Use of phase change materials during compressed air expansion for isothermal CAES plants

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Abstract. Compressed air energy storage (CAES) plants are designed to store compressed air into a vessel or in an underground cavern and to expand it in an expansion turbine when energy demand is high. An innovative CAES configuration recently proposed is the isothermal process. Several methods to implement isothermal CAES configuration are under investigation. In this framework, the present paper deals with the experimental testing of phase change materials (PCM) during compressed air expansion phase. The experimental investigation was carried out by means of an apparatus constituted by a compression section, a steel pressure vessel, to which an expansion valve is connected. The initial internal absolute pressure was equal to 5 bar to avoid moisture condensation and the experimental tests were carried out with two paraffin-based PCM amounts (0.05 kg and 0.1 kg). Results show that the temperature change during air expansion decreases with increasing the PCM amount inside the vessel. With the use of PCM during expansions an increase of the expansion work occurs. The increase is included in the range from 9.3% to 18.2%. In every test there is an approach to the isothermal values, which represent the maximum theoretical value of the obtainable expansion work.

1. Introduction
The increasing share of renewable energy in the existing electricity network leads to several challenges, mainly related to the intermittency and unpredictability of the renewable sources. Due to such a characteristic, there is mismatch between the electricity production and the corresponding consumption, which is currently compensated by spinning reserve and fast start generators. In addition, when the renewable sources are highly available, the produced power exceeds the transmission capacity limits, with a consequent increase of service costs [1]. The introduction of energy storage systems in the above-described scenario provides several beneficial services, allowing the electrical system to run more efficiently [2-3].

There is a wide range of different technologies to store electrical energy: mechanical, electrochemical, chemical, electrical and thermal energy storage systems [4-6]. The most common mechanical storage systems are pumped hydroelectric power plants, compressed air energy storage (CAES), flywheel energy storage and mechanical springs. Electrochemical storage systems consist of various types of batteries (lead acid, NiCd/NiMH, Li-ion, metal air, sodium sulphur, sodium nickel chloride and flow battery). Chemical energy storage focuses on hydrogen and synthetic natural gas (SNG) as secondary energy carriers and, finally, electrical storage systems include double-layer capacitors and superconducting magnetic energy storage [7-14]. Technologies used for high power ranges and energy capacities are pumped hydro storage (PHS) and CAES [15].
CAES plants work by pumping and storing air into a proper reservoir when excess or low-cost electricity is available. Then, during the peak demand periods, the pressurized air is expanded in an expansion turbine to produce electricity. Today only two CAES power plants are in operation worldwide, both based on the diabatic configuration [8]. In the diabatic CAES, heat released during compression is dissipated by cooling and not stored, therefore air must be reheated prior to expansion in the turbine through fuel combustion. To improve efficiency of diabatic CAES, other configurations have been proposed and worldwide other CAES plants are under development and construction. Among the improved or advanced CAES technological proposals, there is the adiabatic CAES, in which heat from the high-temperature compressed air is absorbed, stored and used to reheat the air before expansion. The roundtrip efficiency is over 70 % [16].

The new emerging technology which attempts to overcome the limits of diabatic and adiabatic CAES is isothermal CAES. Isothermal CAES is based on isothermal compression and expansion in situ. In this way the need for fuel and high temperature thermal energy storage is eliminated. Isothermal CAES requires to remove heat continuously during compression and add heat continuously during expansion by means of effective heat transfer [17].

Currently there are no commercial isothermal CAES plants, but some solutions have been proposed. One consists in water spraying into the air-filled chamber of pneumatic cylinders, so that heat is transferred from water to air during expansion or from air to water during compression [18].

Another way to do isothermal air expansion or compression is the use of phase change materials (PCM) as thermal storage media to obtain no temperature change during air transformations. The present paper deals with the experimental investigation on the effects of PCM during compressed air expansion. Tests were carried out in an experimental apparatus, whose main section is constituted by a 100 L pressure vessel in which air is compressed and stored. The experimental campaign has as objectives the temperature decrease monitoring and the evaluation of the obtainable expansion work. Work values were then compared to the theoretical isothermal value.

2. Motivation

Even though CAES technology was historically applied for large-size installations for grid management, greater attention is currently directed to small-size innovative applications [19-23]. Large-size CAES plants require the selection of suitable geological reservoirs, which limit the installed capacity because of geographical and geological constraints [24].

Small-size CAES instead can use custom-fitted above-ground storage vessels, allowing the construction of the plant where the service is requested. This ensures portability and adaptability of the system also for distributed energy productions [25]. Currently, increasing effort is devoted to complete energy evaluation and process optimization studies with the objective of overall performance improvement. Energy and exergy analyses in literature highlighted that micro-CAES systems are very effective systems for distributed energy production applications [23, 26] and they reach high efficiency if based on quasi-isothermal compression and expansion processes [11].

Given the above-mentioned theoretical findings, this paper wants to give an experimental contribution on the advanced highly efficient CAES technology development, especially for small-size applications.

It deals with the evaluation of the effect of PCM during air expansion in obtaining quasi-isothermal conditions. PCM are storage media with a high latent heat value. Latent heat is the energy exchanged in a phase change, during which there is no change of temperature. The use of PCM is proposed in order to control P-v curve during air expansion so that it can resemble or practically approach an isotherm. The phase change of paraffin-based PCM has the effect of both levelling the internal temperature profile during air expansion, getting close to isothermal conditions and increasing the obtainable work.
3. Materials and methods

The experimental procedure consists in storing compressed air in a steel vessel and expanding it in presence of PCM. During expansion, temperature and pressure values are recorded and used for calculation of P-v curve and the extractable useful work. The scheme of the experimental apparatus is shown in Figure 1. It is formed by a compression section, a steel pressure vessel, to which an expansion valve is connected.

![Figure 1. Schematic diagram of the experimental apparatus with the air compressor and high-pressure vessel.](image)

Compression, supplied by Adicomp Italy, is done by an air-cooled two-stage reciprocating compressor. The maximum outlet pressure is 30 bar with a flow rate of 4 Nm³/h. Compressed air is uploaded in a steel vessel with a total internal volume of 100 l. It has been designed for pressure values up to 200 bar. The reservoir is equipped with two temperature sensors, which measure the temperature inside the vessel in the lower part and in the upper part, and a pressure gauge.

The temperature sensors are mineral insulated type K thermocouples; the accuracy class is 1 with ± 1.5 °C tolerance range. The pressure sensor is a 0.5 accuracy class digital piezo-resistive manometer supplied by Kobold; the pressure measurement uncertainty is ± 0.2 bar. Voltage signals from pressure transducers and temperature sensors are collected every 2 seconds by a software for data acquisition on a personal computer.
Tests were conducted in accordance with the following procedure: i) in case of expansion in presence of PCM, the proper amount of PCM is loaded in the tank (50 g or 100 g), ii) air is compressed and loaded inside of the tank until an internal pressure of 5 bar is reached, iii) internal temperature and pressure are adjusted to achieve the correct initial conditions, iv) the expansion valve is opened to complete the expansion of the air.

In this investigation, a turbine to recover the expansion work was not used. In absence of the turbine, air expansion takes place by opening the expansion valve. The effect of PCM on the expansion is estimated by monitoring the values of temperature and pressure, which are used at a later stage for the calculation of the expansion work.

The PCM used in the experimental investigation is a paraffin-based material and was supplied by Rubitherm Technologies GmbH. Physical properties are described in [17]. Physical properties of the used PCM are shown in Table 1. The reported value of the heat storage capacity is a combination of latent and sensible heat in a temperature range of 11 °C to 26 °C, as stated by the supplier.

The calculated amount of PCM is settled on the vessel’s internal wall.

### Table 1. PCM: list of physical properties.

| Properties                        | Material    |
|-----------------------------------|-------------|
| Melting Area [°C]                 | 17-19       |
| Congealing area [°C]              | 19-17       |
| Heat storage capacity [kJ/kg]     | 250         |
| Specific heat capacity [kJ/kg K]  | 2           |
| Density solid [kg/l]              | 0.88        |
| Density liquid [kg/l]             | 0.77        |
| Heat conductivity [W/m K]         | 0.2         |
| Volume expansion [%]              | 12          |

4. Results and discussion

Tests were devoted to determine the effect of PCM on air expansion phase. The initial internal absolute pressure was equal to 5 bar to avoid moisture condensation. The measured air’s relative humidity was equal to 65%. Table 2 summarizes experimental conditions for the carried out tests. Temperature and pressure data were used to calculate specific volume through CoolPack Software. Tests were carried out varying both the PCM amount and the initial air temperature.

The theoretical PCM quantity to obtain isothermal conditions was calculated through Equation 1:

\[
m_{\text{PCM}} = \frac{m_{\text{air}} \cdot c_{\text{air}} \cdot \Delta T_{\text{air}}}{C_{\text{PCM}}} \tag{Eq. 1}
\]

where
- \(c_{\text{air}}\) is air specific heat capacity [kJ/kg K]
- \(C_{\text{PCM}}\) is the PCM heat storage capacity [kJ/kg]
- \(\Delta T_{\text{air}}\) is the temperature difference between initial temperature and final temperature [K]
- \(m_{\text{air}}\) is the air inside the vessel at experimental conditions of pressure and temperature [kg]
- \(m_{\text{PCM}}\) is the quantity of PCM necessary for isothermal expansion [kg].

For a 4-bar expansion, the calculated PCM amount is equal to 47 g (0.047 kg, 0.061 l). It was decided to carry out experimental tests with two PCM amounts: 50 g (0.05 kg) equal to the theoretical value and 100 g (0.1 kg), double the theoretical amount. To increase the interfacial area between air and PCM and to reduce the negative effects of the low thermal diffusivity (1.298·10⁻⁷ m²/s) on the heat...
transfer, PCM was laid down on the internal wall of the vessel. The internal volume occupied by PCM (0.065 l and 0.13 l respectively) is practically negligible with respect to the total volume of the vessel. Thus this does not affect heat transfer conditions, expansion times and air flows during the expansion.

Internal temperature values are calculated as the average of the two temperature values measured by two thermocouples in two different positions. Different temperature values from 28.6 °C and 19.3°C are investigated, comparing expansions without PCM with expansions in presence of different PCM amounts. Temperature values are all above the phase change temperature of the used PCM.

Table 2. Experimental tests.

| N.  | PCM (g) | Initial Temperature (°C) | Final Temperature (°C) | ΔT (°C) | Initial Absolute Pressure (bar) |
|-----|---------|--------------------------|------------------------|---------|-------------------------------|
| 1   | -       | 28.6                     | 1.3                    | 25.6    | 5.1                           |
| 2   | -       | 27.2                     | 1.3                    | 25.9    | 5.0                           |
| 3   | -       | 26.7                     | 2.1                    | 24.6    | 5.1                           |
| 4   | -       | 24.3                     | 1.0                    | 24.3    | 5.0                           |
| 5   | -       | 19.3                     | 0.6                    | 18.7    | 5.1                           |
| 6   | 50      | 28.5                     | 14.9                   | 13.6    | 5.0                           |
| 7   | 50      | 27.2                     | 15.1                   | 12.1    | 5.0                           |
| 8   | 50      | 26.6                     | 12.1                   | 14.5    | 5.0                           |
| 9   | 50      | 24.2                     | 13.2                   | 11.0    | 5.0                           |
| 10  | 50      | 19.3                     | 10.0                   | 9.3     | 4.9                           |
| 11  | 100     | 28.4                     | 16.8                   | 11.6    | 5.0                           |
| 12  | 100     | 27.4                     | 16.6                   | 10.8    | 5.0                           |
| 13  | 100     | 26.6                     | 15.3                   | 11.3    | 5.0                           |
| 14  | 100     | 24.2                     | 15.4                   | 8.8     | 4.9                           |
| 15  | 100     | 19.3                     | 14.8                   | 4.5     | 4.9                           |

The first five tests were carried out without PCM, with an initial temperature of 28.6 °C (test 1), 27.2°C (test 2), 26.7°C (test 3), 24.3°C (test 4) and 19.3°C (test 5). Tests with 50 g and 100 g of PCM were carried out at the same values of initial temperature, so that we can compare test 1 with test 6 (with 50 g of PCM) and test 11 (with 100 g of PCM) and so on.

Table 2 reports, for each test, also the final temperature and the difference between initial and final values. The temperature change during air expansion decreases with increasing the PCM amount inside the vessel. In particular, for tests 1-4 the variation is in the range 24-26°C, while for tests 6-9 with 50 g of PCM the variation is in the range 11-15°C and for tests 11-14 it is included in the range 8-12°C. No substantial temperature differences ΔT are recorded comparing 50 g PCM tests with 100 g PCM tests. For tests at 19.3°C, instead, the temperature variation undergoes a greater decrease, from 18.7°C of test 5 to 9.3°C and 4.5°C of tests 10 and 15 respectively.

Profiles of internal pressure and temperature during air expansion for tests 1, 6 and 11 and tests 5, 10, 15 are shown in Figure 2. Temperature profiles show visibly that in presence of PCM, temperature decrease during air expansion is leveled off and temperature difference at the end of the expansion is lower than that without PCMs. Pressure profiles instead do not show significant dissimilarities.
Figure 2. Temperature and pressure profiles.

For every test, the acquired values of pressure and specific volume were used to build the P-v curve and to calculate the obtainable expansion work. Results from the tests were compared to the theoretical adiabatic and isothermal expansions. Adiabatic and isothermal curves on the P-v plane were depicted in accordance to Equation 2 and Equation 3 respectively:

\[ P = \frac{k}{v^\gamma} \]  
\[ P = \frac{R \cdot T}{v} \]

where:
- \( P \) is pressure;
- \( v \) is the specific volume;
- \( k \) is adiabatic constant;
- \( \gamma \) is the adiabatic index calculated as the ratio of the heat capacity at constant pressure to heat capacity at constant volume;
- \( R \) is gas constant;
- \( T \) is the internal temperature.
P-v diagrams for 4-bar expansions in tests 1, 7, 13 are depicted in Figure 3. Test 1 without PCM is placed between the adiabatic and the isotherm, while tests 7 and 13 with PCM approach the isothermal curve. The benefit of PCM use in terms of obtainable expansion work is better clarified in Table 3.

![Figure 3. P-v curves – Tests 1-7-13 (28.5 °C).](image)

Table 3 shows the expansion work for all the tests. In the same row, work values in J/kg from expansions with the same initial temperature are compared. As a reference, also the isothermal work, calculated considering the same initial conditions, is reported.

Together with the expansion work, also the related increase obtained with the use of PCM is reported and expressed as a percentage value with respect to the baseline tests without PCM. Benefits from the use of PCM during expansions are demonstrated by the increase of the expansion work which occurs in every test with PCM. The increase is included in the range from 9.3% in test 6 to 18.2% in test 15. The general trend of the results shows that there is an approach to the isothermal values, which represent the maximum theoretical value of the obtainable expansion work.

Some other observations can be deduced from data in Table 3. The influence of PCM becomes greater with increasing the amount of PCM. Comparing tests with 50 g of PCM with tests with 100 g of PCM, the increase in the expansion work is bigger. This is quite evident at 19.3°C, when the increase with 50 g of PCM is equal to 14.0%, while with 100 g of PCM it is equal to 18.2%.

This result is in contrast with other tests in which PCM were encapsulated [15]. In that experimental investigation, PCM were encapsulated in several disk packets, resulting in an incomplete phase transition with consequent lower thermal storage.
Table 3. Expansion work.

|             | Test 1 | Test 6 | Test 11 | Isothermal |
|-------------|--------|--------|---------|------------|
| Expansion work (J/kg) | 26.87  | 29.37  | 29.68   | 33.04      |
| Increase (%)     |        | 9.3    | 10.5    |            |
| Expansion work (J/kg) | 26.46  | 29.41  | 30.46   | 32.89      |
| Increase (%)     |        | 11.1   | 15.1    |            |
| Expansion work (J/kg) | 25.91  | 29.95  | 30.05   | 32.83      |
| Increase (%)     |        | 15.6   | 16.0    |            |
| Expansion work (J/kg) | 26.36  | 29.7   | 30.56   | 32.57      |
| Increase (%)     |        | 12.7   | 15.9    |            |
| Expansion work (J/kg) | 26.21  | 29.88  | 30.97   | 32.02      |
| Increase (%)     |        | 14.0   | 18.2    |            |

In the cited paper, higher improvements in the expansion work were obtained with a lower amount of PCM. Heat capacity phenomena play a significant role in the complete exploitation of the transition phase and this aspect should be investigated in the future stages of the research.

5. Conclusion

Great efforts are devoted on CAES systems in order to identify novel highly-efficient configurations. Current research is focused also on the study of materials for thermal exchange and critical components. The present work is well integrated in this context, since the objective of the experimental investigation is the testing of PCM in compressed air expansions to approach isothermal conditions.

The testing took place through the use of an apparatus, constituted by a compression section and a pressure storing vessel, from which air expands via an expansion valve. 15 tests were conducted at an initial pressure of 5 bar and for each expansion achieved was calculated by the obtainable work.

Results show that through the use of the PCM a levelling of the internal temperatures occurs and an increase of the work of expansion up to a maximum of 18.2%. Through the use of PCM, P-v curves approach the isotherm, providing near-isothermal conditions for the expansion phase. Results give experimental evidence of the potential benefit of PCM in CAES plants, providing a viable solution to increase the work of expansion, thereby increasing considerably the efficiency of the whole process.

Nevertheless, some aspects should clarified in the future, such as the role of encapsulation. Different methods of encapsulation and deposition of PCM inside the vessel lead to contrasting results. Finally, a future step of the research is the integration of a 4-bar expansion turbine in the experimental apparatus, so that complete energy balance analysis will be carried out.

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