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Technical Note

The influence of thermodynamic effects on gas storage cavern convergence

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1. Introduction

Convergence (creep closure) of storage cavern is caused by the rock salt creep process, which depends on stress and temperature. In the case of storage caverns filled and emptied in seasonal cycles, during withdrawal periods the effective stress increase in the cavern vicinity is concurrent with temperature decrease. Inversely, during gas filling periods the stress decrease is concurrent with temperature increase. The research presented so far neglected influence of the temperature variation over time during convergence assessment, the temperature field was only depth-dependent there.

Thermal effects have an opposite impact than the stress ones therefore it could be expected that the convergence computed taking into account thermal effects will be significantly different (lower) than computed by traditional methods. The purpose of our work was the quantitative analysis of this phenomenon.

Thermodynamic effects play an important role in underground natural gas storage in solution-mined caverns and should be accounted for when assessing both the stability and optimal cavern filling and withdrawing rates. The most important thermodynamic effects are as follows: rock mass cooling during cavern leaching due to the lower (especially in winter) temperature of the leaching medium compared to the initial rock mass temperature; gas temperature increasing during injection into and decreasing during withdrawal from the cavern due to thermodynamic processes; heat exchange between the natural gas and salt rock mass surrounding the cavern and its casing during cavern operation due to temperature differences; salt rock mass temperature changes associated with the heat propagation due to the rock mass thermal conductivity.

Measuring these processes directly in the cavern and rock mass is not possible in practice. One can only indirectly assess their intensity by measuring the pressure, temperature and flow capacity at the wellhead using numerical simulations.

Thermodynamic processes in the stored gas and thermo-mechanical processes in the rock mass are the best known. Recently, however, they have been considered as cumulative, mutually affecting phenomena.

Previous geomechanical calculations for the discussed issue used two independent simulators: the first analyzes the thermodynamics problems and the second determines the geomechanical issues. Paper[1] uses a SCTS simulator (Salt Cavern Thermal Simulator) developed in the US by PB Energy Storage Services and RESPEC Inc. The SCTS was designed to simulate thermodynamic processes during salt deposit storage cavern operation.[2]

The LOCAS program was adapted to simultaneously solve the above issues.[3] The calculations using this program are presented, among others, in paper.[4] Paper[5] described both of the above approaches. For the first, the temperature distributions obtained using the SCTS program for a spherical cavern wall were introduced to the ABAQUS program; in the second, a cylindrical

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cavern example was used for thermo-mechanically coupled simulations using the LOCAS program. However, the cavern convergence was not analyzed.

2. Thermodynamic process characteristics – the parameters adopted for the rock mass model

The introduction presented four processes affecting the rock mass temperature and, consequently, the stress–strain state and convergence for the surrounding cavern. Determining the impact of these processes requires formulating and solving the set of thermodynamics and fluid mechanics equations.

The above issues are presented over the next three chapters, with special focus on the process characteristics for gas storage caverns.

2.1. Processes in the stored gas

The temperature, density, pressure and flow rate describe the gas state. One can determine them using the equation of state to relate the first three variables and solving the system of integral–differential equations for the continuity, momentum, energy and flow resistance.

The prevailing thermal conditions in the storage cavern differ significantly from the critical ones. Therefore, describing the gas behavior using the Redlich–Kwong equation of state is used:

$$p = \frac{RT}{v-b} - \frac{a}{T^{0.5}v(v+b)} \tag{1}$$

where p is the gas pressure, R is the gas constant, T is the temperature, v is the molar volume, and $\{a, b\}$ are constants that depend on the gas composition. The following values were used for the calculations: $a=0.34161\times10^{7}$ m^{3}K$^{0.5}$/kmol$=$12,674.6 m^{3}K$^{0.5}$/kg, and $b=0.029997$ m^3/kmol$=0.18272\times10^{-02}$ m^3/kg.

The continuity equation describes the mass conservation. This equation does not require a coefficient specific to the gas storage problem.

The gas flow equation describes the conservation of momentum. This compares the momentum change for a given gas volume with a momentum flux passing through the boundary surface. The difference in balance is caused by the gravitational and surface forces.

The gas energy equation compares the energy change for a given gas volume with an energy outflow to its boundary surface. The difference in balance is derived from the heat flowing through the boundary surface and the work performed by external forces on the gas contained within this volume.

The flow resistance equation is important because it determines the wellhead-cavern pressure difference, and heat from friction. The Darcy–Weisbach equation with Nikuradse resistance factor (high Reynolds number) was used. The resistance factor for 8 5/8" withdrawal tubing with a roughness of 0.15 mm was 0.01835.

2.2. Heat exchange between brine, gas and the rock mass

The heat exchange between the gas, brine and rock mass is the least well-known thermodynamic process and is generally expressed by the following formula[6]:

$$\iint_Z \lambda_g \nabla T_g \cdot \mathbf{n} dS = \iint_Z \alpha (T_k - T_g) dS \tag{2}$$

where λ_g is the thermal conductivity of the salt body, T_g is the salt body temperature, T_c is the temperature inside the cavern, Z is the cavern boundary surface element, and α is the heat transfer coefficient,

The basic problem is determining the heat transfer coefficient. Theoretically, this value can be determined based on the empirical relation between the Nusselt and Rayleigh numbers derived for natural convection conditions. However, this paper adopted the following values of the α coefficients based on publication[7] and a fit for the empirical data from the Underground Gas Storage facility (UGS) Mogilno caverns: brine 200 W/m^{2}K, gas 60 W/m^{2}K.

The α coefficient should be determined for each cavern individually due to irregularity of its shape and surface.

2.3. Thermal conductivity of the rock salt mass

The thermal conductivity of the rock mass under transient conditions was described by the Fourier equation using the heat capacity, density and thermal conductivity coefficient as the characteristic parameters.

The thermal conductivity coefficient depends on the state of stress (increasing with intensity); however, the effect is of secondary importance and no appropriate quantitative formulas to analyze heat propagation in the rock salt mass under varying stresses is known by the authors. Thus, the constant value of the coefficient was used in the calculations taken from laboratory tests on rock salt from the Mogilno salt dome. The values of the parameters adopted for the calculations are presented below in Table 1.

2.4. Creep law for rock salt

The cavern convergence, which is the decrease in its volume over time, was calculated based on the rock mass creep rate across the entire cavern influence range. Research indicated the temperature significantly affected the stationary creep rate. These calculations used Norton's creep law:

$$\frac{d\varepsilon_{ef}}{dt} = A\exp(-Q/RT)\sigma_{ef}{}^{n} \tag{3}$$

where $\sigma_{ef} = sqrt\{[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2]/2\}$ is the effective stress, $\varepsilon_{ef} = sqrt\{2[(\varepsilon_1-\varepsilon_2)^2 + (\varepsilon_2-\varepsilon_3)^2 + (\varepsilon_3-\varepsilon_1)^2]\}/3$ is the effective strain, T is the temperature [K], and $\{A, Q/R, n\}$ are constant parameters. The parameters applied to Norton's law are summarized in Table 1.

2.5. Numerical model for the salt cavern

Two programs for axisymmetric analyses, Kaga and Geosolk, were used to perform these calculations. Both programs were developed specifically for the gas storage cavern analysis and have been successfully used during the designing and operation of storage facilities in Poland. The Kaga program has been validated and calibrated based on the operation data from the UGS Mogilno. This program generates grids covering the area up to the surface, because the thermal interaction between gas and rock massif in

Table 1
Salt properties and creep models parameters.

Parameters	Units	Value
Thermal conductivity coefficient	W/mK	6.5
Heat capacity	kcal/m^{3}K	370
Density	kg/m^3	2200
A	[d^{-1}*MPa^{-n}]	0.17572
Q/R	K	6500
n	–	5