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Performance analysis of a small-size CAES system

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Abstract. Energy storage systems represent one of the most concrete solutions for solving the main two limits of the renewable energy sources (RES): punctuality and not programmable generation. Among them, Compressed Air Energy Storage (CAES) technology is an efficient, low cost, and extremely adaptable option for small scale applications. In the present paper performances of a volumetric unidirectional-flow turbine has been studied. This turbine shows good efficiency also when high-humidity air is expanded, because condensation phenomena do not affect turbine performances.

Firstly the experimental apparatus has been realized, then the plant theoretical efficiency has been calculated. This value has been thus compared with the experimental efficiency. Finally theoretical study has been carried out evaluating the possibility to substitute air with waste evolving fluids like flue gas and lime kiln gas, in order to increase the plant efficiency and, reuse these gaseous mixtures. Results show that both flue gas and lime kiln gas allow to increase plant efficiency, so they could represent an interesting option for performing CAES systems.

Keywords: energy storage; compressed air; CAES; quasi-turbine; air expansion.

INTRODUCTION

The increasing of atmospheric pollution originated from climate-changing substances emission and the consequent increase in the average temperature of the Earth's surface have prompted the governments of several countries to increase their investments on renewable energy sources (RES) [1-3]. Additionally, there is a growing need to identify alternative sources of energy to those of fossil origin: fossil energy resources are not unlimited, e.g. oil reserves will end up within this century [4,5]. Furthermore, non-holder countries need to reduce their energy dependence from other countries and thus to become less sensitive to fluctuations in energy prices and even periods of geopolitical instability [6,7]. Since the 1973 oil crisis, public investments in the clean energy sector have increased considerably, leading many technologies to commercial maturity. To date, one of the most important research goals is to overcome the two main limits to RES diffusion: the typical non-programmability and their distributed generation. Energy storage systems (ESS) offer the possibility to act in both directions simultaneously. ESS provide a wide array of technological approaches to managing power supply in order to create a more resilient energy infrastructure and bring cost savings to utilities and consumers [8]. Energy storage is the conversion of energy to other forms so that it can be used at a later stage when required. Industrial scale energy storage technologies are measured in terms of their power output (MW) and their capacity (MWh). According to market research, the energy storage market is set to "explode" to an annual installation size of 6 GW in 2017 and over 40 GW by 2022, from an initial base of only 0.34 GW installed in 2012 and 2013. Electricity storage can be pursued in four different ways: electrical, mechanical, thermal and chemical. In the first case the most important devices are super-capacitors and superconductive magnetic coils. Mechanical systems are composed by Pumped Hydro Storage (PHS), Compressed Air Energy Storage Systems (CAES) and Flywheels. As far as chemical storage is concerned, the most developed solutions are Lithium-ion Battery, Lead-acid Battery, High Temperature Batteries, Flow Batteries, Hydrogen and Natural Gas Storage Systems [9-18]. Among the above-mentioned energy storage technologies, CAES and PHS are the most viable one for large scale storage application [18]. CAES presents lower capital and operational costs than PHS and has less geographic restrictions [19-20]. Nowadays there are two types of

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CAES systems: diabatic and adiabatic CAES [21]. In the first case thermal energy produced during the compression phase is dissipated and therefore it is not transformed into mechanical energy. Accordingly efficiency decreases and, to obtain the same useful work using an equal stored air quantity, it is necessary to carry out an additional air heating before the expansion phase. In the second case, the produced thermal energy is not lost, but stored by thermal energy storage devices (TES) and realesed during the expansion phase. Adiabatic CAESs allow to achieve higher efficiencies, but plant costs are higher, due to the complexity of the system. There are two existing CAES plants, Huntorf in Germany and McIntosh in United States, and they are both diabatic CAES plants. The Huntorf plant has 320 MW power rating and 42 % efficiency, while the Mclntosh plant is about 110 MW and 54 % efficiency. Both CAES plants use underground sites, as salt mines or rock caverns, to store the compressed air between 4 and 8 MPa.

The aim of this work is to evaluate the performances of a small-size diabatic CAES system for residential application. This system could be indeed used to store the surplus of electricity produced by photovoltaic panels or other RES. A small-size CAES system introduces outstanding advantages in comparison with solutions adopted until now: lower used volumes and smaller maintenance necessity [22].

In the second part of this paper, the theoretical performances of the system fed by other gaseous mixtures (waste fluids) were evaluated.

EXPERIMENTAL APPARATUS

The experimental apparatus, built at the Applied Physics Laboratory of the University of Perugia, consists of a small-size plant, which can be easily arranged and managed into a residential unit. The experimental apparatus is shown in Figure 1.

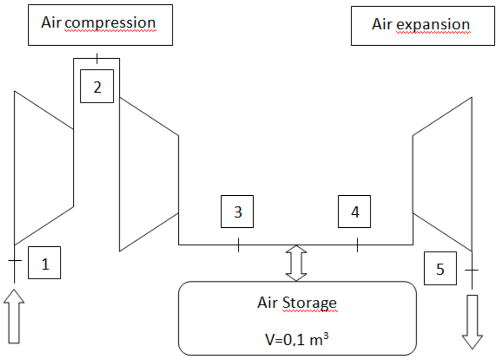

Figure 1. Schematic of the experimental apparatus.

The system is composed by a compression section, an air storage vessel and an expansion section. Air is compressed through an air-cooled two-stage reciprocating compressor. The maximum outlet pressure is 35 bar, with a flow rate of 15 Nm^3/h (G_{airC} = 0.004 Nm^3/s). The compressed air is stored in a stainless steel storage tank with a total internal volume of 100 l. The vessel is equipped with two temperature sensors, which measure the temperature of air inside the vessel both in the lower and upper side, and a pressure gauge. The air expansion section is constituted by an expansion quasi-turbine (Model QT.6LSC Steam), coupled with a mechanical load. The turbine is a pressure driven continuous torque deformable four blades rotor. The volume enclosed between the blades of the rotor and the stator casing provides compression and expansion. Each of the four blades produces two compression strokes per revolution which provides a total of eight expansion strokes per revolution when used as a turbine.

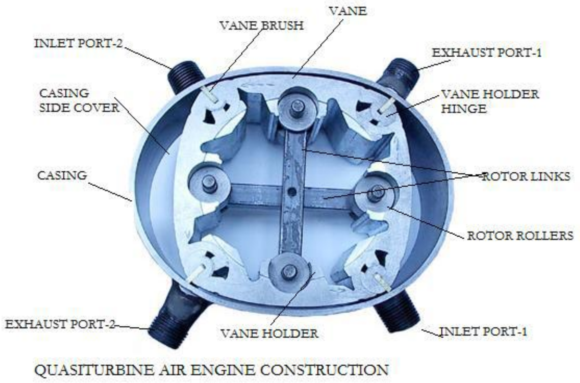

Figure 2. Schematic of the quasi-turbine.

Technical data of the apparatus, used for the numerical simulation, are reported in Table 1.

Compressor			Turbine		
Outlet pressure	bar	30	Intake pressure	bar	4
Flow rate (G_{airC})	Nm^3/h	15	Flow rate (G_{airT})	Nm^3/h	65
Output power	kW	2.1	Output power	kW	1.5
Electrical power	kW	2.2	Maximum torque	Nm	30
Efficiency (η_C)	%	80	Efficiency (η_T)	%	70

Table 1. Technical data of the experimental apparatus.

A pressure reducing valve and a flowmeter were mounted before the quasi-turbine to control both pressure and air flow rate. The maximum inlet pressure on the pressure reducing valve is 35 bar, while outlet pressure can be set between 1 and 7 bar. The flowmeter has been produced by Yokogawa; it measures volume flowrates of a liquid or aerial fluid until to a maximum value of 1.7 Nm^3/min. To test the performance of the air expansion section, a mechanical load was applied to the quasi-turbine, through the use of a hydraulic pump (Polaris PL 20.20 Pump). Between the turbine and the pump a torque meter was also mounted. The torquemeter was used for measuring angular velocity and torque. The torque sensor chosen for the experimentation is TS 3000 NTCE. All components explained before were joined through tailor made joints, forming an axle that joins quasi turbine to the torque meter and this last to the pump. Finally the entire experimental apparatus comprehensively assembled is shown in Figure 3.

Figure 3: Experimental apparatus.

METHODOLOGY

First of all the theoretical efficiency η_{id} of the systems has been calculated. Later it has been compared with the real value η_r resulting from the experimental measurements.

Both efficiencies have been evaluated considering a compression process during which the air pressure is raised to 30 bar. In the ideal case an adiabatic transformation has been assumed. In the real one, the electric energy adsorbed by compressor has been directly measured by means of a volt-amperometric pliers.

For the expansion process has been assumed a constant value both of the inlet pressure (equals to 4 bar) and of volumetric flow rate (G_{airT} = 0.02 m^3/s), in the ideal case. In real operation the measured inlet pressure is not constant but shows a slight decrease in time.

In the last part of this work a research about the using of evolving gaseous fluids different from air has been carried out. In particular three gaseous mixtures have been considered: CO_2, Flue gas and Lime Kiln gas. The same theoretic model used during the characterization of the small-scale CAES plant has been adopted to determine the plant functioning with these mixtures. Therefore global efficiencies obtained for each species have been compared with the plant theoretic global efficiency calculated before. Topic of this section is to identify a waste industrial substance and using it to increase the small-scale CAES plant efficiency.

RESULTS

Theoretical efficiency

For the compression phase, it was assumed an intercooled two-stage compression: a first stage with pressure ratio β_1 and a second stage with β_2. The energy absorbed by the compressor is calculated according to the Equations 1:

$$E_c = G_{airC} \cdot \Delta h_c \cdot \tau_c \tag{1}$$

where τ_C is the time necessary to fill the tank and Δh_C is given by:

$$\Delta h_c = \frac{C_{p1-2} \cdot (T_2 - T_1) + C_{p2-3} \cdot (T_3 - T_2)}{\eta_c} \tag{2}$$

with:

$$T_2 = T_1 \cdot (\beta_1)^{k-1/k} \; ; \; T_3 = T_2 \cdot (\beta_2)^{k-1/k} \tag{3}$$

The energy produced by the quasi-turbine (pressure ratio β_3 equals to 4) is calculated by:

$$E_T = G_{airT} \cdot \Delta h_T \cdot \tau_T \tag{4}$$

where Δh_T is given by:

$$\Delta h_c = \frac{C_{p3-4} \cdot (T_3 - T_4)}{\eta_T} \tag{5}$$

with

$$T_4 = T_3 \cdot (\beta_3)^{1-k/k} \tag{6}$$

The theoretical efficiency is then calculated as:

$$\eta_{id} = \frac{E_T}{E_c} \tag{7}$$

In Table 2 the values obtained by Equations 1-7 are reported.

First stage pressure ratio ($P_2/P_1 = \beta_1$)	6	Δh_C [kJ]	616
Second stage pressure ratio ($P_3/P_2 = \beta_2$)	5	Δh_T [kJ]	140
Expansion pressure ratio ($P_4/P_5 = \beta_3$)	4	E_C [kJ]	1848
τ_C [s]	720	E_T [kJ]	420
τ_T [s]	150	η_{id}	0.228

Table 2. Calculated data.

Real efficiency

The plant real efficiency has been obtained by dividing the real energy produced by the turbine, by the energy absorbed by the compressor. The energy produced has been calculated from the values (torque and rpm) measured by torquemeter (see Table 3). Energy absorbed by compressor is reported in Figure 4.

Time [sec]	Torque [Nm]	Average rps [1/sec]	Energy [kJ]
10	26.2	9.8	16.13
20	26.0	9.8	16.01
30	25.8	9.7	15.72
40	25.6	9.5	15.28
50	25.4	9.4	15.00
60	25.2	9.2	14.57
70	25.0	9.4	14.77
80	25.0	9.2	14.45
90	24.8	8.9	13.87
100	24.6	8.6	13.29
110	24.6	8.5	13.14
120	24.4	8.2	12.57
130	24.2	8.0	12.16
140	24.2	8.0	12.16
150	24.0	7.8	11.76
160	24.2	7.7	11.71

Table 3. Measured values of torque, rps and energy production, evaluated during the expansion phase.

The total energy produced by the turbine E_{Tr} is 222.6 kJ. Thus it's possible to calculate the real plant efficiency as ratio between energy produced by the turbine and energy adsorbed by the compressor; the efficiency is: $\eta_r = 0.188$.

Performance improvement by using a different evolving fluid from air

The small size CAES shown in the previous paragraph was designed to work with air; the efficiency of the plant was evaluated as the ratio of the energy produced by the expansion of the turbine air and the energy absorbed during the air compression phase, that is the energy absorbed by the compressor. The calculated efficiency reaches the value of 22.8%. In this section, a theoretical analysis has been carried out to verify the advantages in terms of efficiency when air is replaced by other gaseous fluids. In particular three different solutions have been explored on the basis of availability, transport costs and the specific heat capacity: pure carbon dioxide, flue gas and lime kiln gas. For each of them, a calculation of ideal work, real work end efficiency during the expansion phase has been carried out. The characteristics (composition and Langen coefficients) of each mixture are reported in Table 4 [23-29]. In Table 4 efficiency is also reported.

Evolving Fluid	Air	CO_2	Flue Gas	Lime Kiln Gas
CO_2 [%]	-	100	9	31
N_2 [%]	80	-	91	69
a [kj/kgK]	0.953	0.832	0.972	0.938
b [kJ/kgK]	$1.50 \cdot 10^{-4}$	$3.59 \cdot 10^{-4}$	$1.77 \cdot 10^{-4}$	$2.21 \cdot 10^{-4}$
L_{id} [kJ]	1433.3	995.9	1440.1	1337.9
L_r [kJ]	280.6	263.1	288.1	282.0
η_T	0.228	0.234	0.223	0.232

Table 4. Parameters necessary for evaluating performances of each evolving fluid taken into account.

Results show that air is not a good solution with regard to efficiency, while carbon dioxide is the best one. In terms of produced energy, the flue gas is the best solution. A good compromise is represented by lime kiln gas. Efficiency obtained is almost equal to the CO_2 one and, at the same time, the real work calculated is very similar to the one calculated with flue gas; so lime kiln gas seems to be the best solution to optimize the necessity of having high values of both work produced and efficiency.

CONCLUSIONS

The first aim of this work was the setting up a small-scale CAES plant, characterized by a little occupied volume and handy, to be used in residential units, and the evaluation of the operating parameters and the calculation of plant efficiency.

The plant has been assembled at the Applied Physics Laboratory of the Engineering Department, University of Perugia. The first step was to calculate the theoretical efficiency which has been possible to achieve with the assembled apparatus, then an experimental campaign has been carried out in order to verify the real plant efficiency and its distance from the ideal one.

We also evaluated the possibility of using fluids different from air to "recycle" waste fluids inside a energy conversion cycle and to verify their effect on plant efficiency. Gaseous mixtures such as flue gas and lime kiln gas were considered: both of them have allowed us to improve plant performances. Lime kiln gas in particular, allow us to reach an expansion efficiency of 23.2 % (air is 22.8%). Instead, flue gas is the best solution for increasing the work produced by the turbine. Even the possibility of using a pure CO_2 flow has been taken into account. In that case efficiency grows up to 23.4%. Carbon dioxide, on the other hand, needs a closed cycle in order to not disperse it in the atmosphere.

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