Journal of Natural Gas Science and Engineering 43 (2017) 167–178

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Potential capacity of gas storage caverns in rock salt bedded deposits in Poland

Jarosław Ślizowski [a, *], Leszek Lankof [b], Kazimierz Urbańczyk [c], Karolina Serbin [a]

[a] AGH University of Science and Technology, Faculty of Drilling, Oil and Gas, al. Mickiewicza 30, 30-059 Kraków, Poland
[b] Mineral and Energy Economy Research Institute of the Polish Academy, Department of Renewable Energy and Environmental Research, Wybickiego 7, 31-261 Krakow, Poland
[c] Research and Development Center for Mining of Chemical Raw Materials CHEMKOP Ltd., Wybickiego 7, 31-261 Krakow, Poland

A R T I C L E I N F O

Article history:
Received 30 August 2016
Received in revised form
6 February 2017
Accepted 14 March 2017
Available online 9 April 2017

Keywords:
Salt cavern
Natural gas
Long-term capacity
Bedded rock salt

A B S T R A C T

The subject of this article is an estimation of the initial capacity of a gas storage cavern, depending on the thickness and the depth of a bedded salt deposit, and the cavern's capacity decrease in time due to its convergence. It was assumed that the relative rate of convergence depends on the depth, the range of the storage pressure and the cavern diameter to height ratio. The discussion will consider the shape of the cavern and the pressure range of natural gas storage. Also, potential locations in Poland for natural gas storage in bedded rock salt deposits in terms of geological and mining criteria are presented in this article. Based on Zechstein isopach maps, as well as maps of its top depth, potential storage capacity maps per unit area were developed. Presented examples will cover two potential regions i.e., bedded salt deposit in the Zatoka Gdańska region and Fore-Sudetic Monocline. These maps will be the basis for the analysis of the suitability of the bedded rock salt Zechstein deposit for natural gas storage.

1. Introduction

Storage in rock salt caverns is one of the three underground storage methods for natural gas. The primary advantage of storage in salt caverns in comparison to depleted gas reservoirs and aquifers is a considerably higher efficiency of gas injection and withdrawal, as well as a small amount of buffer gas. Regardless, the construction of a storage facility requires the establishment of a mining area and the purchase of land, which generates significant investment costs.

In Poland, rock salt occurs in the Zechstein evaporite formation formed 250–270 Ma years ago and Miocene evaporite formation formed approximately 13 Ma ago (Peryt, 2006), but due to geological-mining conditions, gas storage caverns could be constructed only in the Zechstein formation. Bedded rock salt formations in Poland constitute a marginal part of the Zechstein Basin, which occurs under a large part of Europe. Therefore, the criteria on the technical parameters developed for underground gas storage facilities in Germany, France, the Netherlands or the United Kingdom (Lux and Düsterloh, 2015; Fernandez and Guarascio, 1998; Bruckner et al., 2012; Salzer et al., 2012; Hampel et al., 2012; Düsterloh and Lux, 2012) may be according to the authors successfully applied to the deposits occurring in Poland. From the standpoint of economic viability the depth of the rock salt layer top used for natural gas storage is 1800 m b.g.l., and the maximum diameter of caverns depend on their location depth and their layout, as it will be outlined in the article.

The Zechstein rock salt formation covers over half of the territory of Poland, which is shown in Fig. 1. Predominantly it occurs in very deep locations, even up to 5–6 km below ground level, which excludes the greater part of the deposit for gas storage purposes. In Fig. 1, the shaded areas represent prospective regions for gas storage where the top of the Zechstein rock salt formation occurs at a depth smaller than 1800 m b.g.l. These prospective areas are as follows:

– A bedded rock salt deposit in the Zatoka Gdanska region,
– A bedded rock salt deposit in the Fore-Sudetic Monocline.

The salt domes of Central Poland suitable for natural gas storage are also shown in Fig. 1.

In this article, the natural gas storage assessment will be

* Corresponding author.
E-mail addresses: slizow@agh.edu.pl (J. Ślizowski), lankof@min-pan.krakow.pl (L. Lankof), kazeku@poczta.onet.pl (K. Urbańczyk).

http://dx.doi.org/10.1016/j.jngse.2017.03.028
1875-5100/

Nomenclature

Δp	$p_{max} - p_{min}$ [MPa]
Δt_{in}	time of gas injection into the cavern [day]
Δt_{max}	time in which gas is stored at maximum pressure p_{max} [day]
Δt_{min}	time in which gas is stored at minimum pressure p_{min} [day]
Δt_{wi}	time of gas withdrawal from the cavern [day]
η	H/D – slenderness of the cavern [-]
ρ_o, ρ_s	density of overburden and rock salt [kg/m^3]
ρ	density of natural gas at pressure p [kg/m^3]
ρ_N	density of gas at standard conditions [kg/m^3], in the case of natural gas $\rho_N = 0.736$ kg/m^3
A_k, n_k, Q_k, B_k	constant coefficients for the convergence rate of the cavern
C	natural gas which may be stored in underground caverns in rock salt deposits per unit area [Nm^3/m^2]
D	maximum diameter of the storage cavern [m]
d	minimum diameter of the storage cavern [m]
f	part of gross volume V filled with a gas [m^3]
g	gravitational acceleration [m/s^2]
g_{frac}	determined in situ safe fracturing gradient depending on host rock properties [MPa/m]
g_{stab}, p_{stab}	host rock strength parameters based on geomechanical tests and numerical simulations [MPa/m]
g_T	geothermal gradient [K]
H	the height of storage cavern [m]
$h1$	depth of the top of the rock salt layer [m]
$h2$	depth of the cemented casing[m]
$h3$	depth of the cavern roof [m]
$h4$	depth of the cavern dome bottom [m]
$h5$	depth of the cavern center [m]
$h6$	depth of the top of the cavern bottom conical part [m]
$h7$	depth of the lower point of the cavern [m]
$h8$	depth of the bottom of the rock salt layer [m]
k	convergence [‰/year]
$\bar{k}$	average convergence [‰/year]
L	distance between the axis of adjacent caverns [m]
m	mass of the natural gas stored in the cavern [kg]
M	thickness of the rock salt layer [m]
M_{mol}	molar mass of the gas [kg/mol]
P	amount of stored gas in a single cavern [Nm^3]
P_0	initial capacity [Nm^3]
$P(i)$	storage capacity [Nm^3]
$p_\infty(h_5)$	initial stress of the rock mass at the depth of the cavern center [MPa]
p_{max}	maximum storage pressure [MPa]
p_{min}	minimum storage pressure [MPa]
p_N	pressure under standard conditions ($p_N = 1$ atm $= 0.101325$ MPa)
p_{pipe}	gas pressure in pipeline [MPa]
R	universal gas constant $R = 8.3144$ [J/mol*K]
R^*	R/M$_{mol}$ – individual gas constant [J/kg·K], in the case of natural gas R$^* = 505.206$ J/kg*K
S	surface area allocated to a single cavern [m^2]
T	temperature of stored gas [K]
t	time [years]
T_{g0}	reference temperature [K]
T_{max}	maximum temperature of the gas during injection [K]
T_{min}	maximum temperature of the gas during withdrawal [K]
T_N	temperature under standard conditions ($T_N = 273.15$ K) [K]
V	volume of storage cavern [m^3]
Z	compressibility factor [-]
Z_{max}	compressibility factor at pressure p_{max} [-]
Z_{min}	compressibility factor at pressure p_{min} [-]

presented in the form of storage capacity maps representing the volume of gas that could be stored per unit area in (Nm^3/m^2 or billions Nm^3/km^2). The analysis concerns only bedded Zechstein formations and is based on the designing method applied in Poland in such a case. The possibility of gas storage in salt domes is discussed in (Ślizowski and Urbańczyk, 2011). The storage capacity maps have been developed for bedded rock salt deposits with a thickness of at least 150 m occurring not deeper than 1800 m below ground level.

The parameters of storage caverns were determined on the basis of the experience gained in the designing of underground storage facilities in the salt dome Mogilno and bedded rock salt Kosakowo.

Discussion in this paper concerns conventional storage caverns and did not apply to tunnel shape caverns for which the minimum deposit thickness is 60 m (Favert, 2004; Xing et al., 2015). There are other methods of cavern dimensioning, e.g. applying different shape of cavern and their spacing (Wang et al., 2015; Yang et al., 2016). They can lead to quantitatively different results.

When actual geological conditions and mechanical behavior of rock salt in the site are well known, gas storage caverns or even a single cavern are designed taking into account of these specific conditions, to which the shape and the layout of caverns as well as the storage pressure are adapted.

Based on the highly advanced thermodynamic and geomechanical models (Sobolik and Ehgartner, 2012; Song et al., 2012; Costa et al., 2015) and monitoring data (Laouafa et al., 2012; Sobolik and Ehgartner, 2012; Sobolik and Lord, 2015; Zapf et al., 2015) one takes into account the actual geological structure of a deposit and different operation scenarios depending on the intended use of a salt cavern (seasonal or daily peak demand) (Serbin et al., 2015; Lux and Düsterloh, 2015).

2. Capacity of gas storage caverns and dimensions of safety pillars in bedded salt deposits

The storage capacity of a rock salt deposit, i.e., the volume of natural gas which may be stored in a cavern per unit area, depends on three factors:

- the ratio between the cavern volume and the volume of the safety pillars remaining between caverns,
- the range of the pressure and temperature variation of stored gas during the operation of a storage facility,
- the rate of the convergence induced by rock salt creeping.

Below the assessment of the storage capacity of a single cavern is presented, as well as the storage capacity per unit area over the storage facility.