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Geothermal water resources management – economic aspects of their treatment

Introduction

During the last decade most of the countries in the world, including the European Union members, tend to implement the sustainable development principles, according to which the economic development is harmonized with the protection of natural environment and mineral resources. The positive aspects of geothermal resources are well-known (Górecki et al. 2006, 2010; Rybach 2003; Barbacki 2010, 2012; Bujakowski 2010; Bujakowski et al. 2008, 2011a; Chowaniec 2009; Lund et al. 2011):

— practically unlimited and renewable reserves;
— common occurrence of energy source in the vicinity of the users;
— independence on changing weather and climatic conditions;
— environmentally friendly utilization;
— possible utilization not only for heat generation but also for farming, gardening, therapeutic, recreational and technological purposes.

Much attention is to be given to the dissemination of research results, examples are themed international projects in the field (e.g.: Kasztelewicz, Pająk 2010; Bujakowski et al. 2010b).

Key factors that determine the conditions in which geothermal waters are used, the amount of energy obtained and the manner in which cooled water is utilised include water salinity and the presence of specific ingredients. Nowadays, geothermal water extraction in

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Poland is carried out using (Górecki ed. 2006; Bujakowski et al. 2012; Tomaszewska 2011a, b; Tomaszewska, Pająk 2012; Dulewski, Tomaszewska 2012):
1) a closed system of production and injection wells;
2) an open system of production wells (cooled water is mainly transferred to a surface reservoir) and a mixing system of mentioned above processes.

The best procedure should take the following aspects into account: ensuring that geothermal energy resources are renewable, enabling safe long-term reservoir operation, and ensuring that activities are both cost-effective and environmentally sound. Therefore closed systems are the best and safest from the point of view of the geothermal water reservoir. However, owing to the still high cost of drilling and problems related to the corrosion and clogging of injection wells (Tomaszewska 2008; Tomaszewska, Pająk 2012), this manner of water utilisation in Poland is still limited to just a few cases. From the other hand, even where its salinity is low, this water may exhibit elevated contents of undesirable, sometimes toxic elements, which significantly restricts the possibility of discharging it into surface waters. For this reason, in this article, for the efficient geothermal water resources management desalination of cooling water is being considered. Apart from water balance aspects, economic analysis of the implementation of the desalination water process tested in two geothermal systems is presented.

1. Freshwater production using geothermal water desalination process

The first in Poland, geothermal desalination tests of water from three wells was performed on a semi-production scale (respectively ca. 1.0 m^3/h of desalinated water production from the GT-1 well and 0.5 m^3/h from the GT-2 and GT-3). The process was carried out with typical industrial plant components and included a water pre-treatment facility (mechanical filter, iron removal stage and ultrafiltration module), two-stage reverse osmosis (RO) setup with pH correction before first and second stage and final treatment to achieve drinking water parameters (mineralisation, disinfection). Detailed testing equipment and desalination procedure were presented by Tomaszewska (2011), Tomaszewska and Bodzek (2012a, 2012b). The research demonstrated that the use of low transmembrane pressure (1.1 MPa) high-quality water may be obtained even after the first RO stage, with geothermal waters containing up to 7 g/L of TDS (GT-1 and GT-2). A relatively high removal rate was received: 96–97% with respect to conductivity, and 94% with respect to SiO$_2$, 92% for fluoride and not less than 84% for arsenic (Tomaszewska, Bodzek 2012a). A high rejection ratio of radionuclides was also obtained, ranging from 70.7% to 99.6% (Tomaszewska Bodzek 2012b). The results of pilot studies also demonstrated that system extension, i.e. the addition of a second RO stage together with pH adjustment is required where high boron content is present in the water (Tomaszewska, Bodzek 2012a). In this manner, a high-quality end product that meets the requirements applicable to drinking water and water used for irrigating agricultural crops was obtained. The technology for desalinating spent thermal waters may

allows improved water management on a local scale and makes it possible to minimise the environmental threat.

Apart from the results of research presented above, desalination of water from well GT-3, containing 24.4 g/L of TDS, was not successful. The installation capacity dropped from $5 \cdot 10^{-6}$ m^3/m^{2}s to $0.35 \cdot 10^{-6}$ m^3/m^{2}s within one hour, because so much low of the transmembrane pressure has been used (Tomaszewska, Bodzek 2012a).

The results of pilot studies served as the basis for the assessment of the feasibility of implementing the solution analysed on a larger scale.

2. Energy and economic analysis

The industrial use of water desalination processes in geothermal systems will be primarily dependent on their economic performance. The following factors directly affect water desalination costs: the quality of raw water, facility size, facility location, the manner in which the concentrate (waste stream) is disposed of, the quality and skill of the workforce, the cost and type of energy used, and the technology used, etc. One of the main aspect is also the possibility of utilising (selling) treated water, the level of expenditure that can be avoided by not injecting the water back into the formation (also including the expenses related to drilling the appropriate number of injection wells and the cost of the energy used by high-pressure pumps that inject the water into the formation) or the environmental costs resulting from the discharge of cooled water (wastewater) into surface waters.

The entire stream of geothermal water extracted may be desalinated in accordance with the diagram presented in Fig. 1. In this solution, treated water (permeate) and retentate (concentrate) streams are obtained (Bodzek, Konieczny 2011). This solution would not be advantageous from the point of view of the life span of the geothermal system, hence in this article, the implementation of analysed desalination process in a mixed system is presented (Fig. 2).

In calculations concerning the energy and economic effects related to the implementation of the proposed system, the following factors were accounted for:
1. Related to desalination facility (Table 1):
    — capital costs,
    — electricity and chemicals consumption,
    — operation, repair and maintenance costs.
    — revenue from the sale of drinking water (EUR 0.48/m^3)
2. Related to injection well (Table 2):
    — pressure of water injected into the water bearing layer,
    — electricity consumption and costs.
3. Related to injecting geothermal water mixed with the retentate into the formation (Table 3):
    — the impact of the reduction in the stream of water injected back into the formation (the pressure and power of pumps),
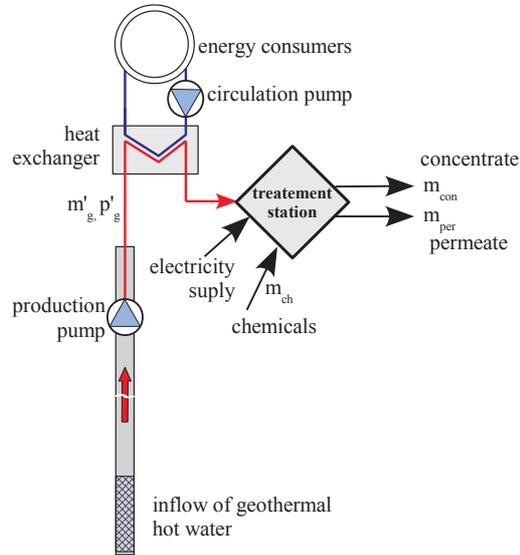
Fig. 1. Desalination of the entire stream of extracted geothermal water

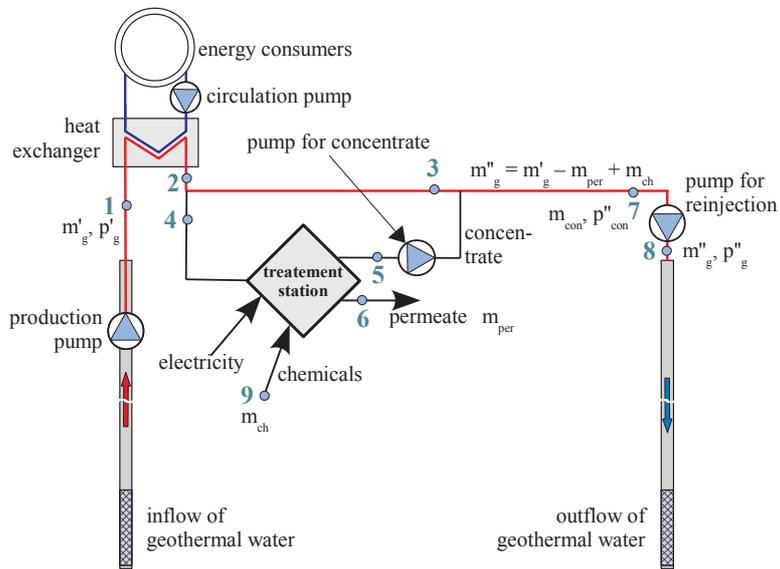Rys. 1. Odsalanie całego strumienia eksploatowanej wody geotermalnej

Fig. 2. Desalination of the partial stream of extracted geothermal water

Rys. 2. Odsalanie części strumienia eksploatowanej wody geotermalnej

TABLE 1

Main technical parameters and cost analysis for desalination facility

TABELA 1

Główne parametry techniczne i analiza kosztów dla instalacji odsalania

Water parameters in the desalination facility	GT-1	GT-2
Stream of raw water – subject to desalination [m³/h]	120	21
Permeate yield [m³/h]	58	10.8
Permeate pH (following pH adjustment – end product)	7	7
Concentrate yield [m³/h]	58	10.8
Concentrate pH	10	10

Consumption of chemicals net costs
    HCl (35% aqueous solution) [kg/yr]
    NaOH (98% solid) [kg/yr]
	
	445
	1 298
		
		78
		227

Purchase of chemicals net costs (HCl and NaOH) [EUR thousand/yr]	2.3	0.4
Energy for the desalination process net costs [EUR thousand/yr]	1 014	23
Desalination facility operation, repair and maintenance net costs [EUR thousand/yr]	34	6
Depreciation charges for the desalination facility (depreciation over 15 years) Net costs [EUR thousand/yr]	114	20
Net revenue from water sales [EUR thousand/yr]	158	28
Simple payback time for the investment expenditure for treatment facility [years]	13	–

TABLE 2

Main technical parameters and cost analysis for the wells

TABELA 2

Główne parametry techniczne i analiza kosztów dla otworów

Geothermal water parameters at the wellhead	GT-1	GT-2
Yield [m³/h]	400	70
Temperature [°C]	70	69
Pressure [MPa]	2.4	0.6
TDS [g/L]	2.6	7.0
S [% by mass]	0.26	0.7
pH	5.5	7.5
Pressure of water injected into the water bearing layer [MPa]	4.4	1.0
Electricity consumption (injecting used geothermal water into the formation) [MWh/yr]	2 096	87
Electricity net cost [EUR thousand/yr]	252	10

TABLE 3

Modelling results based on indicative operating data obtained from geothermal systems and pilot desalination studies

TABELA 3

Prognozowane na podstawie obliczeń efekty eksploatacji wybranych systemów geotermalnych przy założeniu odsalania wody

Parameter	GT-1	GT-2
Pressure of water injected into the water bearing layer after mixing geothermal water with the concentrate [MPa]	3.7	0.84
Total electricity consumption for the desalination process and for injecting geothermal water mixed with the concentrate into the formation [MWh/yr]	2 043	243
Total electricity net cost for injecting geothermal water mixed with the concentrate into the formation [EUR thousand/yr]	139	6
Total net operating cost for the desalination process and for injecting geothermal water mixed with the concentrate into the formation, taking revenue from sales of drinking water into account [EUR thousand/yr]	235	27

— the impact of the retentate stream included in the water injected into the formation (pressure, electricity consumption, operating costs).

The economic analysis it was assumed that 30% of the total extracted geothermal water stream would be desalinated, i.e. 120 m^3/h for water for the GT-1 intake and 21 m^3/h for the GT-2 one.

One should be notice, that chemical composition of the liquid injected is of key importance for the success of the formation injection process and therefore for the proper operation of the entire geothermal facility (Tomaszewska 2008; Tomaszewska, Pająk 2012). During water-rock reaction, the composition of the solution obtained by mixing the concentrate with natural formation water may result in the precipitation of certain mineral phases, which may lead to the clogging of the injection well and a deterioration in the performance of the process of injecting water into the formation (Dulewski Tomaszewska 2012). Therefore the mixed stream (concentrate with geothermal water) should be determined.

In accordance with the process presented in Fig. 2, the operation of the system analysed in this paper is characterised by points (1, 2, 3, …, 8), to which the operating parameters defined by the following elements have been assigned:

— V_s – the volumetric flow rate of the solution [m^3/s],

— p – pressure [Pa],

— t – temperature [°C],

— TDS – total dissolved solids [kg/m^3],

— S – salinity (the percentage of substances dissolved in the solution by mass) [%],

— ρ – solution density [kg/m^3].

Mass flows at individual points may be described by the following set of equations:

$$\begin{cases} m_S(2) = m_S(1) \\ *m_S(3) = f(m_S(2), \text{TDS}(2)) \\ *m_S(4) = f(m_S(2), \text{TDS}(2)) \\ *m_S(6) = f(m_S(2), \text{TDS}(2)) \\ m_S(5) = m_S(4) - m_S(6) + m_S(9) \\ m_S(7) = m_S(3) + m_S(5) \\ m_S(8) = m_S(7) \end{cases} \tag{1}$$

Where * is the initial value assigned on the basis of experimental data and $m_S(n)$ – mass flow at the nth point of the system (according to the diagram in Fig. 2), $f(x, y)$ – is the functional relationship of the variables x, y:

parameter\point (Fig. 2)	1	2	3	4	5	6	7	8
V_r	X							
p	X	X	X	X	X	X		X
t	X	X	X	X	X	X		
TDS	X							
S	X	X	X	X	X	X		
r								

On the basis of water salinity, temperature and pressure, volumetric flow rates at individual points were determined:

$$V_S(n) = \frac{m_S(n)}{\rho(n)} \tag{2}$$

It was assumed that solution density depends primarily on water salinity S, pressure and temperature (McCain 1991):

$$\rho_0 = 16.018 \cdot (62.368 + 0.438603\, S + 1.60074 \cdot 10^{-3}\, S^2) \tag{3}$$

where:

ρ_0 – density mineralized fluid [kg/m^3].

Conversion of mineralized water density under standard conditions at reservoir conditions can be made using the dependence (McCain 1991):

$$\rho = \frac{\rho_0}{B_w} \tag{4}$$

$$B_w = (1 + \Delta V_{wp}) \cdot (1 + \Delta V_{wT})$$

$$p' = \frac{p}{6\,894.757} \qquad \text{from [Pa] to [psi]}$$

$$T' = 32 + \frac{9}{5}(T - 273.15) \qquad \text{from [K] to [°F]}$$

$$\Delta V_{wp} = -1.95301 \cdot 10^{-9}\, p'T' - 1.72834 \cdot 10^{-13}(p')^2\, T' -$$
$$- 3.58922 \cdot 10^{-7}\, p' - 2.25341 \cdot 10^{-10}(p')^2$$

$$\Delta V_{wT} = -1.0001 \cdot 10^{-2} + 1.33391 \cdot 10^{-4}\, T' + 5.50654 \cdot 10^{-7}(T')^2$$

where:

ρ –   geothermal water density in reservoir conditions [kg/m³],
B_w –   mineralized water volume ratio [–],
p', p –   pressure p' [psi], p [Pa],
T', T –   temperature T' [°F], T [K].

The equation (4) is suitable for the full range of salinity and temperature range up to ~127°C and pressures up to ~34.5 MPa.

Mineralization of saline water flow is determined based on the equation:

$$TDS(n) = S(n)\rho(n) \tag{5}$$

It was assumed that the pump injecting the concentrate into the geothermal water stream (Fig. 2) has a power rating resulting from the need to overcome flow resistance between points 5 and 7 (Fig. 2). This power rating is described by the following equation:

$$P_{conc} = \frac{V_s(5)[p(7) - p(5)]}{\eta} \tag{6}$$

where:

η –   pump efficiency (a value of 0.8 was assumed).

As a result, the pressure of geothermal water after the concentrate has been added (point 7 in Fig. 2) is equal to pressure at point 3. The temperature of the solutions mixed was determined on the assumption that the sum total of dissolved solids does not result in a change of the specific heat of water.

The investment expenditure related to the purchase of the desalination facility (INV_{wt}) was estimated in an indicative manner, taking into account the amount spent on the pilot geothermal water desalination facility. An amount of EUR 14,300/($m^3_{raw\ water}$/h) was assumed. The requirement for pumping power for the reverse osmosis system is a function of the stream of treated water, its mineralisation, and permeate and concentrate recovery ratios.

For the GT-1 system, the power requirement was 1 kW/($m^3_{raw\ water}$/h), and for GT-2 it was 1.25 kW/($m^3_{raw\ water}$/h).

It was assumed that the desalination facility operates at rated power for 300 days each year.

The total costs for the system presented in Fig. 2 (net C_t) are described by the following equation:

$$C_t = C_{el} + C_{ch} + C_{mrs} + D_{ft} - R_{tw} \qquad (7)$$

where:

C_{el} – the cost of purchase of electricity for injecting the water used into the formation, the operation of the desalination system and the operation of the pump injecting the concentrate into the geothermal water pipeline (Fig. 2),

C_{ch} – chemical purchase costs,

C_{mrs} – operating and maintenance costs of the UF-RO system (2% of total investments per year),

R_{tw} – revenue from drinking water sales,

D_{ft} – fixed asset depreciation (investment expenditure spread evenly over 15 years).

Simple payback time for the investment expenditure related to the UF-RO facility was determined according to the following equation:

$$SPBT = \frac{INV_{wt}}{(C_o - C_t) - D_{ft}} \qquad (8)$$

where:

C_o – current cost of injecting geothermal water into the formation without the desalination process (only taking the cost of energy carriers purchased into account).

Economic analysis results for the two cases examined (GT-1 and GT-2 intakes) are shown in Table 3.

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Results and conclusion

A favourable economic effect was obtained for the GT-1 system. The assumption is that a 120 m^3/h stream of water is desalinated at a permeate recovery rate of 50%. Simple payback time for the forecast investment expenditure is 14 years in this case. An important factor affecting the energy efficiency and economic performance here is the decrease in the pressure at which water is injected into the formation by 0.7 MPa, which reduces the power required by 24 kW. This decreases annual electricity consumption by 172.8 MWh/year (EUR 20,200/year). The advantageous effect of the reduction in pumping power does not fully balance the power requirements of the desalination facility, but increased electricity consumption may be offset by revenue from the sale of treated drinking or household water.

A less favourable energy and economic effect was obtained for the GT-2 system. In calculations, a reduction in the stream injected to the formation by 21 m^3/h and the injection of cooled water into the formation at the rate of 49 m^3/h was assumed. In practice, the disposal of cooled geothermal water is more complex in this case. As a consequence of technical problems, related *inter alia* to corrosion, two absorption wells were put out of operation and the geothermal water used is discharged into surface waters, generating additional environmental costs. Therefore the geothermal water desalination facility is an interesting alternative for utilising geothermal water compared to the cost of reconstruction of two injection wells or the cost of drilling a new well.

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GOSPODARKA ZASOBAMI WÓD TERMALNYCH – EKONOMICZNE ASPEKTY ICH UZDATNIANIA

S ł o w a   k l u c z o w e

Odsalanie, woda geotermalna, analiza ekonomiczna

S t r e s z c z e n i e

Wody geotermalne to źródło czystej energii. Warto więc wykorzystywać je w sposób racjonalny zwłaszcza w sensie energetycznym i gospodarczym.

Jednym z kluczowych czynników, determinujących warunki eksploatacji wód geotermalnych, wielkość wykorzystania energii oraz sposób zagospodarowania wód schłodzonych jest zasolenie wód. Podwyższone zasolenie oraz występowanie mikroelementów toksycznych w wodach może często determinować trudności związane utylizacją wykorzystanych wód. Tylko w kilku polskich zakładach geotermalnych wody eksploatowane są w układzie zamkniętym (po wykorzystaniu wtłaczane z powrotem do górotworu). Częściej stosowany jest system otwarty (wody odprowadzane są do cieków powierzchniowych lub kanalizacji) lub mieszany (tylko część wód wraca do złoża za pomocą otworów chłonnych, druga część jest zrzucana do rzek). Odsalanie wód

geotermalnych może stanowić, w określonych przypadkach, alternatywę umożliwiającą zaspokojenie lokalnego zapotrzebowania na wodę słodką (np. zdatną do picia).

Ocena możliwości wdrożenia analizowanego procesu na skalę przemysłową w dużej mierze zależy od kierunków i możliwości utylizacji/zagospodarowania koncentratu. Biorąc pod uwagę względy środowiskowe, najkorzystniejszym rozwiązaniem jest wtłaczanie koncentratu do górotworu. Przeprowadzona analiza energetyczna i ekonomiczna wykazała, że opłacalność wdrożenia na skalę przemysłową procesu odsalania w systemie geotermalnym w dużej mierze zależy od czynników związanych z jego pracą, a w szczególności: wielkości wydobycia wód geotermalnych, zasolenia wód, parametrów chłonnych otworów przeznaczonych do wtłaczania wód do górotworu, skali problemów związanych z utylizacją schłodzonych wód, lokalnego zapotrzebowania na wody pitne i gospodarcze i in. Kluczowa dla opłacalności tego procesu jest między innymi redukcja wymaganego ciśnienia przy wtłaczaniu wód do górotworu i redukcja wielkości strumienia zatłaczanych wód. Bardzo ważnym elementem jest również zapewnienie odpowiednich warunków zbytu odsolonych wód (cena/ilość) celem pokrycia zapotrzebowania na energię elektryczną wykorzystaną w procesie odsalania.

GEOTHERMAL WATER RESOURCES MANAGEMENT – ECONOMIC ASPECTS OF THEIR TREATMENT

Key words

Desalination, geothermal water, costs analysis

Abstract

Geothermal waters are a source of clean energy. They should be used in a rational manner especially in energy and economic terms.

Key factors that determine the conditions in which geothermal waters are used, the amount of energy obtained and the manner in which cooled water is utilised include water salinity. Elevated salinity levels and the presence of toxic microelements may often lead to difficulties related to the utilisation of spent waters. Only a few Polish geothermal facilities operate in a closed system, where the water is injected back into the formation after having been used. Open (with water dumped into surface waterways or sewerage systems) or mixed (only part of the water is re-injected into the formation via absorption wells while the rest is dumped into rivers) arrangements are more frequently used. In certain circumstances, the use of desalinated geothermal water may constitute an alternative enabling local needs for fresh water to be met (e.g. drinking water).

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 of, or utilising, the concentrate. Due to environmental considerations, injecting the concentrate back into the formation is the preferable solution. The energy efficiency and economic analysis conducted demonstrated that the cost effectiveness of implementing the desalination process in a geothermal system on an industrial scale largely depends on the factors related to its operation, including without limitation the amount of geothermal water extracted, water salinity, the absorption parameters of the wells used to inject water back into the formation, the scale of problems related to the disposal of cooled water, local demand for drinking and household water, etc. The decrease in the pressure required to inject water into the formation as well as the reduction in the stream of the water injected are among the key cost-effectiveness factors. Ensuring favourable desalinated water sale terms (price/quantity) is also a very important consideration owing to the electrical power required to conduct the desalination process.