

A novel design of a compressed air storage system with liquid pistons

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Renewable energy systems (RES) require more efficient, reliable and cost effective energy storage systems to benefit more from these kind of environmentally friendly energy sources and reduce CO₂ emissions. Compressed air energy storage (CAES) is one of the mechanical energy storage technologies that uses pressurized air to store and generate power when needed. Small scale CAES systems has been developed for RES application due to its advantages like easy installation, low maintaining costs, modular structure and running up time. In this study, a new small scale CAES system, which is running with liquid pistons to obtain isothermal compression and expansion, and a pressure regulator to compensate pressures between liquid pistons and air, is suggested. A detailed description of the novel CAES system design is given and effect of the components' specifications of the system are explained. Experimental results showed that, designed CAES system is a promising technology for RES, standalone and mobile applications. Specific components compatible with operating conditions of the system need to be designed in order to improve effectiveness and reliability.

Keywords: compressed air energy storage, liquid pistons, air compression, experimental setup, component performance

INTRODUCTION

After huge progresses in renewable energy sources, they gained an important role for energy demand and energy storage systems took a significant part in these sources for providing feasibility and quality of the produced energy. Energy storage systems are also a major component of the stand-alone renewable energy systems for home applications. Energy storage systems are stores electrical energy in a different form like chemical energy or potential energy, and convert them to electrical energy when needed. Main energy storage forms of these systems are electrical, mechanical, chemical and thermal energy storage systems [1]. In electrical energy storage systems, energy is stored in a form of electric field where capacitors, super capacitors and superconducting magnetic energy storage (SMES) systems store energy in this form. Pumped hydro energy storage (PHES), flywheel and compressed air energy storage (CAES) systems are mechanical storage systems that store energy in kinetic or potential energy forms. Chemical storage systems are based on electron transmission between two materials during charging and discharging processes. Most of the storage devices used in our daily life like batteries and accumulators store energy in chemical form. In thermal energy storage systems (TES), energy is stored in heat form where special materials are required. CAES systems possesses several practical advantages such as freely available "storage media", no storage time

limit in sealed storage without self-discharge, high life cycle, no harmful waste and no emissions etc. However, further research and studies on CAES systems are required to guarantee the reliability, optimal efficiency and flexible operations for the commercial usage.

CAES systems are one of the commercial plants with PHES for large scale applications. There are two operating CAES plants in the world, one is Huntorf CAES in Germany and the other one is McIntosh CAES in Alabama, USA [1, 2]. The air is compressed in an electrical motor driven compressor and stored in large salt caverns. During electricity generation, pressurized air is expanded in a conventional gas turbine. During expansion, air temperature decreases considerably which can damage the blades of the turbine. Therefore, air is warmed in natural gas heaters during expansion [3]. Adiabatic CAES (ACAES) systems are introduced to avoid this fuel requirement during expansion stage of the conventional CAES system. In ACAES systems, generated heat during compression stage is stored and then used to warm up the air during expansion stage, so the fuel input requirement is eliminated [4]. European Union is focused on this concept to develop this technology for commercial use within the AACAES (Advanced Adiabatic CAES) project [5, 6]. Another concept that eliminates the fuel input is the isothermal CAES (I-CAES) where air is compressed and expanded at a constant temperature [7, 8]. One of the options to achieve isothermal compression and expansion is to use liquid pistons (LP) [8,9,10]. Various CAES designs with LP are under research for renewable

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energy sources and other applications [8, 9]. Kiliç et. al. made a mathematical model of a CAES with LP and they calculated the temperature and the pressure in LP and storage tanks [11]. Mutlu and Kiliç focused on the LP by simulating the compression process using computational fluid dynamics and determined the main parameters affecting the performance of the LP [12].

Although, a large number of study about the CAES is reported in the current literature, there is not too much study and applications present in the context of a standalone renewable energy storage with the CAES system for small scale applications. The aim of this study to present a prototype of the new small scale CAES system using liquid pistons for the compression and expansion processes. The new CAES system with LP is described in details and its performance is experimentally investigated. The system has a 1.5 kWh storage capacity and all system components are purchased from the market. Commercially available common hydraulic oil is used in the pistons and a pressure regulator (PR) which was constructed to adjust pressure between liquid side and air side of the system. Pressure and temperature changes are investigated during compression and component efficiencies are calculated.

CAES WITH LIQUID PISTONS AND EXPERIMENTAL SET UP

LP are similar to conventional pistons that are used in many applications like engines and compressors but in LP systems a fluid which water and oil are commonly preferred is used unlike other pistons. The fluid which is generally forced by a pump goes in to the piston chamber thus air volume decreases and pressure rises. The interface between the air and the fluid provides compression and prevents air leakages. The fluid pressure is related to air pressure, as air pressure increases, fluid pressure rises as well. Hence it can be said that a CAES system with LP has two main components which affect the performance and power of the system: one is the fluid pump and the other is LP. Schematic view of the experimental design is given in Fig.1.

As seen in figure there are two parts which are essential for proper working of the system addition to pump and LP. Air storage tanks are the environment where the compressed air is stored after compression and the pressurized air source of the expansion process. The working pressure of hydraulic systems are higher than pneumatic systems thus a PR is designed in order to

compensate the pressure difference between fluid and air and the PR takes an important role for the system. Some auxiliary equipment which are electrical motor, hydraulic unit and a computer are needed to control and ensure proper working of the system. The AC Electrical motor drives the hydraulic pump which pressurized the working fluid and its technical specifications are crucial to obtain efficient compression. The hydraulic unit consists of several hydraulic valves controlled by a PLC program for propose of directing the fluid flow to desired pipe or component. The computer controls the whole systems' components and stores the collected data from sensors.

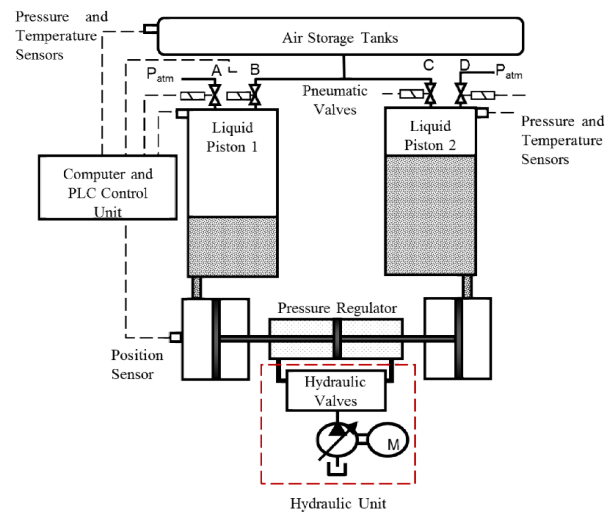


Fig.1. Experimental setup and main components of the system

The working principle of the system is based on pumping the fluid which was hydraulic oil in experiments though in the pistons and reducing the air volume in the piston chamber therefore air pressure rises according to ideal gas law (Eq.1).

$$PV = mRT \quad (1)$$

In this equation P is the air pressure in the piston chamber, V is the air volume, m is the mass of the air inside piston, R is the gas constant whose value is $287 \text{ Pa}\cdot\text{m}^3/\text{kg}\cdot\text{K}$ and T is the temperature of the air. According to critical temperature and pressure, gases behave as an ideal gas at high temperatures unless pressure is too high. Working range of the system is far from the critical values in the experiments thus ideal gas law approach is quite acceptable to calculate air properties. After the fluid is pumped hydraulic valves direct the flow through the piston which one is time for compression. When the air pressure which is measured by sensors that placed above of the piston reaches a previously defined value, valves (Valve C in Fig.1) that provide connection between piston and air tanks is

opened to allow air flow though in the tanks. In that stage of the compression the air pressure in tanks and piston is equalized and compression continues until fluid level reaches predefined upper limit which is similar to top dead center (TDC). Therefore the air mass and pressure rise in storage tanks and the compression process for this piston ends at this time. Then, valve C is closed and valve D connecting the piston to its environment is opened hereby air pressure decreases to atmospheric pressure and piston is able to vacuum air from ambient conditions, meanwhile fluid level in other piston reaches the bottom dead center (BDC) and the process is ready for compression. Using two pistons aims to ensure continuity by operating them simultaneously during compression and expansion. While one piston compresses the air other one vacuums the fresh air from ambient at atmospheric pressure. The energy input to the system is supplied by electrical motor driving the pump. The work which is done by pump increases when air is compressing because pump work is highly related to fluid pressure therefore the required work varies during compression process.

Operating of the system during expansion is fairly similar to compression process. Considering Fig.1, high pressure air enters the piston 2 where the fluid level is at TDC by opening valve C then it is closed in a few seconds therefore the piston 2 is filled up with pressurized air that can cause fluid flow thorough the hydraulic motor which is coupled with a generator to produce electricity. When the air expands in piston 2, valve A is open and fluid level rises up to TDC. Then valve A is closed and valve B is opened to preparing the next expansion step. The produced energy varies according to air pressure in the pistons so it alters during expansion and is needed to control smoothly.

The hydraulic systems operate at high pressures which is more than 250 bar, much as the pressure of the pneumatic systems is less than 10 bar. Therefore a device allowing these two systems to cooperate with each other is required. This issue is solved by designing the PR of which consists three hydraulic cylinders. Diameters of the two cylinders connecting to LP are three times greater than other ones. The main advantage of the PR is establishing a convenient coupling between two systems with different pressure. Moreover the fluid level in pistons can be determined by calculating the fluid flow rate that can be specified by volume difference using cylinder diameter and position measured by a sensor located in cylinders. On the other hand using an additional component in the system causes

energy losses thus the efficiency is influenced negatively.

COMPONENTS OF THE SYSTEM AND EXPERIMENTS

The key parts of the designed CAES system is mentioned above are purchased from the market. Since the compression and the expansion cycles are reverse each other, the components of the compression is given in this study. In expansion process hydraulic pump and electrical motor are substituted with hydraulic motor and generator respectively.

An asynchronous three phase electrical motor which consumes the electrical energy stored in the system was chosen. A 4 kW AC motor, whose speed is 1425 rpm with four pole, is used in experiments and its efficiency is 85.1%. The electrical motor is mounted to pump by using a coupling. As the electrical motor is the only device consuming electricity, it is substantial to measure the amount of the electrical energy which is used for compression in order to evaluate performance of the system. An energy analyzer is used to measure the voltage, current and energy values to determine the energy need of the system. The energy input through the system is measured then transferred energy to the pump is calculated by taking account the efficiency of the electrical motor and the coupling whose efficiency is assumed 90%.

In the designed system a variable displacement axial piston pump is employed by the reason of pressure altering which causes energy demand to vary in the pump during compression. The displacement of the pump is controlled by a load sensing control device according to pressures occurred in pump which is highly related to air pressure in LP. The pump supplied from the market is selected by considering oil mass flow rate which was needed to obtain desired compression time and needed power for the process but as it was designed for hydraulic systems which are commonly industrial application specifications of the pump (Table 1) is inadequate to meet the demands required for a special application like CAES. Hence it can be said that designing more suitable pumps for CAES systems can improve the performance of the system.

Table 1. Characteristics of the hydraulic pump

Nominal Pressure (MPa)	28
Maximum Pressure (MPa)	35
Maximum Displacement (cm ³ /rpm)	32
Maximum Flow Rate (litre/min)	100
Maximum Power (kW)	46

The input energy of the pump ($E_{p,in}$) is assumed being equal to energy transferred from the motor. The work done by pump is calculated by using oil volume and pressure difference which is between pump inlet and outlet (Eq. 2). The data recording interval is 2 seconds, thus the work done by pump was calculated in every 2 seconds and then all of them added in order to obtain total pump energy output.

$$E_{p,out} = \sum V \Delta P \quad (2)$$

In this equation V is the volume of the oil injected through in the PR and was calculated by determining the displacement in cylinders of the PR using position sensor. The energy efficiency of the pump is defined by ratio of output ($E_{p,out}$) and input energy amount (Eq.3).

$$\eta_p = \frac{E_{p,out}}{E_{p,in}} \quad (3)$$

The PR made up of three cylinders which are connected to one another in order (Fig.2). The diameter ratio between cylinder 2 and 1 is chosen 3 which means oil pressure in the LP reduces by three times while the oil flow rate increases with the same rate. The output energy of the device is calculated with the same approach as pump energy calculations and the output pressure of the PR is equal to the air pressure in LP.

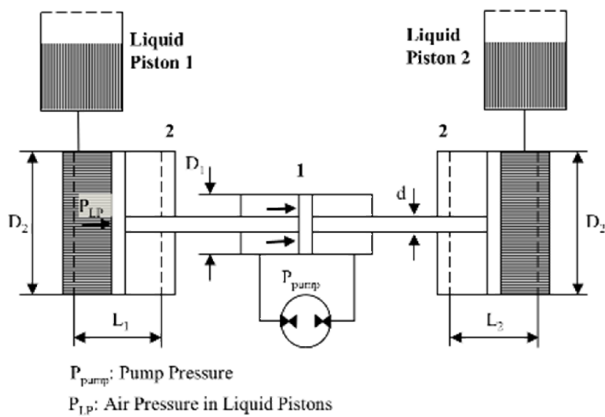


Fig.2. Schematic view of the pressure regulator

The LP whose length and diameter are 1.2 m and 0.2 m respectively were designed to compress air as slowly as possible to obtain isothermal compression that the minimum energy is needed. As a known phenomenon the air temperature increases when it is compressed thus energy transfer from the air is necessary for isothermal conditions. The hydraulic oil plays an important role with the purpose of transferring energy from the air which is in the piston chamber during compression process in the system. The energy required for isothermal compression ($E_{LP,ideal}$) is

calculated by Eq.4 and used in efficiency (Eq.5) calculations of the LP.

$$E_{LP,ideal} = P_1 V_1 \ln \frac{V_2}{V_1} \quad (4)$$

$$\eta_{LP} = \frac{E_{LP,ideal}}{E_{p,in}} \quad (5)$$

In this equations P_1 and V_1 are the air pressure and volume in the beginning of the compression stage respectively. V_2 is the final air volume after compression finishes. $E_{p,in}$ is assumed that it is equal to pump output energy value.

Dimensions of the air storage tanks are the same as LP. The storage capacity can be improved by mounting extra tanks to the system. In the experiments two storage tanks whose volume is around 62 l are used. The illustration of the whole designed system are given in Fig.3.

Temperature, pressure and power measurements are given in dimensionless form derived by dividing the initial values at the beginning of the compression stage on the purpose of comparing the results due to initial values affect the process remarkably and could not be controlled during experiments.

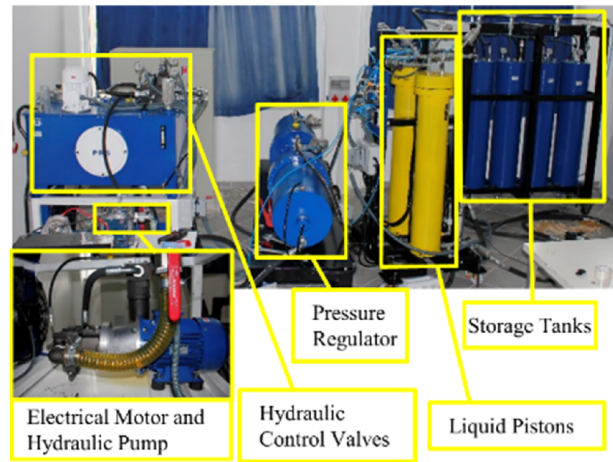


Fig.3. CAES with liquid pistons

Assessment of overall uncertainty

There are some uncertainties associated with instrumentation, the measurements of the temperature and pressure values due to the dynamics of the system cycle. Moreover, certain errors introduced due to the mathematical calculations. Considering a general case in which an experimental result, S is a function of k measured variables x as

$$S = S(x_1, x_2, x_3, \dots, x_k) \quad (6)$$

Eq.6 is the data reduction equation used for determining S from the measured values of the variable x . The uncertainty of the result (U_S) is then given by

$$U_S = \left[\left(\frac{\partial S}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial S}{\partial x_2} w_2 \right)^2 + \dots + \left(\frac{\partial S}{\partial x_k} w_k \right)^2 \right]^{1/2} \quad (7)$$

where the w_k are the uncertainties in the measured variable x_k . It is assumed that the relationship given by Eq.7 is continuous and has continuous derivatives in the domain of interest, that the measured variables x are independent of one another, and that the uncertainties in the measurable variable are independent of one another. It is expected that the overall uncertainty will be within 5%.

RESULTS AND DISCUSSION

The air pressure, temperature occurred in LP and motor power are examined in experiments during compression stage. Additionally, the effect of the compression speed which can be controlled by adjusting a variable hydraulic valve that is located after the pump in the system is investigated. Although the pump is variable, an addition valve is used to specify the desired oil mass flow rate because the aim of using a variable pump is to achieve more efficient system. Thus the oil flow rate can be defined according to valve opening which means that if the valve is fully open the oil flow rate becomes its maximum and if the valve is fully closed the oil flow rate equals to zero. The oil flow rates obtained from experiments are given in Fig.4. As seen in the Fig.4 there is a linear relationship between valve opening rates and oil flow rate.

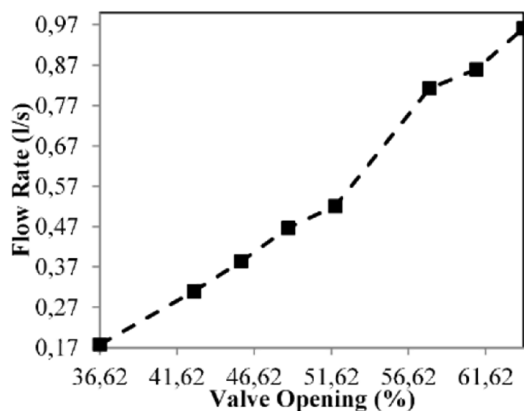


Fig.4. Oil flow rate according to valve opening

When the air pressure and temperature variation according to various valve openings in the liquid piston is examined in a single stroke it can be easily realized that compression takes more time at low

valve openings (Fig.5) and temperature (Fig.6) is highly related to compression speed which affects the heat transfer through the piston surfaces and required compression power (Fig.7).

Fast compression reduces the process time, hence, final air temperature increases inside the LP because sufficient heat transfer rates which are necessary to obtain isothermal conditions cannot be achieved (Fig.6). However, a 15 °C difference in air temperature which can be assumed as an isothermal process between initial and final conditions of the fastest compression stage.

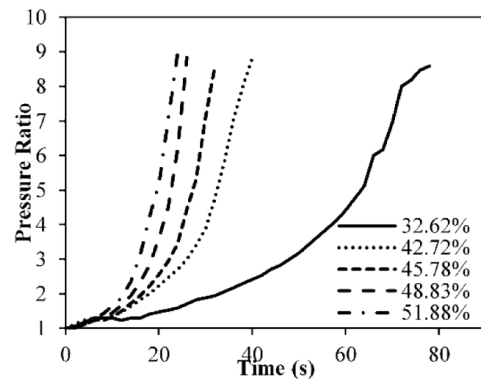


Fig.5. Pressure variation in a single compression stage

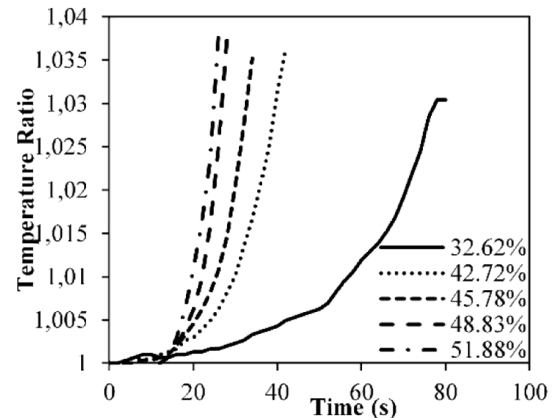


Fig.6. Temperature variation in a single compression stage

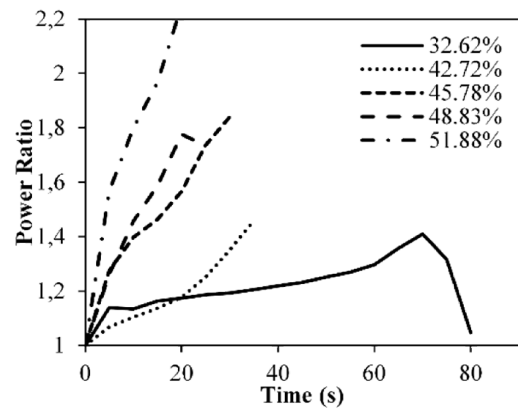


Fig.7. Power consumption of the electrical motor during a single compression stage

Because of minor deviations from isothermal conditions, the only factor affecting the power of the electrical motor is compression time as a result more power is required for faster process (Fig.7). Additionally, fast compression speeds make the system components like pump and PR work faster and increase the frictional energy losses. During compression process required power decreases when the valve between LP and storage tanks opens (Valve B and C in Fig.1 depends on compression stage) because of pressure drop occurred as soon as the valve opens.

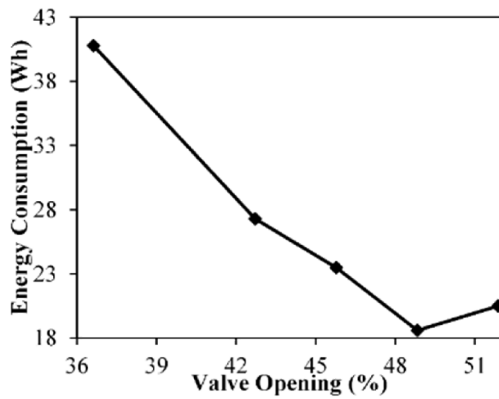


Fig.8. Energy consumption according to valve opening rates

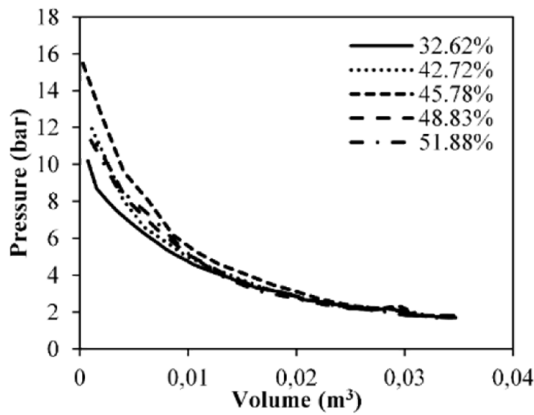


Fig.9. P-V curves with different compression speeds

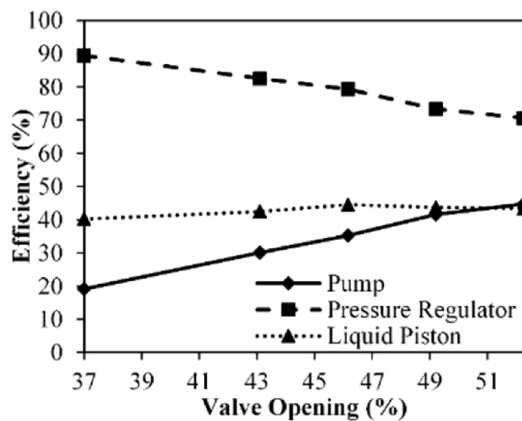


Fig.10. Efficiencies of the system components

Requiring less power does not mean to consume less energy because it is needed more time for compress air to desired pressure. As seen in Fig.8 consumed energy in a single stroke decreases till the valve opening is 48.83%. After that point the required power increases due to high flow rate and the consumed energy increases even the compression time decreases.

Tank pressure rises during the compression process therefore it is necessary to reach higher pressure than previous one which is needed more energy in every single compression stage.

The effect of the isothermal compression can be easily understood by P-V diagrams which explain the whole process. The P-V diagrams with various speed is given in Fig.9 presenting that higher compression speeds has a negative influence on isothermal conditions.

The efficiency of the system components is given in Fig.10. As seen in the figure faster compressions speeds considerably influence the PR efficiency which decreases from 90% to 70% because of increasing the frictional losses and inertia forces in PR. It is observed that compression speed slightly affect the efficiency of the LP much as the efficiency of the pump alters dramatically.

CONCLUSION

Energy storage systems will play an important role in feasibility of the renewable energy systems in near future. Conventional CAES systems are the only proved technology for large scale energy storage requirements. On the other hand renewable energy sources demands more compact and economic storage systems. In this study a new CAES system with liquid pistons is proposed and the experimental results from the prototype of the system are presented. It is observed that the compression speed is the key factor influencing the system performance for the isothermal compression and expansion cycles. Hence, it can be said that the control strategies with a dynamic speed control should have to be planned to consider the dynamic compression process. During the experimental study, the CAES system is run to achieve the isothermal compression which is supposed to be the most efficient process. Despite succeeding the isothermal conditions which the air temperature increases by only 4% of its initial value, the minimum energy consumption does not occurred in minimum speed because of the performances of the system components change with speed and uncontrollable behaviors are observed during the cycle processes. After all, P-V diagrams shows that

compressing slowly the process approaches the isothermal conditions. Unsurprisingly increasing the storage pressure needs more energy for a single compression stage. Since the system is assembled with components commercially available in the market, the efficiencies of the components such as electric motor, hydraulic pumps etc, are highly affected when they work at off design conditions. Therefore, it is concluded that special pump and motor designs must be used for a better system performance. Although, the results presented in this study is promising, further improvements and developments are required for fully reliable and commercially available small scale CAES systems.

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