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COB-2019-0982 DYNAMIC DISCHARGE SIMULATION OF CAVES IN CAES SYSTEM: HUNTORF CASE STUDY

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Abstract. *This work developed a dynamic 3D simulation of saline caves discharge used for a compressed air storage system (CAES). Initially, a reduced scale model of the problem in a discharge cycle is solved to validation. It is used real data provided by the Huntorf plant in Germany. The validation results obtained initially showed a relative error of 8% for pressure and 97% for temperature compared to the proportional results available in previous studies. As a way to investigate the causes of the high temperature error, a new simulation was performed applying the three-dimensional model data in scale to a validated analytical dynamic discharge model, using the same parameters in both. Thus the relative difference passed to 2% in relation to the pressure and 0.5% of the temperature. Obtaining a valid three-dimensional model for a CAES system has advantages over the analytical ones, such as obtaining the different temperatures inside the cave. For the application of this model, future studies are needed to correct temperature differences between the scale model and the real model.*

Keywords: *CAES, Salt Cave, Dynamitic Simulation, Compressed air storage.*

1. INTRODUCTION

The use of alternative energies has a growing trend. Energy production by photovoltaic and wind are variable as it depends on weather. To smooth the generation and assure a constant energy delivery, is necessary a way to store energy. Storage systems has been used with the purpose to store the energy surplus in production peak hours, and release energy in the consumption peak hours. Typical storage systems are batteries, flywheel, pumped storage hydroelectricity and latent thermal storage.

The Compressed Air Energy Storage (CAES) is a system that storage energy in the form of compressed air. Although proven to be viable, it is not used on a large scale as the energy matrix in the world. A conventional CAES system consists of four main elements: compression system, power generation system, compressed air storage tank and gas turbine. In this study, the objective is to analyze the thermal behavior in the storage system of the subsoil and compare with the case of Huntorf.

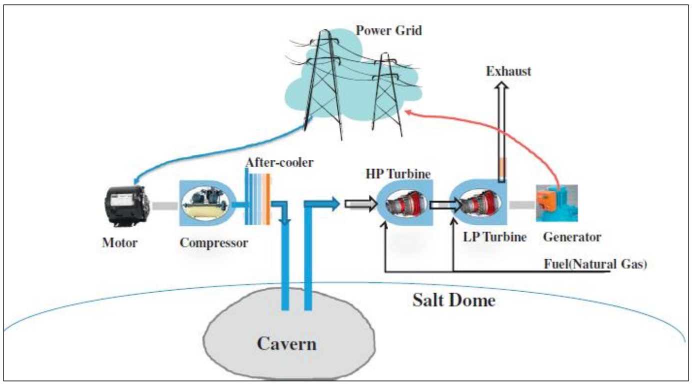

Figure 1. CAES System. Available from: Raju and Khaitan, 2012.

The Huntorf plant represents a reference of CAES. It has two underground storage caves totaling 310,000 m³ of air compressing and it is located 600 m deep, in order to maintain the ideal conditions of storage. This work presents a thermodynamic study of the discharge in caves of a CAES system, referring to the Huntorf plant, analyzing and comparing the behavior of pressure and temperature with previous studies (Crotogino et al., 2001) and (Raju and Khaitan, 2012).

2. MATHEMATICAL FORMULATION

Raju and Khaitan (2012) present a simulation through mass and energy balance inside the cave. The obtained balance considered the volume of control that surrounds the air in the subsoil. The operating range of pressures inside the basin corresponds to 46-66 bar and temperature of about 50 ° C The authors used Eq. (1) as the basis for their model.

$$\rho C_p \frac{dT}{dt} + \frac{\dot{m}_{in}}{V} C_p (T - T_{in}) - \frac{dP}{dt} + h_{eff}(T - T_{amb}) = 0 \tag{1}$$

where h_{eff} is the effective heat transfer coefficient [W / m³ K], T is the temperature [K], Cp is the constant pressure specific heat [J/kgK], ρ is the air density in the cavern [kg/m³], t is the time [s], V is the cavern volume [m³], $\dot{m}_{in}$ is the injected air mass flow rate during charging [kg/s] and P is the pressure [Pa].

The first term of the equation corresponds to the rate of heat accumulation inside the cave, the second represents the rate of heat flow in the cave due to air inlet, the third term is the heat of compression and the last deals with the transfer of heat to the ambient.

3. METHODOLOGY OF SOLUTION FOR SCALED DOWN CAVE

Initially, some considerations were established regarding the problem in question. The values were obtained using the data provided from the Huntorf base, where the values of the model (Tab. 1) were then calculated, reducing the dimensions through the 1/30 scale. The velocity employed in the problem was obtained considering the same discharge time for the Huntorf base and the scaled model.

Table 1. Comparison between simulation values for the scaled model and the Huntorf.

Description	Symbol	Unity	Huntorf base	Scale 1/30
Radius	r	m	30	1.00
Cylinder Height	h	m	66.10	2.20
Total Volume	V	m³	300001.99	11.11
Initial Mass	ma	kg	21355191.09	790.93
Discharge Time	Desc.	s	51211.49	51211.49
Output Mass Flow	$\dot{m}_{out}$	kg/s	417	0.0154
Discharge Velocity	V	m/s	26.55	0.885
Cave Output Diameter	D_out	m	0.530	0.018

The air is modeled as ideal gas, the same consideration of the reference author (Raju and Khaitan, 2012). The solid wall of the cave consists of dolomite, a mineral of calcium carbonate and magnesium, present in deep rocks. The choice of dolomite is due to the existence of its properties in the library of the program used and its presence in subterranean caves of the studied genus.

3.1 Boundary conditions

The conditions in the wall of the cave have a constant temperature of 50ºC and effective heat transfer coefficient, with a value of 1.69 W / m³ K, obtained according to Eq. (2) below (Raju and Khaitan, 2012):

$$h_{eff} = 0.2356 + 0.0149|\dot{m}_{in} - \dot{m}_{out}|^{0.8} \tag{2}$$

At the exit of the cave was adopted constant mass flow, which uses the proportional value obtained in Tab. 1. This value can be verified by reading the Mach number and the air velocity at the exit of the pipe of the cave in the simulation. The values obtained were 0,98 m / s for the velocity and 0.0027 for the Mach number.

The information concerning the boundary conditions was inserted in Fluent, similar to those discussed in the reference article.

3.2 Solution Method

The problem was solved by Finite Volume Method. To solve the problem, the solution was adopted based on the pressure, through the projection method. This method consists of obtaining the conservation of mass (continuity) constraint of the velocity field through a pressure equation (or pressure correction). The pressure equation is derived from the continuity and momentum equations in such a way that the velocity-corrected field satisfies continuity. Since the governing equations are non-linear and coupled to each other, the solution process involves iterations in which the entire set of governing equations is solved repeatedly until the solution converges (Ansys, 2013).

The choice of solution based on pressure was due to the behavior of the fluid, which presents low speed, incompressibility as a function of the low Mach number (0.003) and subsonic flow. Then, the problem was classified as transient in the domain, taking into account the acceleration of gravity on the same axis in which the cave is positioned.

In order to solve the pressure-based system equations, it is necessary to select some parameters, based on the pressure and velocity coupling "SIMPLEC", which has faster convergence of the results.

Gradients of solution variables are required to evaluate diffusive flows, derived from velocity. Already for higher order discretization schemes are needed. In this case, the Least Squares Cell-Based scheme was used due to the polyhedral formation of the mesh and to have precision similar to a gradient based on the node system.

In relation to the pressure on the face, in the case of the cave that is high in relation to the volume in scale, the PRESTO! Method was used. This method is most suitable also in cases with high Reynolds number. The methods for momentum, turbulence, transient formulation and energy were applied in the first order, since the density method was set up in the second order.

3.3 Spatial and Time Discretization Sensitivity Test

To obtain results that are not influenced by the mesh size, tests were performed with different numbers of elements. The refinement parameter selected was the pressure domain slope line of the first simulation steps, corresponding to the range of 0 to 380 steps. All other simulation parameters and models were retained as a way of preserving the results. The convergence criterion adopted corresponds to the value of 1.10^{-3}.

The following are the solutions of four different simulations, proving that the values remain with a minimum difference in relation to the final result. Thus the M3 mesh was adopted to compute the final simulation calculations.

Table 2. Mesh sizes used in domain discretization.

Mesh	Number of nodes	Total number of elements	Slope
M1	24968	118976	-173.673
M2	36534	178061	-159.970
M3	41206	202209	-177.953
M4	48625	240748	-170.990

A similar analysis was done for the time discretization. In this way, different time steps were applied to ensure the independency of the results. Simulations were carried considering the same boundary conditions and the mesh defined in the spatial study, obtaining as final result pressure domain slope line. The same convergence criterion from spatial discretization test was adopted. The different time steps taken to verify the independence of the applied value can be seen in Tab. 3.

Table 3. Pressure slope for different time steps.

Time Step (s)	Straight Slope
1	-173.673
0.5	-176.823
0.1	-177.953

In this way, the final simulation was performed with 1 second time step and M3 mesh. The total simulation time was 14400 seconds (4 hours).

4. RESULTS AND DISCUSSION FOR SCALED DOWN SIMULATION

After defining the parameters used (mesh size and time step), the simulation was performed in order to compare with the data provided by the reference article, called “Model” (Raju and Khaitan, 2012). The model proposed by the authors, in turn, was validated with experimental data obtained from the Huntorf database. (Crotogino et al., 2001).

Because the beginning and end of the pressure and temperature were not the same, the comparison was made considering the difference (delta) in each interval. Then, in the last column, we have the relative error of each result obtained. The results are presented in Tab. 4 and Tab.5.

Table 4. Pressure results comparison between the simulation and reference data.

Pressure (bar)					
Time (h)	Simulated	Delta	Model	Delta	Relative Deviation %
0	66.000	-	69.300	-	-
1	60.800	5.200	64.200	5.100	1.961
2	56.200	4.600	59.200	5.000	8.000
3	51.500	4.700	54.300	4.900	4.082
4	46.700	4.800	49.500	4.800	0.000

Table 5. Temperature results comparison between the simulation and reference data.

Temperature (K)					
Time (h)	Simulated	Delta	Model	Delta	Relative Error %
0	323.,000	-	305.900	-	-
1	320.810	2.190	302.300	3.600	39.167
2	320.600	0.210	297.900	4.400	95.227
3	320.500	0.100	294.000	3.900	97.436
4	320.300	0.200	290.500	3.500	94.286

The results of the pressure drop over time presented similar values in relation to the adopted model, with a relative low percentage error. The results of the temperature drop were different from the model. To investigate why the temperature values differ from the reference, a second problem setup was proposed.

5. PROBLEM OF SECOND STAGE

According to He et al. (2017), when the mass flow rate is very low, the simulation over a given time allows the finite heat transfer rate to effectively minimize the variation of the air temperature. Therefore, the operation of the cave with low mass flow rate is closer to the operation of the isothermal cave.

Based on this information a new proposal was suggested to prove the application of the scale model, such as the aid of the Fluent program.

5.1 Proposal of the Second Stage

In order to evaluate if the parameters used in Fluent are correct, first the modeling of the equations present in He et al., (2017) will be carried out, with the aid of the MATLAB program. The information will be used as available in the article as a difference from the parameters related to the specific heat at constant pressure. According to the author, the general approach can be used to evaluate the cave at any stage of the life cycle only if the boundary conditions and initial conditions are properly defined. The validation procedure of the second stage proposal will be done as follows:

1º Reproduction of the modeling of the reference article, which has results close to the experimental values, using MATLAB software;
2º Evaluation of results and validation;
3º Use of validated MATLAB modeling, applying values from a cave to scale;
4º Dynamic simulation in Fluent with the same parameters used in step 3;
5º Comparison of the results of step 3 and 4.

After the assignment of the input conditions and constants of the problem, the equations used in the modeling will be adapted to a case of decompression. Defining the volume of the cave, with input and output mass, according to the first law of thermodynamics, through conservation of mass and energy and considering that there is no variation in volume, the problem is limited to the interval of air decompression of the cave, according to Eq. (3) and Eq.(4) .

$$\frac{dp}{dt} = \frac{1}{V}(\mathrm{k}\mathrm{R}T\dot{\mathrm{m}}_{out} + (\mathrm{k}-1)\dot{Q}) \tag{3}$$

$$\frac{dT}{dt} = \frac{(\dot{\mathrm{Q}} + V\frac{dp}{dt})}{mC_p} \tag{4}$$

Where κ is the ratio of the thermal capacity of the air, Q is the heat transfer flux [J/s] and R is the gas constant [J/kg·K] . The article of He et al. (2017) considers an average value of the air thermal capacity ratio, corresponding to k = 1.4.

6. RESULTS AND DISCUSSION OF THE SECOND STAGE

In the reference article of the second stage (He et al., 2017), the author presents a validation of the dynamic modeling of pressure and temperature of the air, with test data of the plant of Huntorf, during the initial test. The decompression results from a period of 2.5 hours (9000 seconds) were extracted from the article, and compared with the results obtained with the simulation described in the previous section. The results can be seen in Tab.6 and Tab.7 below.

Table 6. Relative Pressure Error.

Pressure Results (bar)			
Time (s)	MATLAB Simulation With Article Data	Results of the Reference Article (He et al., 2017)	Relative Error %
0	59.0	59.0	0.000
2880	54.0	55.0	1.818
6120	49.0	50.0	2.000
9000	45.3	46.0	1.522

Table 7. Relative Temperature Error.

Temperature Results (K)			
Time (s)	MATLAB Simulation With Article Data	Results of the Reference Article (He et al., 2017)	Relative Error %
0	317.0	317.0	0.000
2088	311.4	313.0	0.505
4356	306.4	308.0	0.519
7056	301.8	303.0	0.399
9000	299.3	299.2	0.033

Thus the set of equations and the way they were used presented satisfactory results, and will be used in the validation study of the numerical model in scale, simulated in Fluent.

For to evaluate if the use of the scale model proposed in the first stage of this study, presents results consistent with a valid reference, two simulations were performed. First, the data suggested in the first stage were inserted into the MATLAB program, previously validated.

Then the same parameters used in the simulated algorithm in MATLAB were inserted in the Fluent, and thus the air decompression in the same time interval of 9000 seconds was executed. To determine the temperature in the walls of the cave, the parameter "Temperature" was used, considering the constant value of 313 K and the material of the cave was kept as dolomite. The Fig. 1 and Fig. 2 below show the comparisons of the results found.

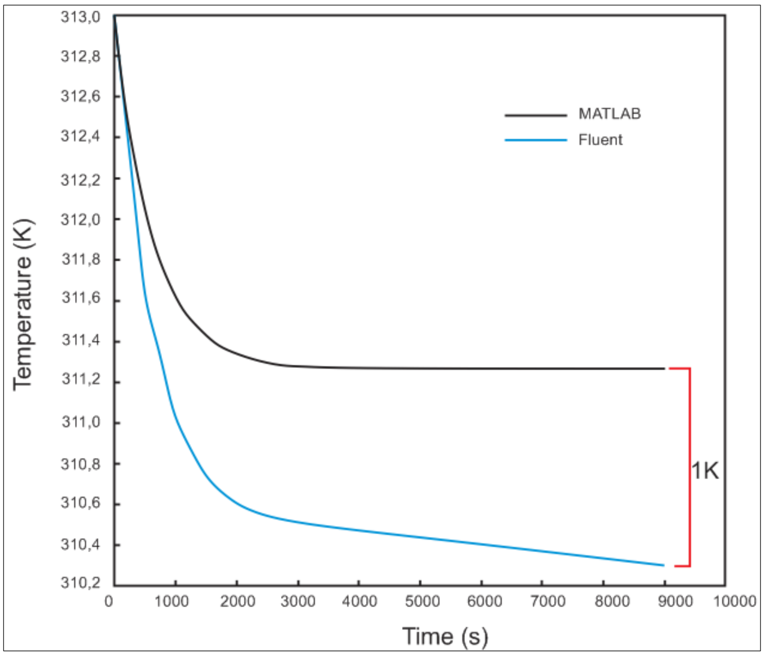

Figure 2. Temperature Comparison - Fluent x MATLAB.

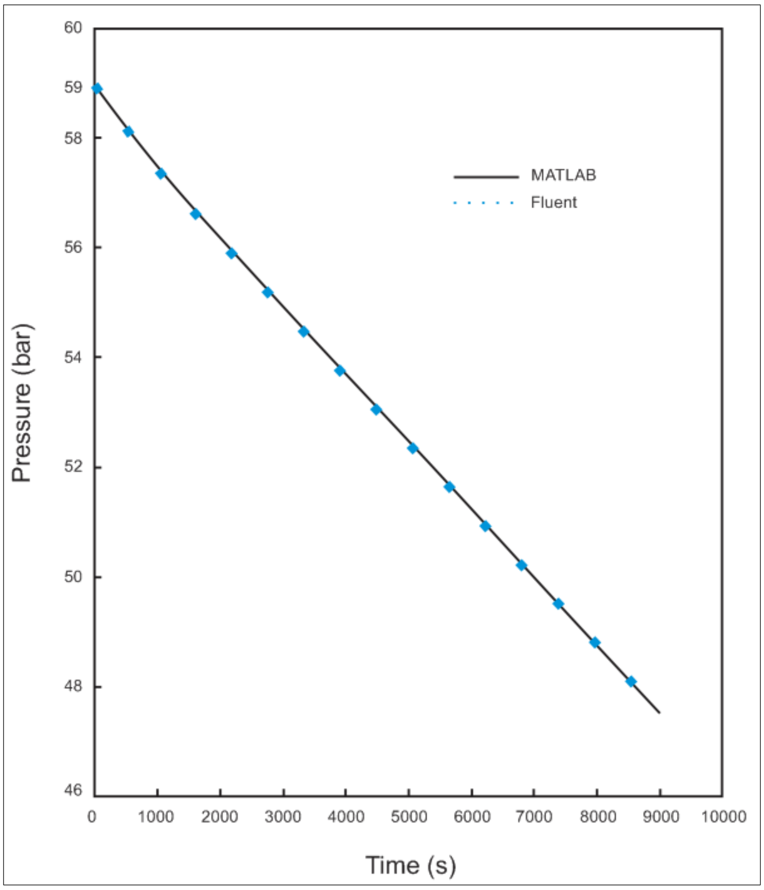

Figure 3. Pressure Comparison - Fluent x MATLAB.

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The simulated result in Fluent, referring to the pressure drop, presents values equal to those obtained in MATLAB. The results of the temperature drop over time showed a difference of 1K. In this way it was possible to verify that the configurations and data used in the simulation parameters inserted in Fluent, present satisfactory results in general. Thus scale-to-simulation relationships can be explored as an alternative to similar studies.

7. CONCLUSIONS

The objective of this work was to simulate the discharge behavior of a salt cave, referring to the conventional CAES system, during peak hours (high energy demand), with the aid of three - dimensional simulation software with the correct application of methods and parameters to obtain relevant results for its use. Due to the high computational time, in a cave with real dimensions, a scale simulation model was proposed in the first stage of the study, based on conservation and mass and energy equations.

First, data from a numerical model validated by Raju and Khaitan (2012), based on experimental data from the cave of Huntorf, Germany, were used. To obtain the results of this study, the same values used by the authors were applied in the three-dimensional simulation, but with the use of scale in the volume of the cave, correcting the velocity of discharge as a function of volume, so that the process time is the same. The parameters used in the 3D modeling were applied based on the pressure, through the projection method that restricts the mass conservation (continuity) equation of the velocity field through a pressure equation (or pressure correction). The properties of the fluid and walls surrounding the cave were the same as those of the reference author. For the solution method, the coupling "SIMPLEC" was used, because it presented faster convergence. The cell-based Least-Squares method was used because of the polyhedric formation of the mesh and because of its precision similar to a gradient based on a node system. On the pressure in the face of the cave in scale, the "PRESTO!" method was used. This method is most suitable also in cases with high Reynolds number.

In relation to the mesh size used and the time step, through the sensitivity test, it can be concluded that the most suitable mesh for the study was 202209 elements, which provided results independent of the increase of elements used for the rat of the problem. In relation to the time, the slope parameter of the line was satisfactory with the results applied to the time step of one second.

The first results obtained in the comparison between the reference article and the three - dimensional simulation showed a maximum relative error of about 8% in relation to the pressure and 97% in the temperature. Due to the large difference in velocity values, an investigation was carried out and it was found that when the mass flow rate is very low, the simulation over time allows the finite heat transfer rate to effectively minimize the variation of the air temperature. So a new proposal for the problem was developed.

Using the knowledge of the first stage, in relation to the method and parameters, in order to validate the settings applied to the three-dimensional simulation, a new sequence was developed. Firstly, the reference article was reproduced numerically, and compared with the results found by the authors, with difference in the use of fixed value for specific heat at constant pressure. Then the volume and velocity data of the scale model defined in the first step were inserted into the modeling. Finally, the results of the numerical scale model and the three-dimensional model were compared. As results were found maximum relative error of about 2% in relation to the pressure and 0.5% in the temperature. Evidencing the assertion that the low mass flow acts directly on the heat transfer effect. The results of the first stage contributed to define the parameters used in the simulations of the second stage.

With the study, it was evident the feasibility of using the three-dimensional model for decompression simulations in saline caves in scale. This technique can provide more information than the current models available in the references of this study, because besides temperature and pressure, it is possible to evaluate the speed behavior and the influence of different geometries in the results. Another important fact in this type of simulation is the behavior of thermal heat exchange between the cave wall and the fluid. Conventional methods, such as those discussed in the articles used as reference, only present the behavior of the pressure and temperature variation, throughout the process. To obtain more reliable answers it is necessary to study in depth the influence on the scale, especially on temperature.

8. REFERENCES

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