [4] have been proposed, which may be viable options if high-power, high-rpm CAES systems are desired.

It has to be noted that while, we have only examined the workings of the compression phase of the developed CAES system in this work, the developed prototype will be examined in the context of functioning as a single-stage compressor/motor hybrid unit (Fig. 3); a prime advantage of such a hybrid unit would be the decrease in energy losses, due to the reduction in the number of moving parts/components required for the multi-stage conversion of solar-energy to compressed-air to powering household units (or individual appliances). Further, such a hybrid system can be suitably customized to suit the needs of individual household/commercial units.

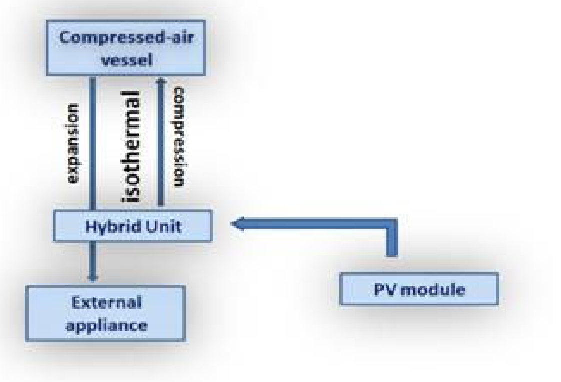

Figure 3: Schematic of the proposed prototype

An important feature of the developed prototype is the implementation of a liquid/fluid piston (Fig. 4). While very informative work on liquid piston gas compression is available [5], we will highlight the important benefits of a liquid piston. The principal advantages of using a liquid piston in a compressor is to increase volumetric efficiency [6] (or the ability to pump out air) as well as to reduce dead volume, which corresponds to the clearance between piston head and outlet. The reduction in dead volume enables the ability to reach much higher pressures during the compression stroke of the compressor. Additional benefits include reduced moisture content in the compressed air. Further, by choosing a fluid with appropriate thermal and viscous properties, one can promote thermal conductivity enabling faster thermal equilibration, while optimizing hydro-mechanical efficiency. In this work, we use a hydraulic fluid-*Petro*

Canada:Antiwear 68 for the fluid piston, due to its reliable thermal and viscous properties.

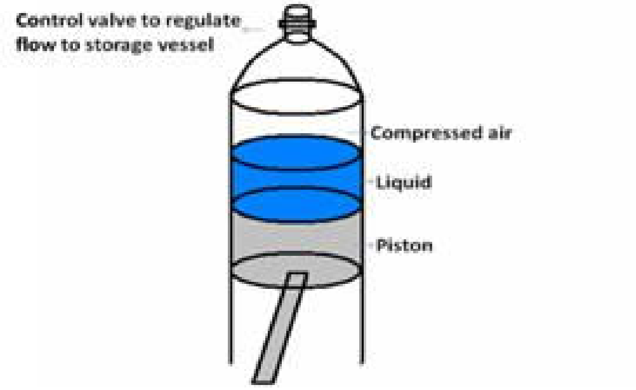

Figure 3: A simplified illustration of the liquid piston

Other salient features of the developed compressor prototype include (i) using a stainless steel cylinder with a high aspect ratio for increased thermal conduction (ii), the use of an electronic timed valve in synchronization with the stroke speed for optimal flow of compressed air into the storage tank, (iii) low-friction moving parts to minimize energy losses, and (iv) mechanically robust to shear cracks.

The various parts comprising the compressor system are shown in Fig. 3. The piston dimensions were selected to match the large aspect ratio of the compressor. The system was designed to accommodate a long stroke length, and care was taken to ensure that the stability and alignment were not compromised; specifically, a crosshead was attached to the piston-end, to align the piston's linear motion. A modified dialed-down Baldor motor (BC140-FBR) was used for the conversion of electric energy to provide the necessary torque for the piston motion. The frame enclosing the compressor system consists of separable top and bottom parts; the top part is capable of moving in the plane perpendicular to the cylinder motion to adjust for piston-cylinder alignment, while the bottom part encloses the crankshaft and the motor.

RESULTS AND DISCUSSIONS

In this section, we present and discuss the workings of the compression phase of the prototype. Specifically, we characterize the prototype and its compression efficiency, with respect to the interplay between the liquid piston, stroke length, and rpm. Both closed system and open system efficiencies will be reported. An analysis of the possible energy losses that lead to less than ideal efficiencies associated with the compression process will also be characterized.

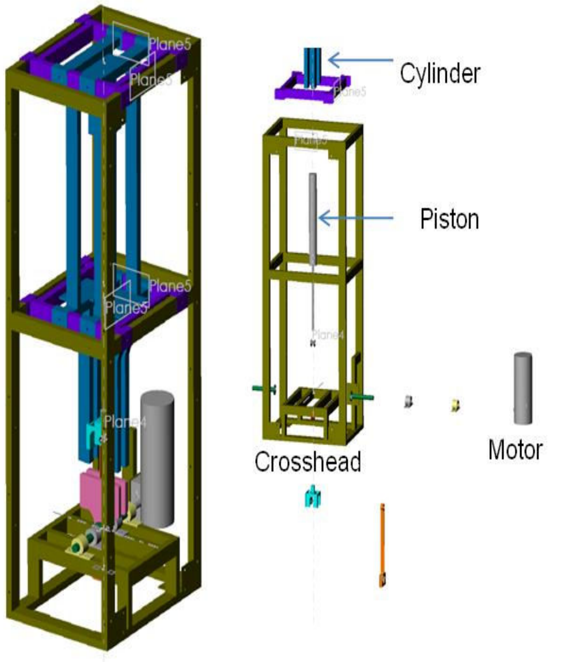

Figure 3: A comprehensive illustration of the developed prototype.

The first part of this section focuses upon evaluating the compressor when working as a closed system. Here, we examine the efficiency of the closed system with respect to the volumetric capacity, and the maximum pressure reached as a function of stroke length and compression rate (i.e. rpm). Here, stroke length refers to the distance traversed by the piston per stroke; by suitably changing the volume of the fluid comprising the fluid piston in conjunction with stroke length, one can then control the final compression volume. For a closed system under isothermal conditions, where the mass of air is constant, the final pressure (P_f) that can be reached is given by Eqn 6. Since P_f is inversely related to the final volume V_f, it is desirable to reduce V_f, if large final pressures are required.

$$P_f = PiV_i / V_f \quad (6)$$

An initial evaluation showed that for mechanical stability, a stroke length of up to 10 inches could be accommodated. For the different stroke lengths, we varied the amount of liquid piston volume and have tabulated the maximum pressure that can be reached as a function of the initial volume (which is the difference between the total volume of the cylinder and the liquid piston volume) as shown in Fig. 4 for a stroke length of 4 inches. In addition the work done associated with each compression process is also shown in Fig. 5.

As obvious from Fig. 4, for the closed compression system, the increase in fluid amount, leads to an increase in final pressure, due to the consequent decrease in 'dead' volume. Further, the maximum pressure reached was independent of the compression speed, which ranged from 6-63 rpm. Most importantly, the fluctuation in temperature of the closed system under the different operating conditions was negligible (± 2° C), implying that the compression conditions were isothermal for all practical purposes. Under these conditions, Eqn. 3 can be rewritten as follows in order to obtain the work done during isothermal compression which is given in Fig. 5.

$$W = -\int_{i}^{f} PdV = P_i V_i \ln(\frac{V_i}{V_f}) \qquad (6)$$

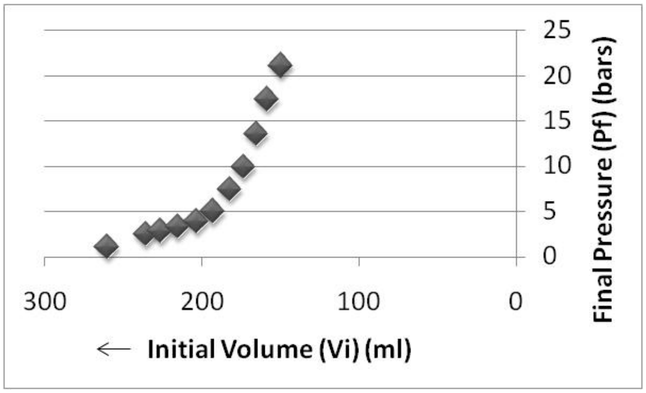

Figure 4: Maximum pressure reached for the closed compression system as a function of initial compression volume.

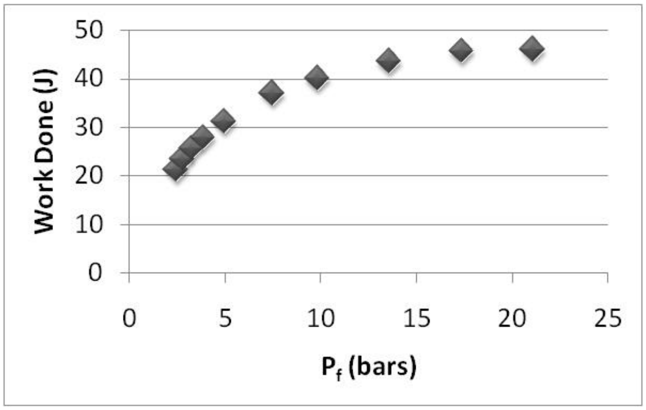

Figure 5: Isothermal work done (Eqn. 6) corresponding to different final pressures

Fig. 6 illustrates the efficiency of the compression system as a function of rpm. The efficiencies at compression speeds closer to maximum rpm were lower than 40 % and not included in the figure. Here, in order to obtain the efficiency, the net electric power being output to the compressor (*Ep*) was measured over a period of time and by knowing the rpm, total amount of work done for compression for the same time period (*Wc*) was estimated. Then the efficiency calculated from the ratio of *Wc* to *Ep*. Fig. 6 demonstrates the fact that the efficiency is a function of the rpm and has a maximum at 15 rpm, which is a direct consequence of the fact that the modified motor used in this system for converting electric power to provide torque to the crankshaft, is best optimized for 15 rpm, which was verified by measuring the torque output of the motor with respect to the input power at different rpm's. Further, it should be pointed out that for the current design, the maximum efficiencies are obtained at operating powers of up to 25 Watts. This implies that in order to completely utilize the PV output, either the current design has to be scaled up to accommodate higher final pressures (such as multi-stage units), or multiple such systems should be used in unison for optimal power utilization. While much larger pressures can indeed be obtained using the current design, the mechanical stability as also the liquid piston chemical stability and its miscibility properties with air at higher pressure have not yet been systematically studied.

Next, at 15 rpm, we evaluated the open system efficiency of the compressor; here we compressed air into an off-the-shelf propane tank that had a rated maximum pressure of 300 psi (~ 20.4 bars). Using the volumetric capacity of the tank (~ 18 litres), and measuring the increase in pressure of the storage tank as a function of time, we calculated the energy capacity of the compressed air stored via Eqn. 4. For example, by running the compressor for 2 hours, we obtained a tank pressure of 10 bar. leading to an overall open system efficiency of 60 %, which is lower when compared to the closed system efficiency at the same rpm. Further analysis is required to characterize the drop in efficiency, while it should be pointed out that within a certain pressure range (3-7 bar), the efficiency was close to 70 %.

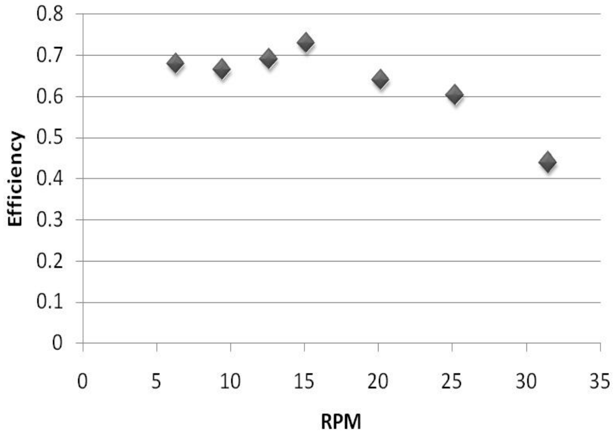

Figure 6: Closed system efficiency as a function of compression rate (RPM).

CONCLUSIONS

A small scale compressed air energy storage system that can work in conjunction with individual PV panels has been proposed. So far, the proposed prototype's compression efficiency has been examined. An important feature of this compressor is its ability to operate under isothermal conditions. The fact that the reported efficiency depends on the operating rpm and ranges between 40 -70 % (which are lower than ideal isothermal efficiencies), can be attributed to losses associated with an off-the-shelf motor used for electric-to-mechanical energy conversion. Future work will involve (i) incorporating a customized motor that works efficiently at low rpm's that correspond to the operating compression rates of the developed compressor as well as (ii) examining the system to work as a hybrid compressor-motor unit. It should be noted that there are pneumatic-electrical conversion systems that have been proposed/available [7] that can be used in the discharge phase independent of the compression phase. This work represents an important first step towards developing a low-power high efficiency CAES storage system that can work seamlessly with PV panels. Developing such low-cost, environmentally-benign energy storage systems that can efficiently power household appliances and residential units, can lead to more off-grid applications, as well as increasing the adoption of individual, customized PV-CAES systems as per the financial and power needs of the end-user.

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