Conversion of existing natural gas storage caverns for hydrogen storage – some selected aspects to be considered

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ABSTRACT: The conversion of existing natural gas storage caverns for hydrogen storage requires the assessment of the mechanical integrity of the wellbore. The additional impact on the wellbore induced by cavern convergence due to long-term operation must be particularly considered. Numerical simulations of an existing cavern and its wellbore using the FTK-simulator are performed to investigate the stress and strain changes in the casing shoe, including casing, annulus cement, and contact interfaces during the operation. In addition, hydrogen transport in the casing shoe area at the borehole contour is numerically simulated during the mechanical integrity test. It is shown that the FTK-simulator can be successfully used to predict the TH2M-couped load-bearing behavior of salt cavern and wellbore throughout its entire life and provides a detailed insight into the development of stress and strain regarding the casing, annulus cement, and contact interfaces.

Keywords: underground hydrogen storage, salt caverns, well integrity, mechanical integrity test.

1 INTRODUCTION

According to LBEG (2022), there are 273 operating natural gas storage caverns in Germany with a maximum working gas storage capacity of about 14.8 billion m^3, about 14% of Germany's total annual natural gas consumption. With further decarbonization in Germany, the number of caverns for natural gas storage could gradually decrease. Therefore, existing natural gas storage caverns can be further converted for green hydrogen storage. In this context, assessing the existing caverns, including their wellbores, is particularly important for conversion and long-term safe operation. Part of the assessment is to evaluate the mechanical integrity of the wellbore in addition to the geomechanical condition of the storage cavern, especially after many years of cavern operation.

In the casing shoe area, the primary barrier, consisting of the last cemented casing, the annulus cement, and the rock salt, is an essential part of the wellbore integrity. The lowest part of wellbore, the so-called casing shoe area is in direct contact with natural gas or hydrogen and must be safe to the extent necessary to seal the cavern. However, this part of the wellbore is most affected by the cavern. The cavern convergence induced by the operation leads to additional stresses in the casing shoe area, which are not considered in the design up to now. BVEG (2017) requires that the casing and annulus cement must withstand all possible loads during the lifetime of the cavern system. Numerical simulations on the effects of additional stresses due to cavern convergence have been performed in several papers (e.g. Park et al. 2006 and Orlic et al. 2016). Lux et al. (2020) have developed a numerical simulator that can explicitly simulate the cavern and the wellbore, particularly in the casing shoe area, including casing, annulus cement, and interfaces after long year cavern operation. Subsequently, gas transport simulation and the well integrity analysis can be performed.

The mechanical integrity test (gas interface method) is a common in-situ method used worldwide to verify the mechanical integrity of the cavern well (Crotogino 1995). A gas-brine interface is created under test pressure 10 m to 15 m below the casing shoe by injecting a test gas (e.g. nitrogen or hydrogen) into a brine-filled cavern. During the test, the pressure and the temperature in the test area as well as the depth of the interface are continuously measured to determinate the mass of the test gas. The leakage rate is then determined by the difference in gas mass in a certain time interval. The cavern well is called technically tight if the measured leakage rate is less than the pregiven critical value. However, the evaluation of technical tightness is a semi-empirical method. The measured leakage rate not only includes the actual leakage due to damage or imperfection of the wellbore, but also a part of the unavoidable gas infiltration (Wolters 2014) during the test in the non-cased borehole below the casing shoe. Therefore, the gas volume of infiltration during the test must be investigated. However, the volume cannot be separated directly from the measurement. Through numerical modeling, the physical processes during the test can be better understood, and the infiltration volume can also be quantified in principle.

2 PHYSICAL MODELING OF CAVERN AND WELL

2.1 FTK Simulator and simulation model

In this study, the FTK-simulator (Lux et al. 2015) was used for numerical simulation. The FTK-simulator is a numerical software package developed by the author's institute for TH2M-coupled processes using the commercial software codes FLAC3D and TOUGH3.

A typical natural gas storage cavern in rock salt in Germany was selected for this study. Figure 1 briefly shows the salt cavern and the wellbore in the casing shoe area. Within the numerical model, the filigree structure of the wellbore is explicitly discretized. By explicitly considering the cavern wellbore within the numerical model, additional stresses and strains due to cavern convergence and thermally induced stresses from cavern operation on the casing, annulus cement, and contact interfaces can be calculated in space and time.

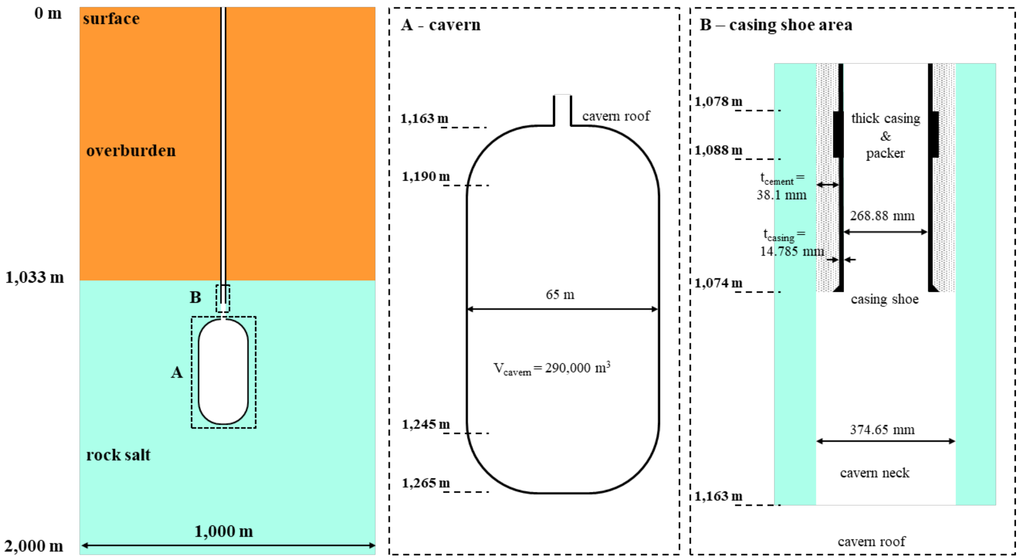

Figure 1. simulation model including cavern and wellbore.

2.2 Parameters for physical modeling

2.2.1 Rock salt

The visco-plastic behavior, as well as the damage and healing behavior of rock salt, are described by the Lux/Wolters/Lerche constitutive model. The required material parameters may be found in the WEIMOS project report by Lux et al. (2022).

The undisturbed rock salt has a primary porosity of about 0.2% and is impermeable. The pressure-driven infiltration process as well as the increase in porosity and permeability induced by thermomechanically induced damage processes used in this study are described in a physical model by Wolters (2014).

2.2.2 Last cemented casing

The final cemented casing has a dimension of 11 ¾" 71# and is made of API N80 steel with a plasticity limit of about 551 MPa. An elasto-plastic material model with the von-Mises criterion is used for the numerical simulation.

Casing is assumed to be an impermeable medium in this study. Hydrogen diffusion in steel and the hydrogen embrittlement of the material are not considered.

2.2.3 Annulus cement and contact interfaces

API class C cement is used in wellbore in the rock salt mass mixed with fully saturated brine and salt powder, so that wellbore contour is not additionally dissolved in the cement suspension during the cementing. Regarding the physical modeling of the behavior of the cement with fully saturated brine, strength parameters for this cement have been systematically determined by a series of laboratory tests. In addition, the strength properties of the casing/cement and cement/rock salt contact interfaces have been determined in direct shear tests. All the material parameters of the annulus cement and contact interface can be found in Lux et al. (2020).

The cement in the casing shoe area is always kept in a humid environment. The pores of the cement are mostly filled with brine. Therefore, potential gas transport through the pores occurs under two-phase conditions and must first overcome the gas entry pressure and the capillary pressure (Ganzer et al. 2019). Gas transport through hydraulic intact contact interfaces requires overcoming rock pressure perpendicular to the contact interfaces. During operation, the maximum gas pressure is limited to approximately 80% of the rock mass pressure. In this context, cement and contact interfaces are assumed to be impermeable to gas in this study.

3 SELECTED RESULTS OF THE NUMERICAL SIMULATIONS

3.1 Convergence-induced additional stresses on the wellbore in the casing shoe

In order to separate the effects of cyclic loading with changing gas pressures and temperatures from the effect of cavern convergence on well integrity and simplify the numerical simulation, an average constant cavern pressure of 14 MPa is used for this study. This approach leads to a convergence of about 25% after 30 years of operation.

Figure 2a shows the vertical strain along the casing during the operating phase. The vertical strain increases with time and after 30 years of operation the maximum strain occurs at about 6 m above the casing shoe with about 0.23%. Figure 2b shows the loading condition of the casing at this location according to API design. After 30 years, the stress state is close to the plastic limit (blue line) and exceeds the API design limit (green dashed line). The stress state of the casing after the long-term operation may be of significant importance for the safe operation of hydrogen in the future. The casing below the packer in the casing shoe is in direct contact with hydrogen, which can reduce the plasticity of the casing due to hydrogen embrittlement. This part can thus be damaged under the additional effect of the cavern convergence.

Figure 2c further shows the stress path in the cement in a depth of 1,068 m over time. It can be seen that the annulus cement has an isotropic stress before operation. During the operation, the vertical stress in the annulus cement decreases due to the convergence of the cavern. The deviatoric stress increases and the stress state tends to the strength limit. If the stress in the annulus cement reaches the strength limit, it can impair the sealing function.

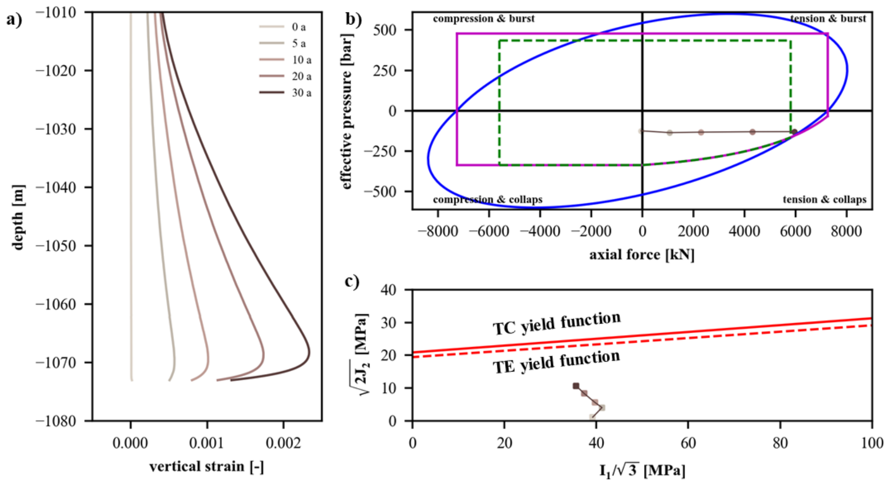

Figure 2. a) Profile of vertical strain along the casing over time, b) load of casing in a depth of 1,068 m using API standard, c) stress state of cement in a depth of 1,068 m.

3.2 Thermally induced damage in the borehole during solution mining

This study also considers the TH2M-coupled processes in the cavern borehole during the solution mining to obtain a realistic condition of the cavern wellbore in the test area before the integrity test. The drilling with cementing takes about 30 days. Subsequently, the cavern will be solution-mined for about two years. The drilling fluid is assumed to be a brine with a temperature of 15 °C. Figure 3 shows the simulation results, for example the well in the casing shoe area after ten days of drilling. Figure 3a shows the damaged area of about 70 mm around the borehole induced by thermal stress. The maximum temperature difference at the depth is about 27 °C at the borehole contour. When the fluid pressure exceeds the minimum principal stress in rock salt as shown in Figure 3c, pressure-driven brine infiltration can occur even in the thermomechanically undamaged region. After ten days, the infiltration area in rock mass around the borehole has an extent of about 0.4 m in the radial direction. The creeping behaviour of the rock salt can also heal the damaged area during the solution phase, if the stresses and temperature are relatively constant.

3.3 Gas infiltration during the mechanical integrity test

The mechanical integrity test consists of two main phases. In the first phase, the pressure in the test area is increased to almost the maximum operating pressure of 21 MPa by brine injection. This process takes three days, and the average pressure increase is about 27 bar/d. Hydrogen is then injected into the wellbore as a test medium for a short time until the hydrogen-brine interface sinks into the test area about 25 m below the last cemented casing shoe. When the pressure and temperature in the borehole have stabilized after about one day, the measurement is started. Figures 4a and 4b show the change in stress and gas saturation for a depth of 1,080 m during the test, respectively. It can be seen that the tangential stress at the borehole contour decreases as the fluid pressure increases, with the fluid pressure exceeding the vertical and tangential stresses since the second day. The test gas hydrogen infiltrates immediately into the borehole contour and displaces the fluid in the infiltration zone after being injected into the test area. The gas saturation increases during time and reaches a maximum value of about 0.6 at the end of the test. Figures 4c and 4d show the infiltrated gas volume and infiltration rate, respectively. It can be seen that a total volume of about 1.8 liters of hydrogen at the test pressure is injected into the borehole contour. The infiltration rate is highest on the first day. Therefore, it is reasonable to wait one day before starting the measurement.

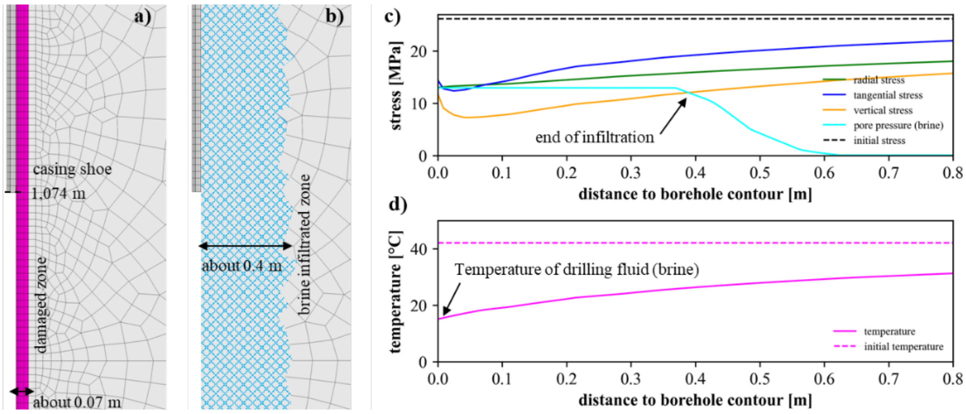

Figure 3. Borehole in the casing shoe area after drilling time t = 10 d, a) damaged zone, b) brine infiltrated zone, c) profile of stresses in a depth of 1,075 m, d) profile of temperature in a depth of 1,075 m.

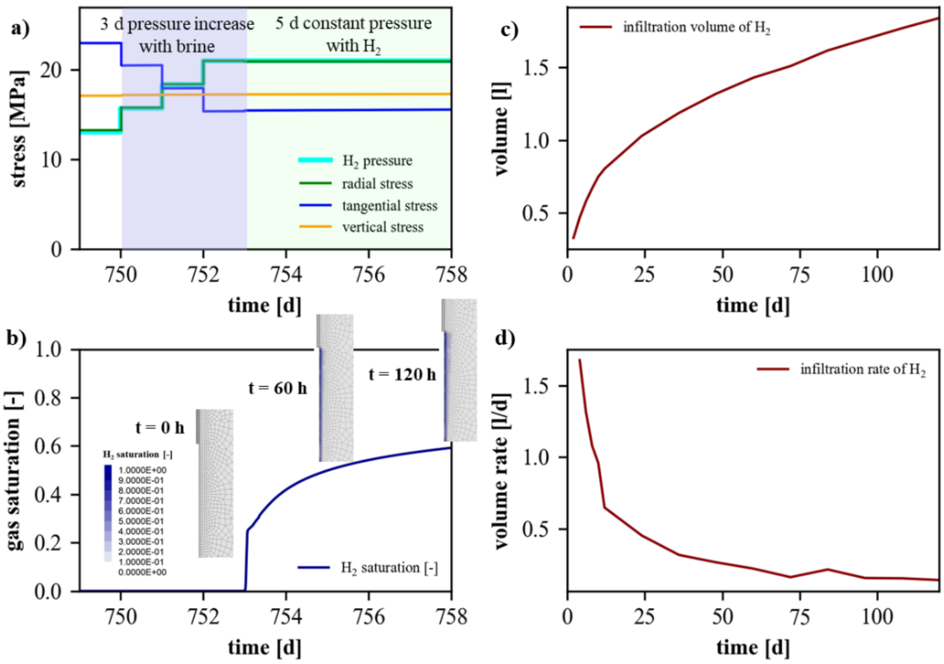

Figure 4. Hydraulic simulation during the mechanical integrity test, a) histories of stresses at borehole contour in a depth of 1,080 m, b) gas saturation at borehole contour in a depth of 1,080 m, c) H_2 infiltration volume, d) H_2 infiltration rate.

4 CONCLUSIONS

The conversion of a natural gas storage cavern in rock salt mass, which has already been in operation for a long time, to hydrogen storage in the future requires the demonstration of cavern stability and well integrity. However, the possibilities for direct physical monitoring of the cavern borehole are limited for technical and economic reasons. Although a mechanical integrity test before the start of gas storage can be used to assess the well integrity, it is impossible to verify the development of well integrity during operation. For this reason, the authors propose a computationally based analysis to complement the measurement-based analysis, thus providing an additional means of monitoring and evaluating well completion integrity.

This article presents numerical simulation results on wellbore integrity obtained with the FTK-simulator. It has been shown in general, that the FTK-simulator can be used to analyze the stress evolution in the wellbore of salt caverns in space and time, considering a time-dependent cavern convergence. The numerical simulation results indicating an essential impact of cavern convergence on cavern well loading situation with time combined with eventually exceeding integrity criteria. Furthermore, numerical simulation can help to understand the complex TH2M-coupled processes in the well by simulating the mechanical integrity test and to provide prerequisites for future studies on the transport of hydrogen during operation of salt caverns.

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