Analytical models for adiabatic compressed air energy storage (A-CAES) systems in lined tunnels

Javier Menéndez1,*, Jorge Loredo2, Laura Álvarez de Prado3, Jesús M. Fernández-Oro4, Antonio Bernardo-Sánchez2

1SADIM, S.A. S.M.E, Mining and Civil Department, 33900 Ciaño, Spain
2UNIVERSITY OF OVIDO, Mining Exploitation Department, 33005 Oviedo, Spain
3UNIVERSITY OF LEÓN, Department of Mining Technology, Topography and Structures, 24071 León, Spain
4UNIVERSITY OF OVIDO, Energy Department, 33271 Gijón, Spain

*Corresponding author’s e-mail: javiermenendezr@gmail.com

Abstract. Adiabatic compressed air energy storage (A-CAES) systems consist of an underground reservoir where compressed air is stored at high pressures. The ambient air is compressed by compressors located at the surface and the thermal energy is stored using thermal energy storage (TES) systems. The compressed air is stored in the subsurface reservoir (charge). Then, when the electricity is needed, the compressed air is released and expanded in gas turbines to produce electricity (discharge). In this paper, an analytical model has been developed to investigate the thermodynamic behaviour during air charge and discharge processes. Operating pressures from 4.5 to 7.5 MPa has been employed in lined tunnels in the compression and decompression stages. The model considers a 20 mm thick sealing layer, a 0.4 m thick concrete lining and a 1 m thick rock mass around the air. Air mass flow rates of 0.19 and 0.27 kg s⁻¹ have been used in the charge processes for polymer material and steel, respectively. Finally, in the discharge processes the mass flow rate increases up to 0.38 and 0.45 kg s⁻¹ for polymer and steel. The air temperature and pressure and the temperature and heat transfer in the sealing layer, concrete lining and rock mass have been analyzed for 100 cycles considering polymer material and steel as sealing layers. The heat transfer through the sealing layer reaches -150 and -95 W m⁻² for steel and polymer, respectively. The results obtained show that the storage capacity increases when the heat transfer through the sealing layer increases.

1. Introduction
Adiabatic compressed air energy storage (A-CAES) and underground pumped-storage hydropower (UPSH) systems could be an alternative to store energy and facilitate the integration of variable renewable energies (VRE) in disused underground structures such as abandoned coal mining areas and salt deposits [1-6]. Figure 1 shows the location of coal mining areas and salt deposits where this systems may be installed in the European Union (EU) [7]. Álvarez et al. [8] developed a numerical and analytical model to analyze the thermodynamic performance of CAES reservoir in abandoned mines. An operation pressure range between 8 and 10 MPa was employed in the models. Fiber-reinforced plastic and steel were considered as sealing layers in the simulations. They concluded that no temperature fluctuation was obtained in the rock mass and the air temperature fluctuations decrease when the thermal conductivity of the sealing layer increases. In addition, good agreements were reached between
analytical and numerical models considering lined and unlined tunnels. Schmidt et al. [9] developed a numerical study to investigate the geomechanical performance of CAES systems in coal mines for 10,000 cycles of compression and decompression. They concluded that a volume increase less than 0.5% was obtained by applying the operating conditions (4.5-7.5 MPa) and the rock mass deformations reached moderated values. Zhou et al. [10] carried out a numerical analysis for the coupled thermo-mechanical performance in a lined rock cavern considering an operating air pressure of 4.5-6.9 MPa for 100 cycles. Different thickness of concrete lining, between 0 and 0.1 m were also considered. Kushnir et al. [11] carried out a study to investigate the temperature and pressure in CAES reservoirs.

In this paper, an analytical model has been developed in MATLAB to investigate the thermodynamic performance of A-CAES systems in lined tunnels. Polymer material and steel as sealing layers, concrete lining and rock mass are considered as model materials around the compressed air. In addition, operating air pressures from 4.5 to 7.5 MPa have been employed during air charge and discharge processes. Air mass flow rates of 0.19 and 0.27 kg s⁻¹ have been used in the charge processes for polymer material and steel, respectively. The air temperature and pressure, and the temperature and heat flux in the sealing layer, concrete and rock mass were studied for 100 cycles of compression and decompression.

2. Methodology

2.1. Analytical model

The problem statement is shown in Figure 2. A lined tunnel with 4 m in diameter and 0.4 m thick concrete lining has been considered in the model. The values of the r1, r2, r3 and r4 are 1.58, 1.6, 2 and 3 m, respectively. In the analytical model developed in MATLAB, the energy equation has been applied as shown in Equation (1). In this equation, \( \dot{Q} \) is the net heat transfer, in W, \( \dot{W} \) is the net work, \( \varepsilon \) is the specific energy, \( \rho \) is the air density, \( V \) is the reservoir volume, \( v \) is inlet velocity and \( S \) is the cross section.
Figure 2. Cross-section of the underground lined tunnel. Compressed-air, sealing layer, concrete lining and rock mass.

The heat convection between the compressed air (fluid) and the sealing layer (solid) is represented in the Equation (2), where $h$ is the heat transfer coefficient, in W m$^{-2}$K$^{-1}$ and $m$ is the air mass flow rate, in kg s$^{-1}$ and $C_v$ is the specific heat at constant volume.

$$\dot{Q} - \dot{W} = \frac{\partial}{\partial t} \int \rho e \, dv + \oint \rho \dot{e} \, (\vec{v} \cdot dS)$$  \hspace{1cm} (1)

$$- h A_1 (T_a - T_1) = \frac{d}{dt} (m C_v T_a) - \dot{m} (m C_v T_0 + RT_0 + \frac{v^2}{2})$$  \hspace{1cm} (2)

$$m = m_0 + \dot{m} \, t$$  \hspace{1cm} (3)

The air temperature increases when the air pressure increases inside the reservoir. The air temperature is calculated by applying Equation (4). The temperature on the sealing layer ($T_1$), concrete lining ($T_2$) and rock mass wall ($T_3$) are obtained by applying non-stationary heat transfer Equations (5-7). An inlet temperature of 310 K is considered by the air.

$$\frac{dT_a}{dt} = \frac{\dot{m}}{m} \left[ \frac{C_p}{C_v} T_0 + \frac{1}{2} \left( \frac{\dot{m}}{m} \right)^2 - T_a \right] - \frac{h 2 \pi r L}{C_v m} (T_a - T_1)$$  \hspace{1cm} (4)

The temperature on the sealing layer ($T_1$), concrete lining ($T_2$) and rock mass wall ($T_3$) are obtained by applying non-stationary heat transfer Equations (5-7). An inlet temperature of 310 K is considered by the air.

$$\frac{dT_1}{dt} = \frac{2U_s}{m_s C_{ps}} (T_a - T_1) - \frac{2U_s}{m_s C_{ps}} (T_1 - T_2) - \frac{dT_2}{dt}$$  \hspace{1cm} (5)

$$\frac{dT_2}{dt} = \frac{2U_s}{m_s C_{pc}} (T_1 - T_2) - \frac{2U_s}{m_s C_{pc}} (T_2 - T_3)$$  \hspace{1cm} (6)
\[
\frac{dT_3}{dt} = \frac{2U_c}{m_{ss}C_{pss}}(T_2 - T_3) - \frac{2U_{ss}}{m_{ss}C_{pss}}(T_3 - T_4)
\]

The boundary conditions for both polymer and steel sealing layers (air mass flow rates in charge and discharge processes, compression and decompression time and inlet temperature in the underground reservoir are presented in Table 1.

**Table 1. Boundary conditions.**

| Boundary conditions | Polymer material | Steel |
|---------------------|-----------------|-------|
| Mass flow rate - charge (kg/s) | 0.19 | 0.27 |
| Mass flow rate - discharge (kg/s) | -0.38 | -0.45 |
| Compression time (h) | 8 | 8 |
| Stored time (h) | 6 | 6 |
| Decompression time (h) | 4 | 4 |
| Inlet temperature (K) | 310 | 310 |

### 2.2. Material properties

The thermal properties of the materials used in the analytical model are shown in Table 2. The air is considered as compressible fluid and steel and polymer material (sealing layers), reinforced concrete and rock mass are considered as solid domains in the analytical model.

**Table 2. Thermal properties of the materials used in the model.**

| Material          | Specific Heat (J kg\(^{-1}\)K\(^{-1}\)) | Thermal conductivity (W m\(^{-1}\)K\(^{-1}\)) | Density (kg m\(^{-3}\)) |
|-------------------|------------------------------------------|---------------------------------------------|-------------------------|
| Air               | 1.006                                    | 0.0242                                      | 1.2                     |
| Concrete          | 1.000                                    | 1.6                                         | 2,500                   |
| Rock mass         | 700                                      | 5                                           | 2,600                   |
| Steel             | 500                                      | 45                                          | 7,800                   |
| Polymer material  | 1,950                                    | 0.095                                       | 920                     |

### 3. Results and discussion

The analytical model has been conducted for 100 compression and decompression cycles using polymer material and steel as sealing layers. The temperature and pressure variations were observed during the simulations.

#### 3.1. Polymer material

The temperature of air, polymer and concrete is shown in Figure 3a for the first cycle using polymer material as sealing layer. As shown in Figure 3b, the air temperature varies between 315 (charge) and 286 K (discharge) from the first cycle. In addition, the temperature of the polymer material and concrete is constant during the 100 cycles. The evolution of the air pressure is represented in Figure 4a for the first cycle (day 1). Due to the reduction of the air temperature, the pressure decreases from 7.5 to 7 MPa in the stored time (6 h). The heat transfer through the sealing layer and concrete lining is shown in Figure 5a for the first cycle. The heat flux reaches 140 and -85 W m\(^{-2}\) in the charge and discharge processes, respectively. As indicated in Figure 5b, from the first cycle the surface heat flux decreases down to 55 and -95 W m\(^{-2}\) in the charge and discharge processes through the polymer wall. The surface heat flux through the concrete wall reaches 52 and -75 W m\(^{-2}\) in the compression and decompression stages.
Figure 3. Temperature of air, polymer and concrete lining for 100 charging and discharging cycles. (a) First cycle; (b) 100 days of operation; (c) 100th cycle.

Figure 4. Air pressure for 100 charging and discharging cycles considering polymer as sealing layer. (a) First cycle; (b) 100 days of operation; (c) 100th cycle.

Figure 5. Surface heat flux of polymer and concrete lining for 100 charging and discharging cycles. (a) First cycle; (b) 100 days of operation; (c) 100th cycle.
3.2. Steel
The results obtained in the simulations considering steel as sealing layer are presented in this section. Note that the thermal conductivity increases up to 45 W m$^{-1}$ K$^{-1}$. Figure 6b shows the temperature of air, sealing layer and concrete for 100 cycles of charge and discharge using steel as sealing layer. The variations in the air temperature within the subsurface reservoir are reduced with respect to the values obtained for the polymer material. The air temperature ranges between 305 and 297 K when steel is used as sealing layer. The air pressure for the first cycle using steel is shown in Figure 7a. The reduction of the air pressure during the stored time decreases when steel is used as sealing layer. The surface heat flux through the sealing layer and concrete lining for the first cycle is presented in Figure 8a when steel is used as sealing layer. The heat transfer reaches 200 and -150 W m$^{-2}$ in compression and decompression stages, respectively. Compared to polymer material, the heat transfer increases significantly when steel is used as sealing layer.

![Figure 6](image1.png)

**Figure 6.** Temperature of air, steel and concrete lining for 100 charging and discharging cycles considering steel as sealing layer. (a) First cycle; (b) 100 days of operation; (c) 100th cycle.

![Figure 7](image2.png)

**Figure 7.** Air pressure for 100 charging and discharging cycles using steel as sealing layer. (a) First cycle; (b) 100 days of operation; (c) 100th cycle.
Variations in air temperature decrease when the material used as sealing layer has a higher thermal conductivity. Finally, the storage capacity increases when the thermal conductivity of the materials around the fluid increases, and therefore the heat transfer through the sealing layer also increases.

4. Conclusions
An analytical model using MATLAB has been conducted to investigate the thermodynamic performance of A-CAES systems in lined tunnels. Two different sealing layers, polymer material and steel, have been considered as sealing layers. In addition, a 0.4 m thick concrete lining and a 1 m rock mass have been employed around the sealing layer. Air mass flow rates of 0.19 and 0.27 kg s\(^{-1}\) have also been considered in the charge processes for polymer material and steel, respectively. The air temperature and pressure within the reservoir, and the heat transfer and temperature in the materials considered around the fluid have been analyzed for 100 compression and decompression cycles between 4.5 and 7.5 MPa. The results obtained show that the air temperature fluctuations decrease when the thermal conductivity of the sealing layer increases. The heat transfer through the sealing layer reaches -150 and -95 W m\(^{-2}\) for steel and polymer material, respectively. Finally, the storage capacity increases when the air temperature variations decrease and the heat transfer around the fluid increases.

5. References
[1] Pujades E, Orban P, Archambeau P, Erpicum S, Dassargues A. Numerical study of the Martelange mine to be used as underground reservoir for constructing an Underground Pumped Storage Hydropower plant. Adv. Geosci. 45, 51–56 (2018).
[2] Pujades, E.; Orban, P.; Archambeau, P.; Kitsikoudis, V.; Erpicum, S.; Dassargues, A. Underground Pumped-Storage Hydropower (UPSH) at the Martelange Mine (Belgium): Interactions with Groundwater Flow. Energies, 13, 2353 (2020).
[3] Menendez J, Loredo J, Fernandez-Oro JM, Galdo M. Energy storage in underground coal mines in NW Spain: Assessment of an underground lower water reservoir and preliminary energy balance. Renew. Energy 134:1381-1391 (2019).
[4] Pujades E, Orban P, Bodeux S, Archambeau P, Erpicum S, Dassargues A. Underground pumped storage hydropower plants using open pit mines: how do groundwater exchanges influence the efficiency? Appl Energy 190:135–46 (2017).
[5] Menendez J, Loredo J. Use of closed open pit and underground coal mines for energy generation: Application to the Asturias Central Coal Basin (Spain). E3S Web of Conf ; 80: 01005 (2019).
[6] Menendez J, Fernandez-Oro JM, Galdo M, Loredo J. Pumped-storage hydropower plants with underground reservoir: Influence of air pressure on the efficiency of the Francis turbine and energy production. Renew. Energy 143:1427-1438 (2019).

[7] Menendez J, Ordóñez A, Álvarez R, Loredo J. Energy from closed mines: Underground energy storage and geothermal applications. Renew Sustainable Energy Rev 108:498–512 (2019).

[8] Alvarez A, Menendez J, Bernardo-Sanchez A, Galdo M, Loredo J, Fernandez-Oro J.M. Thermodynamic analysis of compressed air energy storage (CAES) reservoirs in abandoned mines using different sealing layers. App Sci 11, 2573 (2021).

[9] Schmidt F, Menendez J, Konietzky H, Pascual-Muñoz P, Castro J, Loredo J, Bernardo-Sanchez A. Converting closed mines into giant batteries: Effects of cyclic loading on the geomechanical performance of underground compressed air energy storage systems. J Energy Storage 32, 101882 (2020).

[10] Zhou S, Xia C, Zhao H, Mei S, Zhou Y. Numerical simulation for the coupled thermo-mechanical performance of a lined rock cavern for underground compressed air energy storage. Journal of Geophysics and Engineering, 14(6), 1382–1398 (2017).

[11] Kushnir R, Dayan A, Ullmann A. Temperature and pressure variations within compressed air energy storage caverns. Int. J. Heat Mass Transf. 55, 5616–5630 (2012).