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Numerical calculations of main stress in the rock massif around salt cavern for compressed air storage

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Abstract. The article presents the results of numerical calculations of main stress around salt cavern for energy storage in compressed air. The calculations based on the operating installation - the Huntorf power plant - using the CAES technology (Compressed Air Energy Storage). This paper discusses the results of calculations for scenario of work the storage cavern where model including thermal effects - the influence of changes in the temperature of the rock massif around the cavern and without thermal effects - with a constant temperature distribution of the rock massif around the storage cavern.

1. Introduction

The CAES technology (Compressed Air Energy Storage) combines two types of energy: conventional (gas turbine) and renewable (energy accumulate in compressed air). When there is a surplus of electricity it is using to drive compressors, which compressing air in the salt cavern. During the increased demand for electricity, the air is released from the cavern and delivered to the gas combustion process in the turbine.

The changes of pressure in the storage cavern are very fast [1]. Those changes can affect for the rock massif around storage cavern so the calculations for stresses and strains are made [6,9]. As a part of consideration, there were performed numerical calculations to verify how big is the influence of temperature changes on the state of deformation-stress case around the storage cavern [9,10]. This article discus the results of numerical calculations of main stress around salt cavern for energy storage of compressed air with and without thermal influence. The scenario used in calculations based on the Huntorf power plant parameters – the operating installation using the CAES for energy storage in compressed air [4,11].

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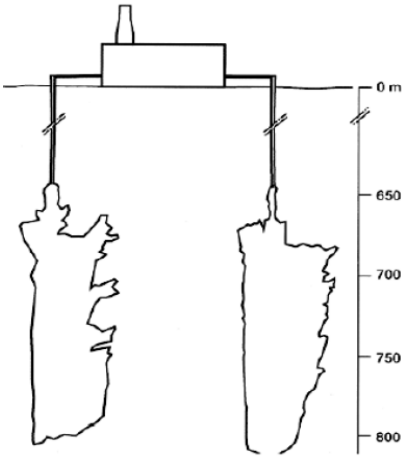

Figure 1. Depths of storage cavern in the CAES Huntorf power plant [2]

Parameters of the Huntorf installation [2]:
Volume of storage caverns: 140 000 m3 and 170 000 m3 (total volume 310 000 m3)
Total power plant output: 290 MW
Energy delivery time (emptying time): 2-3 hours
Filling time: 8 hours
Working pressure: 5 -7 MPa
Depth of cavern foundation: 650 - 800 m

2. Numerical calculations

2.1. *Creep law and thermal properties*

The program GEOSOLK was used for the numerical calculations. It was extended by a module of the temperature distribution in the rock massif around the cavern. In the simulations there were applied the strength criteria for rock salts in Poland. The Norton's creep law based on the results of laboratory tests and literature studies was used in model.

$$\frac{d\varepsilon_{ef}}{dt} = Ae^{-\frac{Q}{RT}}\sigma_{ef}{}^{n} \tag{1}$$

where:
Q - activation energy [J/mol],
R - universal gas constant [J/mol·K]
T - temperature [K]
A, n - fixed coefficients, A = 219.65 ‰, n = 4.

For the calculation was used the Q/R ratio = 6500 K, which means that at 50°C the salt creep rate will be almost eight times higher than at 20°C.

The initial temperature of the salt rock changes linearly [8]:

$$T = \alpha_g \cdot H + \beta \tag{2}$$

where:
α_g – temperature gradient,
β – constant ratio,
H – depth.

The value of the temperature gradient varies depending on the salt structure, so for the purpose of computer simulation it was necessary to adopt some averaged values of parameters regarding thermal properties for salts, which are listed in Table 1.

Table 1. Thermal properties of salt used in numerical model

Thermal conductivity of a salt rock massif [W/m·K]	6.5
Thermal diffusivity [m2/s]	$0.45 \cdot 10^{-5}$
Density of salt [kg/m3]	2155
Heat exchange in salt [W/m2·K]	50
Temperature gradient α_g [K/m]	0.025
Coefficient β	298
Considered interval [m]	0 - 2000

Based on the adopted temperature gradient, it was determined that the range of temperature changes in the rock massif, in the interval 0 - 2000 m, was 15-75ºC.

2.2. *Scenario for numerical calculations*

The scenario used for the simulation based on a working CAES installation [9,10] where pressure drop by 2 MPa within 2 hours, so it expects even rapid temperature changes inside the cavern, which should have been included in the calculations [1,11].

The calculation scenario consisted of 29 cycles of daily cavern operation. One cycle includes: 2 hours of compressed air intake from the cavern, 6 hours break (the cavern remains under the minimum pressure), 8 hours of injection of compressed air into the cavern, 8 hours of break at maximum pressure. In numerical calculations the maximum pressure in the cavern is 6.6 MPa (with full storage), and the minimum pressure is 4.6 MPa when the cavern is empty [2, 4, 6, 7].

The cavern model used in the calculations (Figure 2) had a height of 150 m located in the interval 650 – 800 m, and radius 17.84 m, so cavern volume is nearly 150,000 m3. A pipe with an outside diameter of 21" (internal diameter 20") was used for the cavern's operation. The cavern operating pressures was 46 - 66 bar.

The model grid (Figure 2) used in the GEOSOLK program is built from 660 elements. The horizontal range of caverns was 250 m, including a 17.84 m radius of cavern. The vertical range (measured from the cavern axis) was also 250 m.

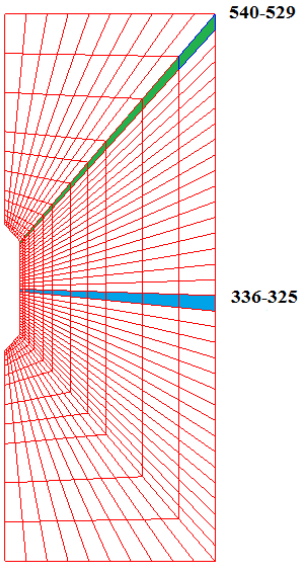

Figure 2. Grid of cavern model in calculations with marked elements on the ceiling and the middle.

Figure 3 presents a scenario used in simulations. The graph shows the changes in pressure and temperature in the cavern determined in the KAGA program using the above assumptions. Analyzing the temperature graph, in the initial stage of the cavern's work, there is a slight trend of its growth in the initial cycles of work. However, with the time of further exploitation, the temperature in the cavern shows a falling trend.

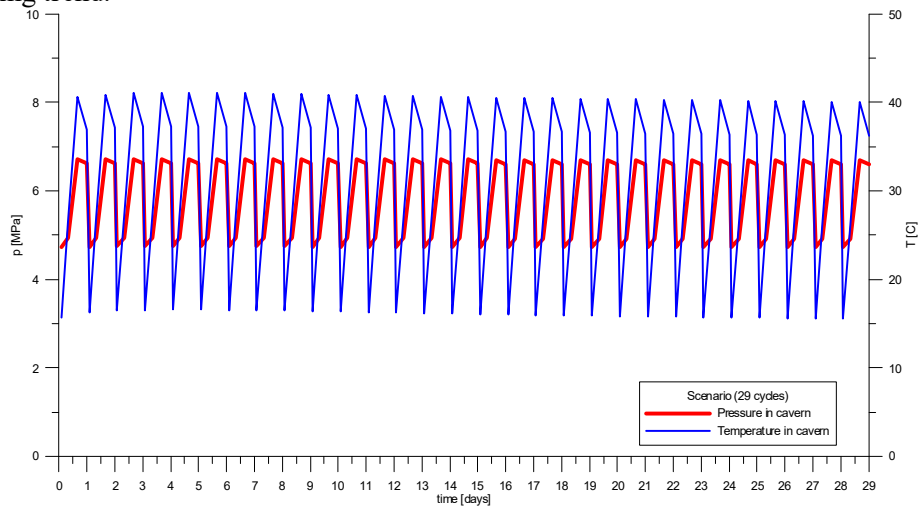

Figure 3. The 29 cycles scenario used in simulations.

2.3. Results of numerical calculations

The presented results include the calculations made for two models:

Without thermal effects - with a constant temperature distribution of the rock massif around the storage cavern,

With thermal effects - taking into account the influence of changes in the temperature of the rock massif around the storage cavern.

Table 2 presents the results of the simulations for main stresses and strains for elements located on the cavern ceiling. carried out. These elements were marked on green at the cavern grid shown in the Figure 2.

Table 2. Summary results for the ceiling

	Without thermal effects			**With thermal effects**	
Element number	R [m] (distance form cavern axis)	Stress [MPa]	Strain EI [‰]	Stress [MPa]	Strain EI [‰]
540	19,19	15,84	1,66	15,24	2,23
539	21,89	14,78	0,79	16,34	1,05
538	25,94	14,40	0,42	15,17	0,46
537	31,34	13,98	0,23	14,39	0,22
536	39,44	13,76	0,11	13,92	0,08
535	50,23	13,54	0,06	13,58	0,03
534	66,43	13,18	0,03	13,19	0,02
533	88,03	12,70	0,01	12,70	0,01
532	109,62	12,20	0,01	12,20	0,01
531	142,02	11,39	0,01	11,38	0,01
530	185,21	10,33	0,01	10,33	0,01
529	228,40	9,29	0,01	9,30	0,00

The results in the Table 2 are also presented on the graphs below (Figure 4 and Figure 5). Results obtained during the simulation, indicate that the greatest differences in stress between the adopted models occur directly on the cavern wall and in a very close vicinity (Figure 2). It is clear that in the case of a model without temperature changes, the stresses have the highest value in element 540 (cavern wall), then they fall as the distance increases from the wall. On the other hand, in the case of the model of temperature changes in the rock around the cavern, the highest value of the main stresses occurs in the second element of the model, i.e. 21.9 m from the cavern axis (i.e. about 4-5 m from the cavern wall). Then, as the distance increases, the stress values fall off, and within approx. 50 m of the cavern axis, they take approximate values for both computational models.

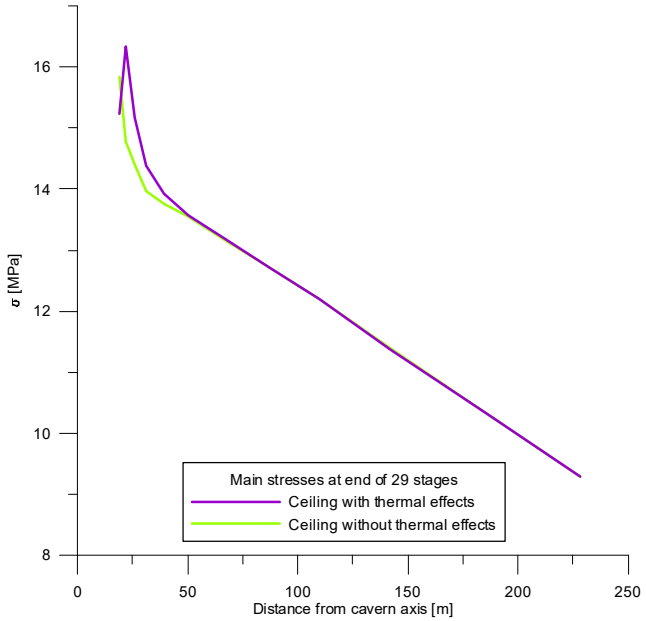

Figure 4. Main stresses on ceiling at the end of 29 cycles without thermal effects and with influence of temperature changes.

In the case of deformations (Figure 3), the situation is similar in both computational models. In the case of the model with temperature variation of the cavern wall deformation is higher (EI = 2.2‰) but

already at 31 m from the cavern axis (13 m from the wall) the deformation values are similar in both models.

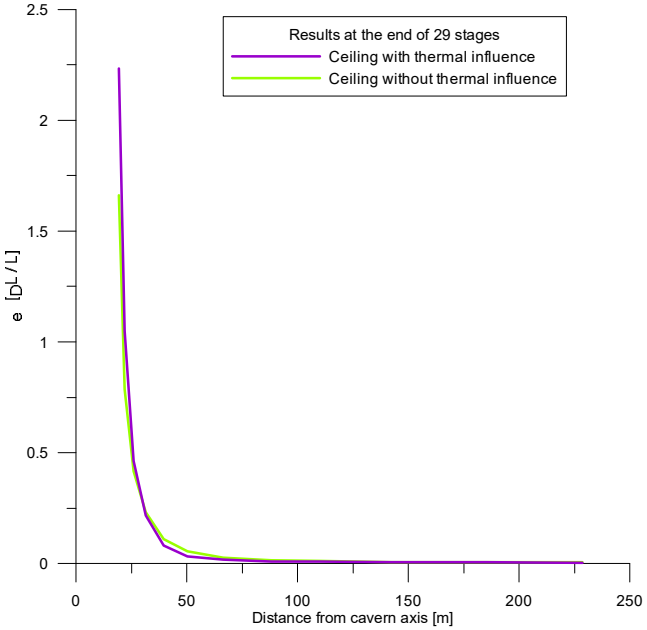

Figure 5. Strains on ceiling at the end of 29 cycles without thermal effects and with influence of temperature changes.

Table 3 shows the simulation results for main stresses and deformations in the middle of cavern, depending on the distance from the cavern axis. These elements were marked on blue at the cavern grid assumed in the simulations shown in Figure 1.

The results, as in the case of ceiling elements, account for the calculations made for the two models: without analyzing the impact of the rock temperature and with the influence of rock temperature changes around the storage cavern.

Table 3. Summary results for the middle of cavern

	Without thermal effects			**With thermal effects**	
Element number	R [m] (distance form cavern axis)	Stress [MPa]	Strain El [‰]	Stress [MPa]	Strain El [‰]
336	19,19	12,85	2,45	11,99	2,88
335	21,89	13,63	1,81	14,62	2,20
334	25,94	14,47	1,21	15,31	1,38
333	31,34	15,09	0,76	15,94	0,81
332	39,44	15,46	0,45	15,93	0,45
331	50,23	15,59	0,27	15,72	0,25
330	66,43	15,63	0,15	15,61	0,13
329	88,03	15,62	0,08	15,57	0,06
328	109,62	15,59	0,05	15,55	0,04
327	142,02	15,56	0,02	15,54	0,02
326	185,21	15,55	0,01	15,53	0,01
325	228,40	15,57	0,01	15,55	0,01

The results shown in the Table 3 are also presented on the figure 6 and figure 7. The obtained results show that the largest differences in the main stresses between two models occur directly on the cavern wall and in a very close vicinity (Figure 4). In the case of a model without temperature changes, the stresses on the wall are 12.85 MPa and with increase the distance there goes to 15.57 MPa at 200 m from the cavern wall.

In the case of model with temperature changes in the rock massif, the initial stress value is lower (11.99 MPa), then there increase sharply in the element 333 and 332 to the highest values (15.93 MPa), and after that, at 66 m distance from the cavern axis the values of the main stresses are almost identical for both computational models.

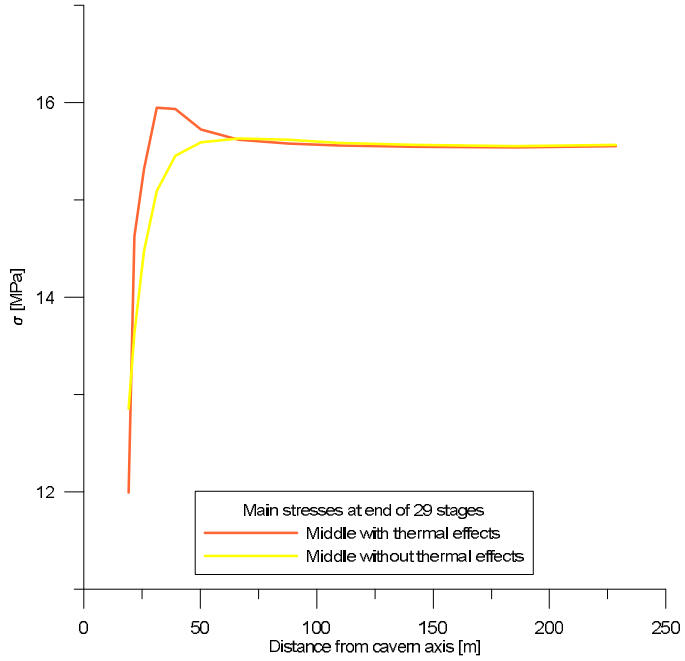

Figure 6. Main stresses in the middle of cavern at the end of 29 cycles without temperature influence and with influence of temperature changes.

In the case of deformations (Figure 5), the situation is similar in both computational models. It is true that in case of a model that takes into account the temperature variation of the cavern wall deformation is higher (EI = 2.8‰), but already at a distance of 40 m from the cavern axis (23 m from the wall) the deformation values in both models are similar.

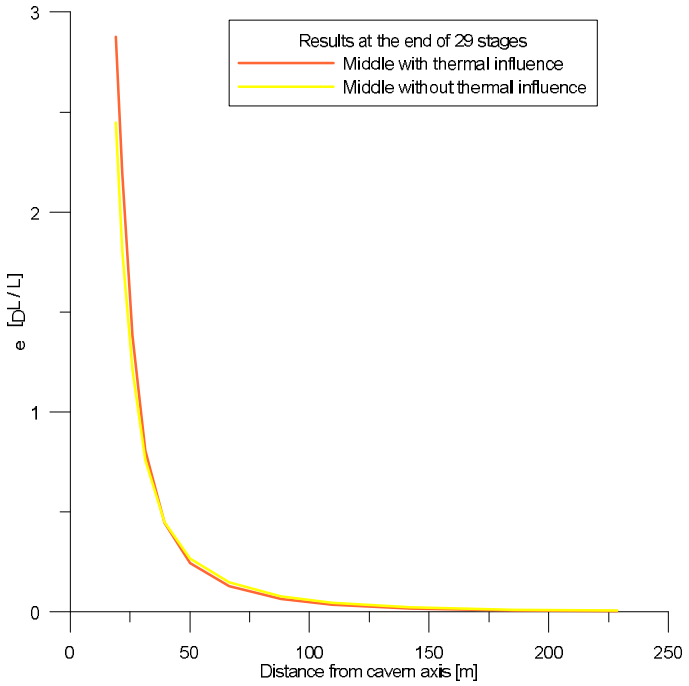

Figure 7. Strains in the middle of cavern at the end of 29 cycles without temperature influence and with influence of temperature changes.

3. Conclusions

The numerical calculations shown that the influence of temperature on the deformation-stress case of the CAES cavern is importance when considering the stress state at a distance of less than 50 m from the cavern axis (at caverns diameter 30-35 m).

The results of the calculations compared in the above tables indicate that the influence of the temperature change in the cavern ceiling on the stress is significant in the immediate vicinity of the salt cavern. Comparison with the results obtained during modelling without the influence of temperature changes on stresses indicates that the largest differences in obtained results occur up to a distance of 50 m from the axis of the cavern.

In case of strains around storage cavern this distance is smaller and it is around 30 m for ceiling and 40 m for middle.

There are differences in the values obtained for deformations directly on the wall of the cavern, while in subsequent elements of the model, the values are close to each other and they decrease as the distance from the axis of the cavern increases.

It is probably that with the increase of cavern diameter the impact range will be proportionately larger, but each case requires individual modelling include shape of cavern and the scenario of cavern working cycle.

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