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Energy and environmental analysis of disposing of concentrate by injecting it back into the deep geological formation

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ABSTRACT

Protection of the environment is one of our most important obligations. All types of water treatment processes can have some impact on the environment, but the degree or extent of this impact depends on the technology used. The assessment of the feasibility of implementing the water desalination process on an industrial scale is largely dependent on the method and possibility of disposing or utilizing the concentrate. Concentrate is generated as a by-product of the separation of the minerals from the source water used for desalination. The characteristics of the waste stream depend on the quality of the feed water, the quality of the produced water (depends on various recovery levels), the pre-treatment method (added chemicals) and cleaning procedures used. In sea water desalination, the concentrate is usually discharged back into the sea. More difficulty should be expected when such systems are operated inland. The concentration of minerals and contaminants in brines or concentrate is usually approximately double that in feed water or higher. Therefore, the manner in which the concentrate is disposed of will largely determine the cost of desalinating water in an inland setting. Due to environmental considerations, injecting the concentrate back into the deep geological formation could be the preferable solution. This paper presents an energy and environmental analysis in disposing concentrate from the membrane process in inland water systems.

Keywords: Concentrate; Desalination; Injection; Geothermal system

1. Introduction

Concentrate is generated as a by-product of the separation of the minerals from the source water used for desalination [1–3]. The characteristics of the waste stream depend on the quality of the feed water, the quality of the produced water (depends on various recovery levels), the pre-treatment method (added chemicals) and cleaning procedures used [1,3–5]. The concentrate total dissolved solid (TDS; or ion concentrations) can be calculated [4] in terms of the feed and permeate TDS and the fractional plant recovery (Y):

$$\mathrm{TDS}_{\mathrm{concentrate}} = \mathrm{TDS}_{\mathrm{feed}}\left(\frac{1}{1-Y}\right) - \frac{Y\cdot\mathrm{TDS}_{\mathrm{permeate}}}{100(1-Y)} \tag{1}$$

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where $Y = \dfrac{\text{Permeate flow rate}}{\text{Feed flow rate}}$.

In sea water desalination, the concentrate is usually discharged back into the sea. More difficulty should be expected when such systems are operated inland. The concentration of minerals and contaminants in brines or concentrate is usually approximately double that in feed water or higher [1,2,4,5]. This is why in areas where there is a deficit of water for human consumption, the use of separation techniques for obtaining drinking water requires an in-depth analysis of possible directions of environmentally safe concentrate disposal. Various directions can be considered, including reduction of concentrate volume, surface water discharge, sewer disposal, land application, evaporation ponds and the injection of this waste substance into deep geological formations [4–6], and in particular into deep reservoir levels that are not used to extract water. Such an approach requires a detailed analysis of geological and reservoir conditions in order to identify sufficiently "absorbent" rock reservoirs. At the same time, the geological structure in question must not be in hydraulic contact with shallow aquifers that are used as drinking water resources. These issues must also be taken into consideration at the stage of designing the absorption well, which requires tight isolation from the surrounding rocks. Geological and reservoir conditions directly impact the amount of energy required to inject the required volume of concentrate into the formation. The aforementioned issues are important elements of geological and reservoir studies, and require very careful analysis.

Taking into account the various mineralogical, petrographic and petrophysical properties of reservoir rocks, it is not possible to determine beforehand the demand for energy required in order to inject the required amount of concentrate into the formation in each case. Of key importance, however, is using such geological structures for these purposes that exhibit the best possible hydrogeological parameters such as permeability, porosity and fracturing [7–9].

Earlier work by authors [1,2,9,10] demonstrated that after using them for heating purposes, cooling and desalination, geothermal waters may be used to meet local needs related to supplying the population with drinking water. However, in order for the process of desalination of geothermal waters to be feasible, the manner in which concentrate will be disposed of must be indicated. This paper presents model energy calculations associated with the injection of concentrate into a deep absorption well drilled within a carbonate, fissure-porous aquifer structure. The work has been based on actual hydrogeological and reservoir data. They are based on the operation of an absorption well into which cooled geothermal waters previously used for heating purposes are injected. The forecast concerning energetic and environmental effects has been conducted for six variants of absorption well operation, assuming that the flow rate of the water injected amounts to 50 and 100 m^3/h, respectively: (1) only geothermal water in its natural state; (2) a 50:50 mixture of geothermal water and concentrate; and (3) only concentrate produced as a result of the desalination of geothermal water.

2. Materials and methods

2.1. Hydrogeological structure

The geological structure consists of Middle Eocene carbonate conglomerates and limestones and Middle Triassic limestones and dolomites. These are fissured and fissure-porous rocks with a considerable total thickness [8,9]. They exhibit a secondary porosity of up to 10%–20% and good permeability. The rocks in question represent a broad spectrum of structures and textures, and they exhibit traces of tectonic activity, with a dense network of cracks that are either filled with calcite or empty, and accessible to water. The calcium carbonate content ranges from 50% to 90%, and that of dolomite from 10% to 60%. At some places, carbonate content (the sum of $CaCO_3$ and $CaMg(CO_3)_2$) reaches 100% [9].

The absorption well reaches 2,450 m below ground level and is cased with pipes with a diameter of 9 5/8" to a depth of 2,040 m below ground level. From 2,040 to 2,450 meters, there is a depth filter in the form of a perforated pipe with a diameter of 7 5/8". This is the active absorption zone through which the injected medium penetrates the formation. In the geological and reservoir zone under consideration, geothermal waters are present with a temperature of 86°C and an average mineralization of 2.5 g/L. The maximum absorption capacity of the well analyzed is 500 m^3/h and the maximum water injection pressure is 94.8 bar. Static pressure of geothermal water at the wellhead is 18 bar.

2.2. Concentrate characterization and quality

The TDS of the concentrate after desalination of geothermal water was 8.7 g/L [11]. In the solution high concentrations of silicates (metasilicic acid 262.99 mg/L) and microelements were found, such as: strontium (18.64 mg/L), boron (22.86 mg/L), arsenic (0.0165 mg/L), fluoride (5.92 mg/L), chromium (0.081 mg/L) and nickel (0.079 mg/L). Carbonate hardness was about 237.8 mg$CaCO_3$/L and the total hardness 2,115 mg$CaCO_3$/L.

2.3. Mathematical modeling of concentrate injection into formation

To estimate the clogging dynamics of the injection well, geochemical modeling was first performed (using the PHREEQC software; [12]) and this has been further used to determine the quantitative and qualitative tendency for precipitation of secondary sediments from the geothermal water. This information was then used to evaluate the decrease in absorbance and to forecast changes in pressure necessary to inject the water/concentrate into the rock formation.

In order to evaluate the energy effects, the calculation algorithms presented in Table 1 were used in mathematical modeling.

Additionally, the required injection pressure was determined by the following formula:

$$\Delta p = \Delta p_p + \Delta p_w + \Delta p_s - H_z\,\rho_{\mathrm{sr}}\,g - \left(H_w - H_z\right)\left(\rho_{\mathrm{sr\,z}} - \rho_{\mathrm{sr\,n}}\right) g \quad (2)$$

Table 1
The calculation algorithms used in mathematical modeling of the effects related to clogging of the active zone

Parameter	Calculation algorithm
Flow resistance in the absorption well (based on [13])	$\Delta p_p = \lambda \frac{L}{d} \frac{\rho}{2} w^2$ λ – coefficient of friction [–], L – borehole length [m], d – inner borehole diameter [m], ρ – water density [kg/m^3], w – water flow speed in the borehole [m/s]
Resistance associated with the injection of water into the reservoir (based on [14])	$\Delta p_w = \frac{V \mu}{4 \Pi k_h h} \ln\left(\frac{2{,}25 k_h \tau}{\phi \mu c_t r_w{}^2}\right)$ τ – repressure settling time (Δp_w) [s], ϕ – effective aquifer porosity [–], c_t – compressibility factor [1/Pa]
Aquifer resistance in the zone adjacent to the filter (so-called skin effect) (based on [14])	$s = \left(\frac{k}{k_s} - 1\right) \ln\left(\frac{r_{wa}}{r_w}\right) + \left(\frac{h}{h_p} - 1\right)\left(\ln\left(\frac{h}{r_w}\sqrt{\frac{k_h}{k_v}}\right) - 2\right) + \left(\frac{\mu_{t1}\, \rho_{t0}}{\mu_{t0}\, \rho_{t1}} \ln\left(\frac{r_s}{r_w}\right) + \ln\left(\frac{r_d}{r_s}\right)\right)$ k – aquifer permeability [m^2], k_s – permeability of the near-well zone [m^2], r_{wa} – damaged zone range [m], h_p – thickness of the active layer [m], k_v – vertical aquifer permeability [m^2], μ_{t1} – dynamic viscosity of water at injection temperature [Pa s], μ_{t0} – dynamic viscosity of water at natural reservoir temperature [Pa s], ρ_{t1} – water density at injection temperature [kg/m^3], ρ_{t0} – water density at natural reservoir temperature [kg/m^3], r_s – cold front radius [m], r_d – radius of pressure changes caused by injection [m]
The effect of changes in the properties of water injected on repression pressure (based on [15])	$\rho_0 = 16{,}018 \cdot \left(62.368 + 0.438603\, S + 1.60074 \cdot 10^{-3}\, S^2\right)$ ρ_0 – water density under standard conditions [kg/m^3], S – salinity (as mass percentage) [%]
Effect of heat exchange between water and the rock medium (based on [16])	$q_{\mathrm{str}} = \frac{-4\Pi \lambda_g \left(t_s - t_\infty\right)}{\ln\left(\frac{4 a_g \tau}{r_w^2} - 2\gamma\right)}$ λ_g – coefficient of thermal conduction through the rock medium [W/(m K)], t_s – water temperature [°C], t_∞ – rock medium temperature [°C], a_g – temperature compensation factor for the rock medium [m^2/s], τ – heat settling time [s], γ – Euler's constant [–].

where Δp is total required excess pressure to be generated by the injection pumps [Pa], H_z is level of the static water table, calculated versus ground surface [m], H_w is depth of the borehole [m], ρ_{sr} is averaged density of the liquid injected in the borehole, above the static water table [kg/m^3], $\rho_{\mathrm{sr}\ z}$ is average density of the liquid injected into the source formation layer at the depth interval of H_z to H_w [kg/m^3], $\rho_{\mathrm{sr}\ \mathrm{n}}$ is average density of the liquid in the borehole, under natural conditions, at the depth interval from H_z to H_w [kg/m^3], g is earth gravity [m/s^2].

The absorbance index q_c, [m^3/(s·Pa)], expressing the ratio between the flow of liquid being injected into the source layer and the excess pressure to be generated by the injection pumps has been defined as follows:

$$q_c = \frac{V}{\Delta p} \tag{3}$$

where V is flow of injected water [m^3/s], Δp is pressure head generated by the injection pumps [Pa].

The calculations took into account the construction of the absorption well, the flow of water injected, and the mineralization level and temperature of the fluid injected into the formation in the following variants:

1. injection of natural geothermal water with a mineralization of 2.5 g/L at a temperature of 50°C at the following rates: (1a) 50 m^3/h; (1b) 100 m^3/h;
2. injection of a 50:50 mix of geothermal water and concentrate with a mineralization of 5.6 g/L at a temperature of 40°C at the following rates: (2a) 50 m^3/h; (2b) 100 m^3/h; and
3. injection of concentrate with a mineralization of 8.7 g/L at a temperature of 30°C at the following rates: (3a) 50 m^3/h; (3b) 100 m^3/h.

For the purposes of calculations the following parameters were assumed: thermal conductivity of the geological formation (λ_g) of 5 W/(m K), rock medium density of 2.8 Mg/m^3, its specific heat of 0.8 kJ/(kg K), temperature change in the vicinity of the well in accordance with the geothermal gradient from a reservoir temperature of 88°C to a surface temperature of 8°C, effective aquifer porosity of 15%, aquifer thickness of 700 m, active thickness of 410 m, aquifer level permeability of 310 mD (horizontal) and 5 mD (vertical), static water table level of 180 m above ground level, the extent of the zone affected by the skin effect of 1.25 m and its permeability of 90 mD (90 10^{-15} m^2). It was assumed that the products resulting from precipitation may cause clogging and are deposited on the inside of the filter.

3. Results

The permeability and extent of the zone affected by the skin effect were established during model calibration based on absorption well logging data. Fig. 1 shows measurement data reflecting the relationship between the required injection pressure and water temperature on the one hand and its flow rate for the absorption well examined on the other hand under real-life conditions of injecting geothermal water into the geological structure analyzed. The quality of the fit between the mathematical model and the measurement data, which are shown in Fig. 1, is presented in Fig. 2.

At a temperature of 50°C (temperature of the natural geothermal water injected into the rock formation), water is supersaturated especially with carbonate mineral phases (aragonite and calcite) and iron-based forms, mainly oxides and oxyhydroxydes (goethite and hematite). Taking into account the thermodynamic parameters of the water under the conditions described, it has been estimated that the amount of sedimentation in the immersed filter zone can reach 0.05 mg/L of solids, mainly in the form of aragonite.

At a temperature of 30°C concentrate is also supersaturated with carbonate mineral phases (aragonite, calcite), especially silicate phases, aluminosilicates and clay minerals: albite, illite, K-mica, kaolinite, quartz and also iron-based forms. The amount of sedimentation in this case can reach 0.065 mg/L of solids.

Where geothermal water mixed with concentrate is injected into the formation, the estimated amount of sedimentation is ca. 0.055 mg/L of solids.

Results of model calculations for the variants under consideration are shown in Figs. 2 and 3.

In the case where only geothermal water cooled to 50°C is injected into the formation (Variants 1a and 1b), the results of forecasts concerning the change in the pressure generated by injection pumps as a function of time are in line with the injection effects observed during the actual operation of the absorption well. During periods of peak demand for geothermal heat, the well analyzed is used to inject approximately 400 m^3/h of fluid at a pressure of approximately 38 bars. The hole was drilled in 1997 and it has operated continuously for 18 years – since the launch of the geothermal plant.

In Fig. 3, the pressure generated by the pumps installed in the absorption well is presented. The pressure at the wellhead is the sum of hydrostatic pressure and the pressure generated by the pumps. The chart in Fig. 3 shows a continuous increase in the pressure generated by the pumps over time. This is caused by the decrease in the permeability of the zone adjacent to the filter as a result of the precipitation of secondary minerals in the volume of the fluid injected. This effect is illustrated in Fig. 4.

The injection of concentrate and of concentrate mixed with geothermal water at a flow rate of 50 m^3/h requires a lower pressure than the injection of pure cooled geothermal water (Fig. 3). This effect may also be explained by the fact that for smaller flow rates, the increased hydrostatic

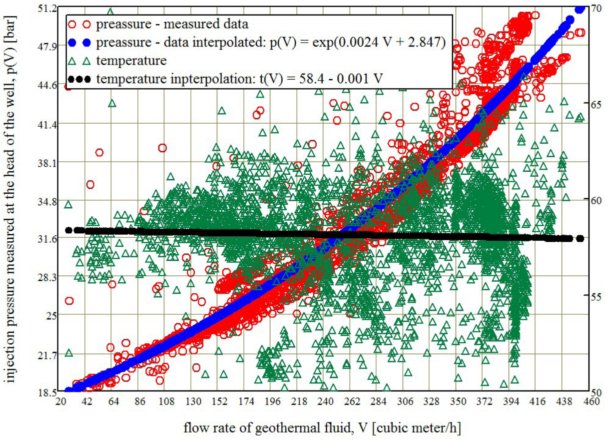

Fig. 1. Chart showing the changes in the required geothermal fluid injection pressure and temperature as a function of its flow (based on source data). In order to use the equations, fluid flow (V) in m^3/h must be provided; the results obtained will be in [bar] for pressure (p) and in [°C] in the case of temperature (t).

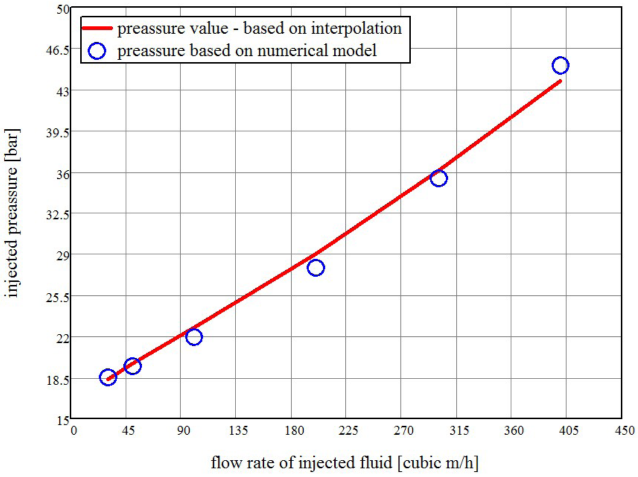

Fig. 2. Presentation of the quality of the fit between the numerical model and actual data.

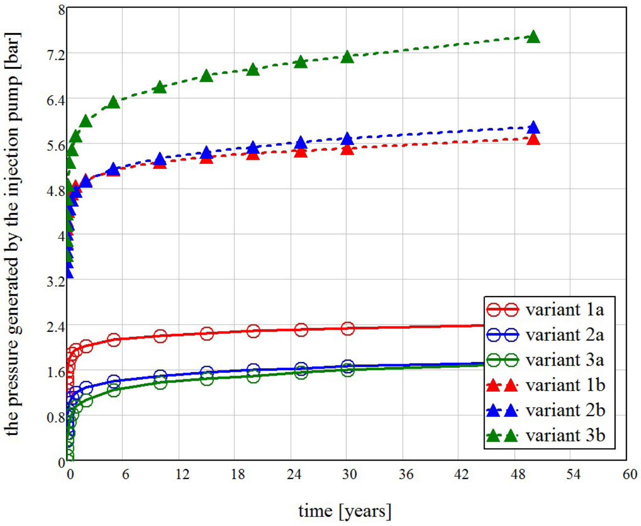

Fig. 3. Changes in pressure generated by injection pumps over time.

pressure of the fluid filling the well has a greater effect than the flow resistance resulting from an increase in viscosity. On the other hand, flow resistance is more significant for higher flow rates, i.e., 100 m^3/h. In all variants, a continuous increase in the required fluid injection pressure over time is observed (Fig. 3). This is due to the continuous decrease in the permeability of the zone affected by the skin effect (Fig. 4). The decrease in the permeability of the absorption well results from the precipitation of minerals in the volume of the geothermal fluid injected.

Table 2 presents the cumulative energy and environmental effects related to the consumption of electricity by injection pumps, calculated for a period of 50 years. The environmental effect has been estimated for the primary energy consumption structure typical of Polish conditions. It takes into account the fact that in Poland, slightly less than 94% (in 2014 according to data published in 2015 [17]) of electricity is generated from the combustion of: coal, lignite and natural gas in conventional power plants. On the basis of calculations, it has been demonstrated that as a result of the consumption of the amount of electricity required to drive the pumps injecting fluid into the formation, cumulative CO_2 emissions over a period of 50 years will range from 1.193 Gg (Variant 3a) to 11.04 Gg (Variant 3b). SO_2 emissions are estimated to range from 7.373 Mg to 68.241 Mg, and NO_2 emissions from 2.169 to 20.078 Mg depending on the amount of fluid pumped and its quality (Table 2). In this context, the use of alternative, renewable energy sources to meet the energy demands of driving high pressure pumps would significantly reduce this adverse environmental effect.

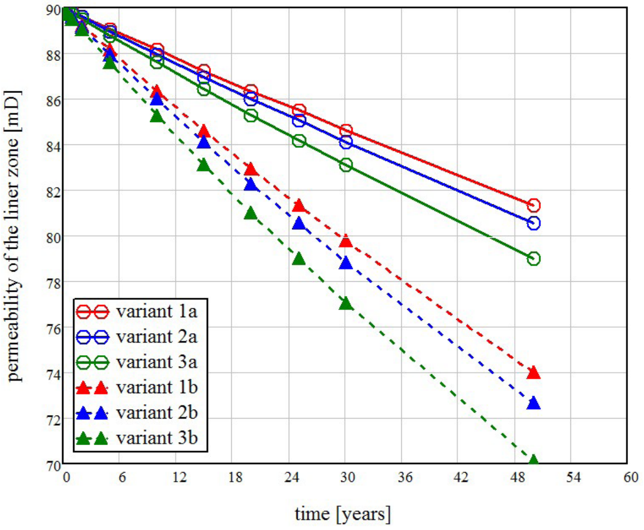

Fig. 4. Change in the permeability of the zone adjacent to the filter (affected by the skin effect) in time for the variants analyzed [mD = 10^{-15} m^2].

4. Conclusion

The possibility of injecting into the formation the concentrate obtained as a by-product of water desalination conducted in order to obtain drinking water or water for other household purposes is an interesting solution when water is desalinated at inland locations. However, this solution requires a detailed geological and reservoir reconnaissance in order to identify geological structures with appropriate absorption capacity. It is also the most reasonable solution where geothermal waters are desalinated. In the long-term perspective, however, one must take into account the possible decline in absorbance index and increased demand for the energy necessary to inject the concentrate into the formation. The main product of precipitation of secondary minerals from geothermal water during the operation of the system described in this paper is calcium carbonate in the form of aragonite and calcite. The geochemical modeling conducted revealed the tendency of these crystalline forms of $CaCO_3$ toward precipitation. Depending on the temperature and the physicochemical properties of the solution

Table 2
Cumulative energy and environmental effects related to the consumption of electricity by injection pumps, calculated for a period of 50 years

Amount	Variant 1a	Variant 2a	Variant 3a	Variant 1b	Variant 2b	Variant 3b
Cumulative consumption of electricity to drive injection pumps [MWh]	1,728	1,209	1,139	8,242	8,433	10,543
Cumulative B(a)P emissions [g]	32.9	23.0	21.7	156.9	160.5	200.7
Cumulative soot emissions [kg]	31	22	21	14.8	15.2	19.0
Cumulative total dust emissions [Mg]	0.66	0.461	0.435	3.145	3.218	4.023
Cumulative CO_2 emissions [Gg]	1.81	1.266	1.193	8.63	8.83	11.04
Cumulative CO emissions [Mg]	4.113	2.876	2.71	19.613	20.068	25.088
Cumulative emissions of nitrogen oxides converted to NO_2 [Mg]	3.291	2.302	2.169	15.696	16.061	20.078
Cumulative SO_2 emissions [Mg]	11.187	7.824	7.373	53.349	54.588	68.241
Cumulative aliphatic hydrocarbon emissions [kg]	205	144	135	979	1,002	1,252
Cumulative polycyclic aromatic hydrocarbon emissions [kg]	205	144	135	979	1,002	1,252

Note: Pollutant emissions were estimated on the basis of [18].

injected, favorable thermodynamic conditions may also exist for the precipitation of other secondary minerals from solutions. Forecasts concerning these phenomena, including the clogging of the absorption well as a result of scaling, are a very important part of the overall engineering considerations related to injecting concentrate into the formation.

It has also been demonstrated that as the amount of concentrate injected increases, where positive (artesian) pressure is present in the reservoir, flow resistance in the absorption well increases, which may result in the steady increase of the required injection pressure over time during long-term operation. As a result, the demand for energy also increases. In order to limit the environmental effects related to the emission of pollutants resulting from the use of fossil fuels for electricity generation, measures should be taken to supply the energy required to drive the pumps from renewable sources.

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