Modelling and Dynamic Simulation of an Underground Cavern for Operation in an Innovative Compressed Air Energy Storage Plant

LASSE NIELSEN
Technische Universität Braunschweig and Energy Research Centre Lower Saxony in Goslar
Institute for Heat- and Fuel Technology
Franz-Liszt-Straße 35, D-38106 Braunschweig
GERMANY
lasse.nielsen@tu-bs.de

REINHARD LEITHNER
Technische Universität Braunschweig
Institute for Heat- and Fire Technology
Franz-Liszt-Straße 35, D-38106 Braunschweig
GERMANY
r.leithner@tu-bs.de

Abstract: An innovative concept of an compressed air energy storage (CAES) plant is developed at the Institute for Heat- and Fuel Technology (IWBT) of the Technische Universität Braunschweig. This concept aims to minimise the negative aspects of state-of-the-art CAES-plants and is named isobaric adiabatic compressed air energy storage plant with combined cycle (ISACOAST-CC). To increase the storage efficiency, one aspect of this concept is to reduce compressor losses due to high differences of the storage pressure within the cavern by the use of a brine shuttle pond at the surface to drive out the stored air at nearly constant pressure. In the presented article the main focus is on the modelling and the calculation results of the isobaric salt cavern which is used in this concept.

Key- Words: Compressed Air Energy Storage (CAES), Enbipro, Dynamic simulation, Underground salt cavern

1 Introduction

Due to the worldwide rising energy consumption, the negative aspects of the present structure of power supply are becoming more significant. The finite nature and unequal distribution of fossil fuels and the decrease of CO₂-production is challenging the energy industry concerning supply guarantee and price stability in future. Besides the improvement of efficiency, the application of renewable energy is helping to solve these issues. Wind energy has the highest potential as a significant assistance to ensure future power supply [1]. Due to the the rising amount of produced wind energy in Germany, future adjustments of the grid infrastructure become necessary. The characteristic of wind energy is, that the converted power is fed in fluctuating and is not always available when it is needed. At present the required regulating power is provided mainly by fossil-fueled power plants in partload mode resulting in lower efficiency and higher material wear as a result of fluctuating operating temperatures. Energy storage facilities can be used to provide positive and negative regulating power, reduce the amount of inefficient part load fossil-fired power plants and raise the efficiency, stability and durability of the whole power generation network.

1.1 Compressed Air Energy Storage Plants

One type of energy storage plant which is able to buffer large amounts of renewable electric energy is the so called CAES-plant. Worldwide there are two CAES-plants in operation, one in McIntosh, Ohio (USA) and one in Huntorf, Germany. However, there are still several concepts in design state. In general

![adiabatic system](image1.png)

![diabatic system](image2.png)

Figure 1: Adiabatic and diabatic CAES concepts [2]
motor to store air in underground salt caverns. When energy is needed at peak load time the air is expanded in a gas or air turbine. The difference between these concepts is the heat storage and the combustion chamber. Due to inlet temperature limitations for stability reasons of the cavern the air needs to be cooled down before it enters the cavern. At the Huntorf-plant the air is cooled down by heat exchange to the environment without using a heat storage. In discharge mode the air is heated up by burning natural gas in a combustion chamber to reach the needed turbine inlet temperature. At the McIntosh-plant in discharge mode, the air is pre-heated additionally with the exhaust gas in a recuperator, thus reducing the consumption of natural gas. However the efficiency of state-of-the-art CAES-plants with 41.8 % (Huntorf) and 53.8 % (McIntosh) [3] is very low in comparison with pumped hydro plants i.a. due to the air cooling losses. The adiabatic concept stores the heat from the hot compressed air in a heat storage before the air enters the cavern. In discharge mode the air flows through the heat storage again and is heated up to the turbine inlet temperature without fuel consumption. There is no adiabatic CAES built at present but it shall reach storage efficiencies of around 70 % [2]. A negative aspect of this concept is, that every heat storage has ambient losses and a temperature breakthrough curve. The turbine inlet temperature can not be ensured over the whole discharging time. Due to the decreasing turbine inlet temperature, the pressure difference which is expanded in the turbine needs to be downsized to avoid that the turbine outlet temperature gets too low. Therefore the power output is reduced with progressing discharging time. Both concepts use a salt cavern with constant volume. A negative aspect of such a cavern is, that the air is stored at a higher pressure than the inlet pressure of the turbine to reach long discharging time. At Huntorf, for example, the air is stored with up to 72 bar while the high pressure-turbine needs an inlet pressure of 41 bar. Hence the air has to be throttled before entering the turbine which results in a decreased efficiency.

1.2 Concept developed at the IWBT

In general the concept developed at the Institute for Heat- and Fuel Technology is a combination of the adiabatic and the diabatic process, because it uses a heat storage and a combustion chamber. The schematic diagram in figure 2 shows the design of the ISACOAST-CC concept. This new CAES system differs from existing ones, by the use of a brine shuttle pond at the surface which enables to operate the air storage nearly isobarically. In storage mode the compressor of a state-of-the-art gas turbine is driven by a motor/generator, the turbine is decoupled and the brine is driven out of the cavern into the shuttle pond by the compressed air. This process takes place at nearly constant pressure. While state-of-the-art CAES suffer from efficiency losses due to pressure variation, losses of this type are avoided in this concept since it is operated at nearly constant pressure. Before entering the cavern, the heat of the air, resulting from the compression, is stored in a special heat storage. This unit consists of a large number of pressure resistant helical steel tubes that transfer the heat to the surrounding material (at atmospheric pressure). In discharge mode, the compressed air flows from the cavern to the combustion chamber of a state-of-the-art gas turbine. By passing through the heat storage, the air is heated up nearly to the compressor outlet temperature again. As a result, there is nearly no difference between air from the storage and air from the compressor. The motor/generator is operated as a generator in discharge mode to convert the additional power which is consumed by the compressor –now decoupled– in regular operation of the gas turbine. This avoids duplication of equipment and redesign of the gas turbine shaft. A heat recovery steam generator (HRSG) is used to produce steam using the energy of the hot turbine exhaust gas for a steam cycle.

2 Mathematical model of the isobaric cavern

The plant is simulated with the software ENBIPRO (ENergie Bllanz PROgramm / energy balance program) which is used for stationary and dynamic simulation of power plant cycles and has been developed at the IWBT. The different component models consist of balance and transport equations (mass, energy, etc.) and substance property calculations. This article
presents the modelling and the simulation results of the isobaric cavern used in the ISACOAST-CC concept.

The model describes an underground excavation in a salt dome created by solution mining. The cavern is linked to the surface by two boreholes with inner pipings or one borehole with two concentric pipes from which one is the connection between the brine shuttle pond to the air storage and reaches down to the bottom of the cavern. The other one, ending at the top of the cavern, is used for the transport of the compressed air which is driven out of the cavern to the surface by the brine. The brine column between cavern and shuttle pond creates a nearly isobaric pressure level which varies only by the difference in the geodetic height resulting out of the changing brine filling level inside the cavern. The pressure of the air inside the storage equals the resulting pressure of the brine. Additional equations are implemented to calculate the pressure losses out of initially given pressure loss coefficients. Two volumes (brine, air) are linked by an isochoric equation and the in- and outlets affect these in form of the ideal gas law and a simple volume calculation for the incompressible brine. The implemented energybalance of the air, according to the first law of thermodynamics, regards the change of the storage temperature resulting out of the changing pressure during the storage processes. The heat transfer between the two mediums and the cavern wall is described by nonstationary heat conduction in a semi-infinite body. With an input/output routine it is possible to set a given temperature field as initial value and write out the resulting temperature characteristics inside the wall. The model has separate in- and outlets for each medium to avoid that following components in a cycle simulation calculate with negative mass flows, since the direction of flow changes between charge and discharge operation. In reality the medium will flow in both directions through the boreholes or concentric pipes respectively.

\[ T_m = \frac{(T + T_{ref})}{2}, \quad T_{ref} = 298.15 \text{ K} \]  
\[ c_{p,m} = f(T_m, p) \]  
\[ \frac{dm_a}{dt} = -\dot{m}_{a,out} + \dot{m}_{a,in} \]  
\[ \frac{dm_b}{dt} = -\dot{m}_{b,out} + \dot{m}_{b,in} \]  
\[ V_b = \frac{m_b}{\rho_b} \]  
\[ V_a = \frac{m_a \cdot R_a \cdot T_a}{p_a} \]  
\[ V_c = V_a + V_b \]  
\[ \text{Energy balance:} \]

The nonstationary energy balance is implemented according to the first law of thermodynamics for open systems as stated in [4]. The storage process is a polytropic change of condition because temperature, pressure and volume of the air are varying in every timestep. The index \( a \) for air is omitted for the purpose of clarity.

The general equation of the first law of thermodynamics for open systems:

\[ \frac{d}{dt} \int_{V_{cw}} \rho (u + \frac{v^2}{2} + gz) dV = \]

\[ \sum_{k} [\dot{m}_k (h + \frac{v^2}{2} + gz)]_k + \dot{Q} + \dot{W}_t - p \frac{dV_{cw}}{dt} \]
The technical work in this system is zero and the kinetic and potential energies are neglected. With the flow of volume-change work \( W_v = p \frac{dV_v}{dt} \), the equation is reduced to:

\[
\frac{d}{dt} \int_{V_v} \varrho u dV = \sum_k [\dot{m}h]_k + \dot{Q} + \dot{W}_v \tag{14}
\]

The density of the air inside the storage is regarded as constant along the cavern height and only one air-massflow is entering or leaving the volume, depending on the current storage process:

\[
\frac{d(mu)}{dt} = \dot{m}h + \dot{Q} + \dot{W}_v \tag{15}
\]

\[
\frac{du}{dt} + u \frac{dm}{dt} = \dot{m}h + \dot{Q} + \dot{W}_v \tag{16}
\]

\[
\frac{dm}{dt} = \frac{\dot{m}h + \dot{Q} + \dot{W}_v - u \frac{dm}{dt}}{m} \tag{17}
\]

The internal energy is calculated through the heat capacity at constant volume multiplied by the temperature difference of the actual and the reference temperature.

\[
u = c_v,m \cdot \Delta T \tag{18}
\]

\[
u = (c_{p,m} - R_a) \cdot \Delta T \tag{19}
\]

With

\[
\Delta T = T - T_{ref} \tag{20}
\]

follows:

\[
(c_{p,m} - R_a) \frac{d\Delta T}{dt} = \dot{m}h + \dot{Q} + \dot{W}_v - (c_{p,m} - R_a) \cdot \Delta T \frac{dm}{dt}
\]

\[
- \frac{d(c_{p,m} - R_a)}{dt} \Delta T
\]

\[
\frac{m}{(c_{p,m} - R_a)} \Delta T
\]

For small timesteps and with index \( i \) as the current timestep:

\[
(c_{p,m,i} - R_a) \frac{\Delta T}{\Delta t} = \dot{m}h + \dot{Q} + \dot{W}_v - (c_{p,m} - R_a) \cdot \Delta T \frac{m}{\Delta t}
\]

\[
- \frac{\Delta(c_{p,m} - R_a)}{\Delta t} \Delta T - \frac{m}{(c_{p,m} - R_a)} \Delta T
\]

\[
\frac{m}{(c_{p,m} - R_a)} \Delta T
\]

The formula is rearranged to give \( T_i \):

\[
T_i = \frac{\Delta mh_m + \Delta Q + \Delta W_v - (c_{p,m,i} - R_a) \cdot \Delta T \Delta m}{m}
\]

\[
- \frac{\Delta(c_{p,m} - R_a)}{(c_{p,m,i} - R_a)} \Delta T + T_{i-1}
\]

\[
T_i = \frac{\Delta mh_m + \Delta Q + \Delta W_v - (c_{p,m,i} - R_a) \cdot \Delta T \Delta m}{m}
\]

\[
- \frac{\Delta(c_{p,m} - R_a)}{(c_{p,m,i} - R_a)} \Delta T - (c_{p,m,i} - c_{p,m,i-1})(T_i - T_{ref}) + T_{i-1}
\]

The volume-change work of a polytropic change of condition is defined as:

\[
\Delta W_{v,pol} = \frac{p_i V_i - p_i-1 V_i-1}{n_{pol} - 1}
\]

with the polytropic exponent:

\[
n_{pol} = \frac{ln\frac{p_i}{p_i-1}}{ln\frac{V_i}{V_i-1}}
\]

The heat exchanged with the brine and cavern wall between two timesteps is averaged:

\[
\Delta Q = \left( \frac{\dot{Q}_{a,w,i} + \dot{Q}_{a,w,i-1}}{2} + \frac{\dot{Q}_{a,b,i} + \dot{Q}_{a,b,i-1}}{2} \right) \cdot \Delta t
\]

like the exchanged enthalpy with the air-massflow \( (T_{in} \) averaged between two timesteps)

\[
\Delta mh_m = \Delta m(c_{p,m}(T_m - T_{ref}))
\]

The nonstationary energy balance of the air is calculated as followed:

\[
T_i = \frac{\Delta m(c_{p,m}(T_m - T_{ref}) - (c_{p,m,i} - R_a)(T_i - T_{ref}))}{m_i}
\]

\[
- \frac{\Delta(c_{p,m} - R_a)}{(c_{p,m,i} - R_a)} \Delta T + T_{i-1}
\]

Energy balance of the brine:

\[
T_{b,i} = \frac{\Delta Q_{b,w} + \Delta Q_{a,b}}{m_{b,i} \cdot c_{p,b}} + \frac{\Delta m_{b,w} \cdot c_{p,b} \cdot (T_{b,b,w,in} - T_{ref})}{m_{b,i} \cdot c_{p,b}} + \frac{m_{b,i-1} \cdot c_{p,b} \cdot (T_{b,i-1} - T_{ref})}{m_{b,i} \cdot c_{p,b}} + T_{ref}
\]
Temperature of the cavern wall:

The calculation of the cavern wall temperature is modelled with nonstationary heat conduction in a semi-infinite body according to [5]. It can be calculated with an initial balance or with a given distribution of temperatures. In the first case, the temperature-vector at timestep zero is overwritten with \( T_\infty \) and based on this the characteristics are calculated during the simulation. The basic equation used, is the differential equation of Fourier for constant heat conduction coefficients:

\[
\frac{\partial T}{\partial \tau} = a \text{ div grad } T + \frac{\tilde{q}_i}{\varrho c_p} \tag{33}
\]

Because no inner heat sources are located in the wall, the equation is reduced to:

\[
\frac{\partial T}{\partial \tau} = a \text{ div grad } T \tag{34}
\]

and for the one dimensional case of an infinite cylinder:

\[
\frac{\partial T}{\partial \tau} = a \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right) \tag{35}
\]

Figure 4 shows the schematic discretisation of the cavern wall. The temperature of the wall is located between two supporting points, whereby the approximation becomes more exact [5].

\[
\begin{align*}
- T_{j,i-1} &= F_{o^+}(1 - r^*) T_{j-1,i} \\
- (1 + 2 F_{o^+}) T_{j,i} + F_{o^+}(1 + r^*) T_{j+1,i} \tag{36}
\end{align*}
\]

\[
T_{j,i} = \frac{T_{j,i-1}}{(1 + 2 F_{o^+})} + \frac{F_{o^+}(1 - r^*) T_{j-1,i} + (1 + r^*) T_{j+1,i}}{(1 + 2 F_{o^+})} \tag{37}
\]

The dimensionless location coordinate \( r^* \) for cylindrical coordinates and the current location:

\[
r^* = \frac{\Delta r}{2r_j} \tag{38}
\]

The Fourier-number \( F_{o^+} \) is equivalent to the relation of time according to thermical time constant exclusively at heat conduction in the wall [5]. For cylindrical coordinates with \( a \) as the conductivity of temperature for rock salt it is:

\[
F_{o^+} = \frac{a r_s}{\Delta \tau \Delta r^2} \tag{39}
\]

As basis for the calculation the 3rd boundary condition is chosen, because the temperature of the fluid is known and heat is transferred between medium and wall. As boundary condition for the other side at infinity of the salt dome \( T_n \) is set to \( T_\infty \). For the transition between fluid and wall the following boundary condition is applied:

\[
T_{a,i} B_{i^+} = T_{0,i} \left( \frac{B_{i^+}}{2} + 1 \right) + T_{1,i} \left( \frac{B_{i^+}}{2} - 1 \right) \tag{40}
\]

The local Biot-number \( B_{i^+} \) physically describes the relation of heat conduction inside the wall to the heat transfer coefficient at the surface. It is calculated with the given heat transfer coefficient and the heat conductivity of rock salt.

\[
B_{i^+} = \frac{\alpha_{a,w} \Delta r}{\lambda_{rs}} \tag{41}
\]

The temperature of the wall between the supporting points 0 and 1 is calculated with the arithmetic mean of these two temperatures.

\[
T_{w,a} = \frac{T_{0,i} + T_{1,i}}{2} \tag{42}
\]

The distance \( \Delta r \) and the number of supporting points can be given in the properties of the component at the graphical user interface of ENBIPRO. The calculation
of the brine sided wall is carried out in the same way with own temperature characteristics.

\[ T_{w,b} = \frac{T_{b,i} + T_{i,i}}{2} \]  

(43)

The heat transfer caused by the changing contact to air and brine respectively during the changing filling level of the cavern is neglected.

The equations for heat transport are calculated with constant heat transfer coefficients and the appropriate surfaces and temperatures:

\[ \dot{Q}_{a,w} = \alpha_{a,w} \cdot A_{a,w} (T_{w,a} - T_a) \]  

(44)

\[ \dot{Q}_{a,b} = \alpha_{a,b} \cdot A_{a,b} (T_a - T_b) \]  

(45)

\[ \dot{Q}_{b,w} = \alpha_{b,w} \cdot A_{b,w} (T_{w,b} - T_b) \]  

(46)

Calculation of the cavern cross section area:

\[ A_0 = \frac{\Pi}{4} \cdot d_c^2 \]  

(47)

Calculation of the cavern volume:

\[ V_c = A_0 \cdot H_c \]  

(48)

The surfaces are calculated with an enlargement factor \( A_c \) which regards the fissures of the cavern walls.

\[ A_{a,w} = (\pi \cdot d_c (H_c - z) + A_0) A_c \]  

(49)

\[ A_{b,w} = (\pi \cdot d_c \cdot z + A_0) A_c \]  

(50)

The filling level of the cavern:

\[ z = \frac{V_b}{A_0} \]  

(51)

The pressures are calculated according to Bernoulli’s equation. In this model the in- and outlet pressure of the brine is the pressure of the compressed air inside the cavern.

\[ p_{a,c} = p_{env} + g_b \cdot g \cdot (H_d + H_c - z) \]

\[- \zeta_b \cdot \frac{\rho_b}{2} \cdot v_{b,\text{in}}^2 \text{ for } \dot{m}_{a,\text{out}} > 0 \]  

(52)

\[ p_{a,c} = p_{env} + g_b \cdot g \cdot (H_d + H_c - z) \]

\[ + \zeta_b \cdot \frac{\rho_b}{2} \cdot v_{b,\text{out}}^2 \text{ for } \dot{m}_{a,\text{in}} > 0 \]  

(53)

\[ p_{a,\text{out}} = p_{a,c} - \rho_{a,m} \cdot g \cdot (H_d + H_c - z) \]

\[- \frac{\rho_{a,\text{out},m}}{2} \cdot v_{a,\text{out},m}^2 \cdot (1 + \zeta_a) \text{ for } \dot{m}_{a,\text{out}} > 0 \]  

(54)

\[ p_{a,\text{in}} = p_{a,c} - \rho_{a,m} \cdot g \cdot (H_d + H_c - z) \]

\[- \frac{\rho_{a,\text{in},m}}{2} \cdot v_{a,\text{in},m}^2 \cdot (1 - \zeta_a) \text{ for } \dot{m}_{a,\text{in}} > 0 \]  

(55)

The links of temperature between storage and in-/ outlet:

\[ T_{a,\text{out}} = T_a \text{ for } \dot{m}_{a,\text{out}} > 0 \]  

(56)

\[ T_{b,\text{out}} = T_b \text{ for } \dot{m}_{b,\text{in}} > 0 \]  

(57)

### 2.2 Simplifications and assumptions

The cavern model uses the following simplifications and assumptions:

- the air is considered as an ideal gas
- regarding of fissures of the cavern walls by an enlargement factor
- constant substance properties of the brine
- simulation with dry air
- no influence of pressure to substance properties
- no heat transfer between medium and tubings

### 3 Simulation

A complete storage cycle (charge and discharge processes are simulated separately) starting with balanced temperatures (298.15 K) was taken as basis for the second cycle. The whole cavern is dimensionated as one of two caverns used in the ISACOAST-CC process as described in [6]. Regarding the pressure losses of the tubings, two boreholes are assumed per cavern and each medium. Table 1 and 2 show the initial and boundary values that are used for the second simulation of the discharge process.

<table>
<thead>
<tr>
<th>Initial values of the second discharge process</th>
<th>(133,847,66 \text{ m}^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>volume of air</td>
<td>127,212,76 m³</td>
</tr>
<tr>
<td>volume of brine</td>
<td>6,634,90 m³</td>
</tr>
<tr>
<td>mass of air</td>
<td>6,785,946,5 kg</td>
</tr>
<tr>
<td>mass of brine</td>
<td>7,789,371,90 kg</td>
</tr>
<tr>
<td>filling level</td>
<td>2,85 m</td>
</tr>
<tr>
<td>temperature of air</td>
<td>311,32 K</td>
</tr>
<tr>
<td>temperature of brine</td>
<td>288,85 K</td>
</tr>
<tr>
<td>temperature of air-sided wall</td>
<td>309,71 K</td>
</tr>
<tr>
<td>temperature of brine-sided wall</td>
<td>288,96 K</td>
</tr>
</tbody>
</table>

Table 1: Initial values of the cavern
Boundary values of the second discharge process

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>depth of cavern head</td>
<td>350 m</td>
</tr>
<tr>
<td>height of cavern</td>
<td>57.46 m</td>
</tr>
<tr>
<td>diameter of cavern</td>
<td>54.46 m</td>
</tr>
<tr>
<td>heat transfer coefficient air-wall</td>
<td>$100 , \frac{W}{m^2K}$</td>
</tr>
<tr>
<td>heat transfer coefficient air-brine</td>
<td>$1.531 , \frac{W}{m^2K}$</td>
</tr>
<tr>
<td>heat transfer coefficient brine-wall</td>
<td>$743.12 , \frac{W}{m^2K}$</td>
</tr>
<tr>
<td>diameter of air tubing</td>
<td>0.7 m</td>
</tr>
<tr>
<td>diameter of brine tubing</td>
<td>0.7 m</td>
</tr>
<tr>
<td>pressure loss coefficient air tubing</td>
<td>10.87</td>
</tr>
<tr>
<td>pressure loss coefficient brine tubing</td>
<td>11.57</td>
</tr>
</tbody>
</table>

Table 2: Boundary values of the cavern

Figure 5 shows the massflows of air and brine over the entire simulation time of six hours. The curve progression of the air is raised slowly to the constant design value of $317 \, \frac{kg}{s}$ and is equal for charging and discharging process. The massflow of the brine at the charging process results from the changing volume inside the cavern which is displaced by the influent air. At discharge process the air flow is held at the constant design value too and the influent brine shows a characteristic which results from the changing density of the air.

Figure 6: Pressures of air inside cavern and outlet

The discharge process the temperature of the air is slightly higher than the temperature of the walls, but the effect of the heat transfer is marginal compared to the change of pressure. During the discharge process the temperature of the air is dropping beneath the wall temperature and at the end it is slightly heated up by the higher temperatures of the wall.

Figure 7: Temperature and density of the air at discharge process

As shown in figure 6, the pressure of the air inside the cavern and at the outlet (surface) are following the raising filling level and the pressure losses due to the raising massflows of air and brine.

Figure 7 shows the characteristics of the air temperature and density inside the cavern while discharging. Both values are influenced by the changing cavern pressures depending on the filling level and increasing pressure losses of the tubings when the massflows are rising as well as the heat losses from the air to the brine and the cavern walls. At beginning of the discharge process the temperature of the air is slightly higher than the temperature of the walls, but the effect of the heat transfer is marginal compared to the change of pressure. During the discharge process the temperature of the air is dropping beneath the wall temperature and at the end it is slightly heated up by the higher temperatures of the wall.

The temperature characteristics inside the cavern wall next to the air at the end of the charge and the discharge process is shown in figure 8. The influenced length is set to one metre inside the salt dome and is divided into 100 supporting points. The value at location 0 represents the wall and the one at -1.5 cm the air temperature.
Figure 8: Temperatures of the cavern-wall at the end of the charge and discharge process

4 Conclusion

In the presented paper the modelling and simulation of an underground cavern in a salt dome combined with a brine shuttle pond at the surface for nearly isobaric operation is described and examined. This model enables to simulate the dynamic operation of the ISACOAST-CC (isobaric adiabatic compressed air energy storage plant with combined cycle) concept developed at the Institute for Heat- and Fuel Technology with the cycle simulation software ENBIPRO. The same energy balance (without volume change work) is used in another cavern model with constant volume, which is used to simulate the operation of the Huntorf CAES-plant. The results have been validated by comparison with operational data of this cavern. Further development of the presented model is required, regarding the heat losses inside the tubings or dynamic adaptation of the pressure loss coefficients which is not implemented so far.

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>m²K⁻¹</td>
<td>conductivity of temperature</td>
</tr>
<tr>
<td>A</td>
<td>m²</td>
<td>area</td>
</tr>
<tr>
<td>A_e</td>
<td></td>
<td>surface enlargement factor</td>
</tr>
<tr>
<td>Bi⁺</td>
<td></td>
<td>Biot-number</td>
</tr>
<tr>
<td>c_p</td>
<td>Jkg⁻¹K⁻¹</td>
<td>specific heat capacity at const. pressure</td>
</tr>
<tr>
<td>c_v</td>
<td>Jkg⁻¹K⁻¹</td>
<td>specific heat capacity at const. volume</td>
</tr>
<tr>
<td>d</td>
<td>m</td>
<td>diameter</td>
</tr>
<tr>
<td>F_0⁺</td>
<td></td>
<td>Fourier-number</td>
</tr>
<tr>
<td>g</td>
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Index | Description
---|---
a | air
b | brine
c | cavern
cv | control volume
d | depth
ten | entire
env | environment
i | timestep
j | location
in | inlet
m | mean
out | outlet
pol | polytropic
rs | rock salt
Ø | cross section
∞ | infinity

References:

[1] Deutsche Energie-Agentur GmbH (dena), *Energiewirtschaftliche Planung für die Netzintegration von Windenergie in Deutschland an Land und Offshore bis zum Jahr 2020*, Köln, 24.02.05


