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Original Research

Using Treated Geothermal Water to Replenish Network Water Losses in a District Heating System

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Abstract

This paper examines the use of geothermal water to replenish network water losses in the largest Polish geothermal heating system. The geothermal installation capacity (under artesian conditions) is 670 m^3/h. The total power of the geothermal water source is 15.4 MW, and it is assisted by peak load boilers. The total capacity of the heating plant is 80.5 MW, and energy output amounts to 324 TJ/year. The system serves ca. 1,500 customers and includes ca. 95 km of district heating distribution network (Fig. 2). Distribution network water losses amount to ca. 6,600 m^3/year. The water used to replenish the losses is currently treated using ion exchange water softeners and vacuum degasifiers. It is suggested that the missing water be replaced with treated geothermal water; following treatment, this water must meet the requirements set forth in the water quality standards for heating systems (PN-85/C-04601 – Table 1).

The treatment uses membrane processes within the framework of a double hybrid arrangement, including ultrafiltration and reverse osmosis. Artesian pressure is used to a certain extent during treatment, which makes it possible to reduce the power required for the distribution pump, decreasing electrical power consumption. Thus, the requirements set forth in the standards have been met and the treated geothermal water can be used to replenish network water losses in the district heating system following pH adjustment and degassing.

Keywords: water treatment, ultrafiltration, reverse osmosis, geothermics, network water losses

Introduction

The use of geothermal energy in large centralized heating installations involves the simultaneous extraction of reservoir fluids. In low-temperature geothermal systems, mineralized reservoir water is the geothermal energy carrier. The degree of water mineralization depends on many characteristics of the geothermal reservoir. Spent (cooled) geothermal water may be discharged, e.g. into surface waters, or reinjected into the reservoir. In both cases, it is treated as a waste product of the energy extraction process. Water reinjection prevents its excessive extraction, which could result in a decrease of the formation pressure. However, the injection process poses numerous technical challenges and requires additional consumption of energy to drive the pumps [1]. Cooled geothermal water can be used for many purposes [2-11]. This paper examines the use of geothermal water to replenish distribution water losses in the largest Polish geothermal heating system located with-

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in the Podhale Basin Reservoir (Fig. 1). The area has considerable geothermal water resources while at the same time exhibits a fresh water deficit. Therefore, attempts have been made to determine the possibility of using desalinated geothermal water in order to replenish water losses in the heat distribution network. Only part of the total geothermal water volume is used and treated; this is roughly equivalent to the district heating system demand for treated fresh distribution water. The underlying motivation for the research project implemented at PAS MEERI's Division of Renewable Energy in Krakow is a desire to research the opportunities for comprehensive management of cooled thermal water by introducing new applications for it. The project is utilitarian in character and its purpose is to examine new opportunities to enhance the operational efficiency of geothermal installations [12-14]. Pilot research is being conducted at the PAS MEERI Geothermal Laboratory at Bańska Niżna (Fig. 1).

Experimental Part

Podhale Heating System

The Podhale Heating System is the largest geothermal installation in Poland. It is operated by PEC Geotermia Podhalanska S.A. The system has already been described in the literature [3, 14, 16, 17]. It utilizes two production wells with a total geothermal water production capacity of 670 m^3/h and two reinjection wells through which a maximum of 600 m^3/h of water can be injected. Wellhead pressure in the production wells is artesian pressure and amounts to ca. 2.7 MPa in static conditions; when operating at maximum capacity, wellhead pressure is ca. 1.2 MPa. Surplus water is discharged into the nearby Biały Dunajec River (the maximum admissible discharge is 200 m^3/h). The total capacity of the geothermal system is 15.4 MW, while the total installed capacity of the heating plant

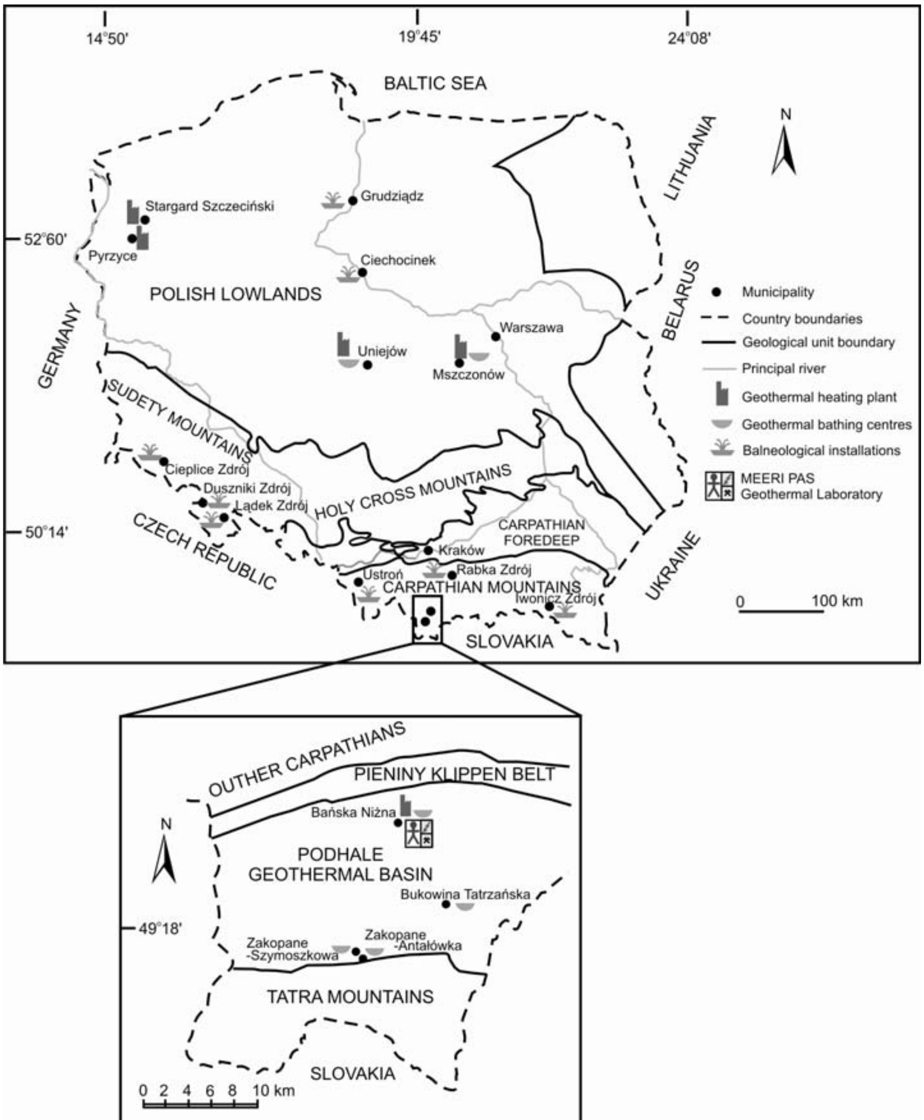

Fig. 1. Location of geothermal facilities in Poland in relation to geothermal units [after 13].

is 80.5 MW (geothermal power plus the capacity of the peak load gas/oil boiler room and combined heat and power units) [3]. The facility's total annual energy production amounts to 324 TJ, of which 226 TJ is geothermal energy [3]. The pipeline between the heating plant and the peak load boiler room in Zakopane is around 14 km long. About 1,500 customers are connected to the system using 1,358 district heating substations. The current total length of the heating network for the system in question is ca. 94,982 metres. The distribution network includes pipes with nominal diameters ranging from 25 to 500 mm; lengths of sections by diameter within the PEC Geotermia Podhalańska heating system are shown in Fig. 2.

Sections of pipe with a diameter of 40 mm (10.9 km, i.e. 11.5% of total pipeline length) and 25 mm (10.4 km – 11%) form the largest elements in the distribution network (Fig. 2), while sections of 300 mm pipe (737 m – 0.8%) and 250 mm pipe (987 m – 1%) are marginal. Network water losses amount to ca. 550 m^3 per month (for the years 2008, 2009, and 2010). Without accounting for major leaks due to failures, this translates to 6,600 m^3 annually. When major leaks due to failures occurr, recorded monthly losses have exceeded 2,600 m^3. Unit network water losses per metre of distribution network amount to ca. 5.8 litres/metre per month, which translates to 70 litres/metre per year. In the installation described here, geothermal water only circulates within a short circuit between the production and reinjection wells. It does not fill the extensive energy distribution system; the role of the carrier distributing geothermal energy is fulfilled by treated network water. Currently, network water losses are replenished using water from the water mains. The water treatment stage includes ion exchange water softeners and vacuum degasifiers.

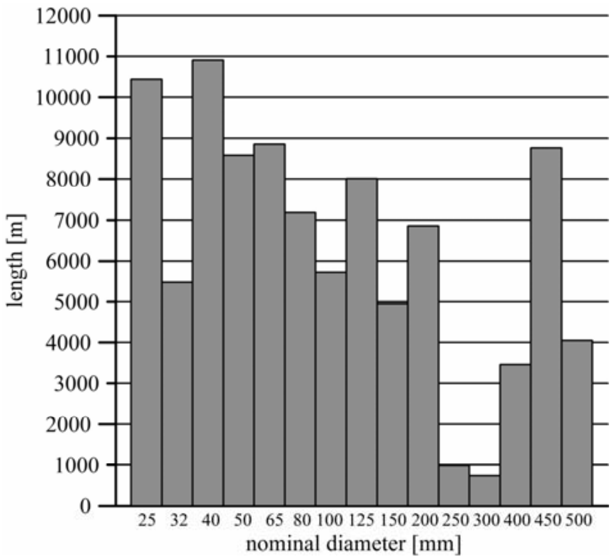

Fig. 2. Diameters of sections of the heating network within the PEC Geotermia Podhalańska SA energy distribution system.

Parameters of Water Circulating in the Heating System

Distribution water that circulates in heating installations must meet certain parameters depending on the technical requirements set by the manufacturers of the equipment through which it flows. It should not cause scaling of boilers, should not corrode parts of the installation, and should not foam. The deposition of boiler scale decreases the heat transfer coefficient of exchangers, thereby reducing their efficiency; additionally, it may obstruct flow and cause an unwanted increase in flow resistance. Boiler scale formation is primarily caused by the presence of carbonates, silicates, sulphates, suspensions, and oils in the water [18, 19]. The foaming of distribution water is most frequently caused by the presence of organic compounds, high salinity, and excess alkalinity [19]. Boiler water corrosivity is mostly caused by the presence of CO_2, and oxygen, and excessive chloride, sulphate, and nitrate content [19].

In Poland, the requirements for distribution water and water used to replenish heating circuits are set forth in Polish Standard PN-85/C-04601 Water for Power Engineering Purposes. Water Quality Requirements and Tests for Water Boilers and Closed Heating Circuits [20]. The standard sets separate requirements for water in installations that are replenished to a limited extent (up to 5 m^3/h) and with respect to those where losses exceed 5 m^3/h. Requirements concerning the quality of boiler water for filling and replenishing heating circuits are listed in Table 1.

Geothermal Water Desalination Research

Geothermal water desalination research was conducted at the Geothermal Laboratory of the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences in Kraków (PAS MEERI, Fig. 1). Part of the water extracted from the Bańska IG-1 well (ca. 4.5 m^3/h) and cooled in heat exchangers was subject to the desalination process. The Bańska IG-1 well is part of the heating circuit operated by the major operator of the Podhale geothermal system – the PEC Geotermia Podhalanska S.A. company.

Physical Properties and Chemical Composition of Raw Geothermal Water Subject to Desalination

The geothermal water extracted from the Banska IG-1 well is of the SO_4-Cl-Na-Ca type according to the Altowski-Szwiec classification [21]. When operated at the maximum approved capacity of 120 m^3/h, the well yields water with a temperature of 82ºC. After being cooled to 30ºC, the water retains its reduction potential (Eh is ca. –270 mV) and a natural content of dissolved gases, mostly carbon dioxide, hydrogen sulphide, and nitrogen. The pH reaction of saturated water is acidic (ranging from 4.5 to 5), while that of degassed water is close to neutral (ranging from 6.73 to 7.8). During the period from April 2010 to July 2011, water mineralization ranged from 2.1 to 2.9 kg/m^3. The water exhibited a high sulphate ion content ranging from 749.6 to 938.2 g/m^3 and considerable hardness (from 556.3 to 645.4 g ($CaCO_3$)/ m^3). Silica content also was elevated (from 33.86 to 55.2 g (SiO_2)/m^3), as were those of

Table 1. Requirements concerning the quality of boiler water for filling and replenishing heating circuits (Polish Standard PN-85/C-04601).

Parameter	less than 5 m³/h		5 m³/h or more	
	circulating water	water used to fill and replenish circuits	circulating water	water used to fill and replenish circuits
pH	9-10 where exchangers with brass or copper pipes are used: 8.5-9.2	≥ 8.5 so that the range for circulating water is maintained	9-10 where exchangers with brass or copper pipes are used: 8.5-9.2	≥ 8.5 so that the range for circulating water is maintained
Total hardness, eq/m³	≤ 0.035	≤ 0.02	≤ 0.02	≤ 0.02
Total alkalinity, eq/m³	not standardized	not standardized	≤ 1.4	≤ 1.0
Dissolved oxygen, g/m³	≤ 0.05	≤ 0.03 thermal degassing obligatory, value before sodium sulphite is applied	≤ 0.05	≤ 0.03
Sulphites, g SO_3^{2-}/m³	3-5	≥ 3 so that the sulphite range in circulating water is maintained. Where circuit is being filled and maintained during standstill, 30-50 is admissible	3-5	≥ 3 so that the sulphite range in circulating water is maintained. Where circuit is being filled and maintained during standstill, 30-40 is admissible
Total iron, g Fe/m³	not standardized	not standardized	≤ 0.1	≤ 0.05
Phosphates, g PO_4^{3-}/m³	≤ 10	so that the threshold for circulating water is not exceeded	5–10	so that the threshold for circulating water is not exceeded
Total suspended matter, g/m³	≤ 5	≤ 5	≤ 5	≤ 5
Substances extracted using organic solvents, g/m³	≤ 1	≤ 1	≤ 1	≤ 1
Inhibitors, g/m³	on a case-by-case basis	on a case-by-case basis	on a case-by-case basis	on a case-by-case basis

boron (from 6.83 to 9.46 g/m³), barium (from 0.06 to 0.125 g/m³), strontium (from 4.97 to 6.12 g/m³), and iron (from 1.21 to 4.5 g/m³). Heavy metal content was low.

Methodology and Apparatus Used

In order for the geothermal water analyzed to be used for replenishing losses in the heating system, high performance desalination methods have to be utilized in order to remove virtually all suspended matter, iron, calcium, and magnesium ions (total hardness) and phosphates. Membrane methods have been considered the most suitable, since water treated using these processes, particularly reverse osmosis, exhibits high purity [18, 22, 23]. At the same time, the desalination of warm water is more efficient than that of cold water (with a temperature of around 10ºC) owing to lower water viscosity. At 30ºC, the water dynamic viscosity coefficient η is $8.02 \cdot 10^{-4}$ Pa s, while at 10ºC it is more than 50% higher [24]. This also is confirmed in the literature and the guidelines provided by the manufacturer of the RO membranes in question (Fig. 3). However, technical constraints related to the material used to manufacture

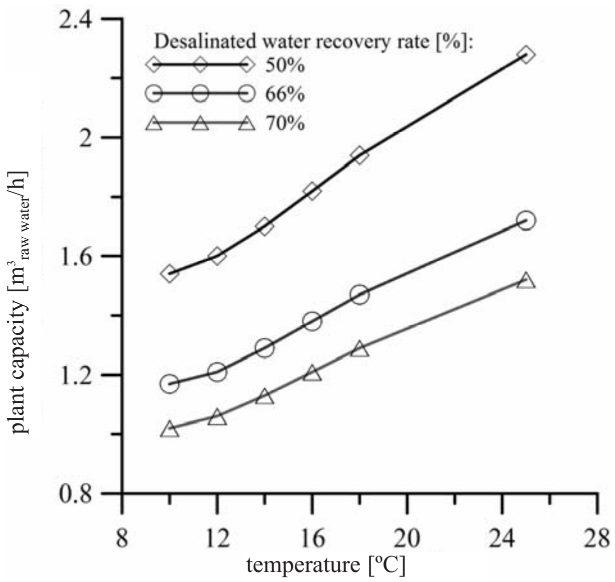

Fig. 3. Plant capacity (volume of treated raw water) for the installation in question for different RO permeate recovery ratios as a function of temperature for pressures ranging from 1 to 1.5 MPa [25].

reverse osmosis and ultrafiltration membranes limit the maximum treated water temperature to the range of 40-45ºC, which is mentioned further in this paper.

A double hybrid arrangement has been selected, including ultrafiltration (UF) and two independent reverse osmosis stages (RO-1 and RO-2) connected in series (Fig. 4). The pilot installation is modular, i.e. its individual parts can be modified, extended, or removed from the water treatment system. It has been installed inside a container, which enables it to be transported and used to conduct tests at other locations (Fig. 5a).

Water pre-treatment involves cooling, degassing, mechanical filtration, iron removal, and ultrafiltration (Fig. 5b). The desalination facility is fed with geothermal water cooled to ca. 35ºC. In order to reduce the iron content of the water, an iron remover has been used where water under a reservoir pressure of 0.5 MPa (without using pumps) flows through a catalytic bed layer, on the surface of which oxidized iron hydroxides are retained, precipitating as floccules that settle easily. The bed is regularly rinsed in order to remove precipitated oxidized iron compounds and is regenerated at fixed intervals using a chemical oxidizer

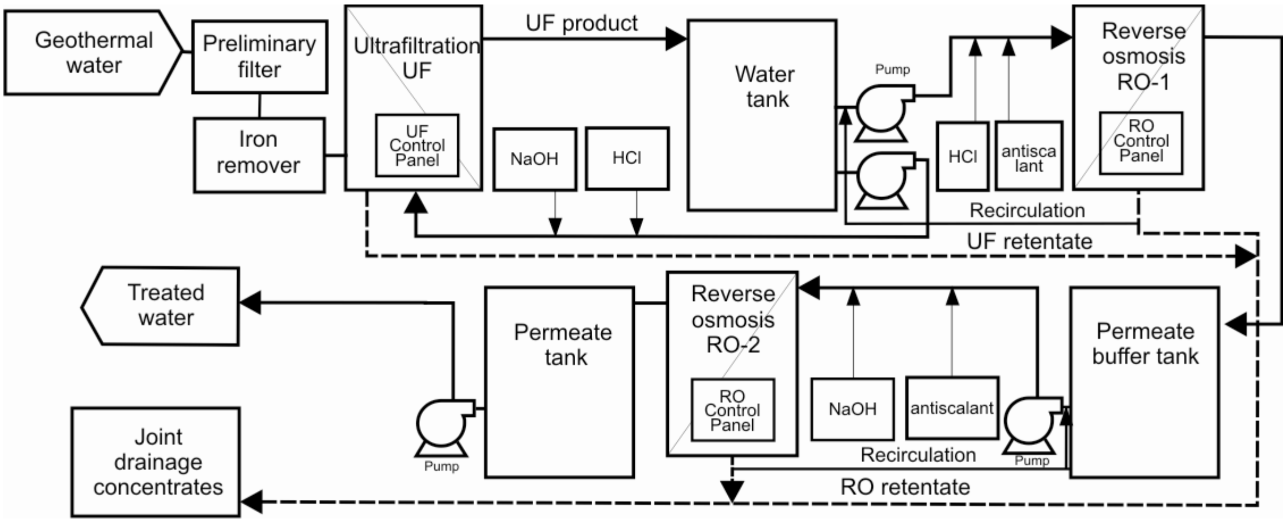

Fig. 4. Technological diagram of the pilot geothermal water desalination facility [26].

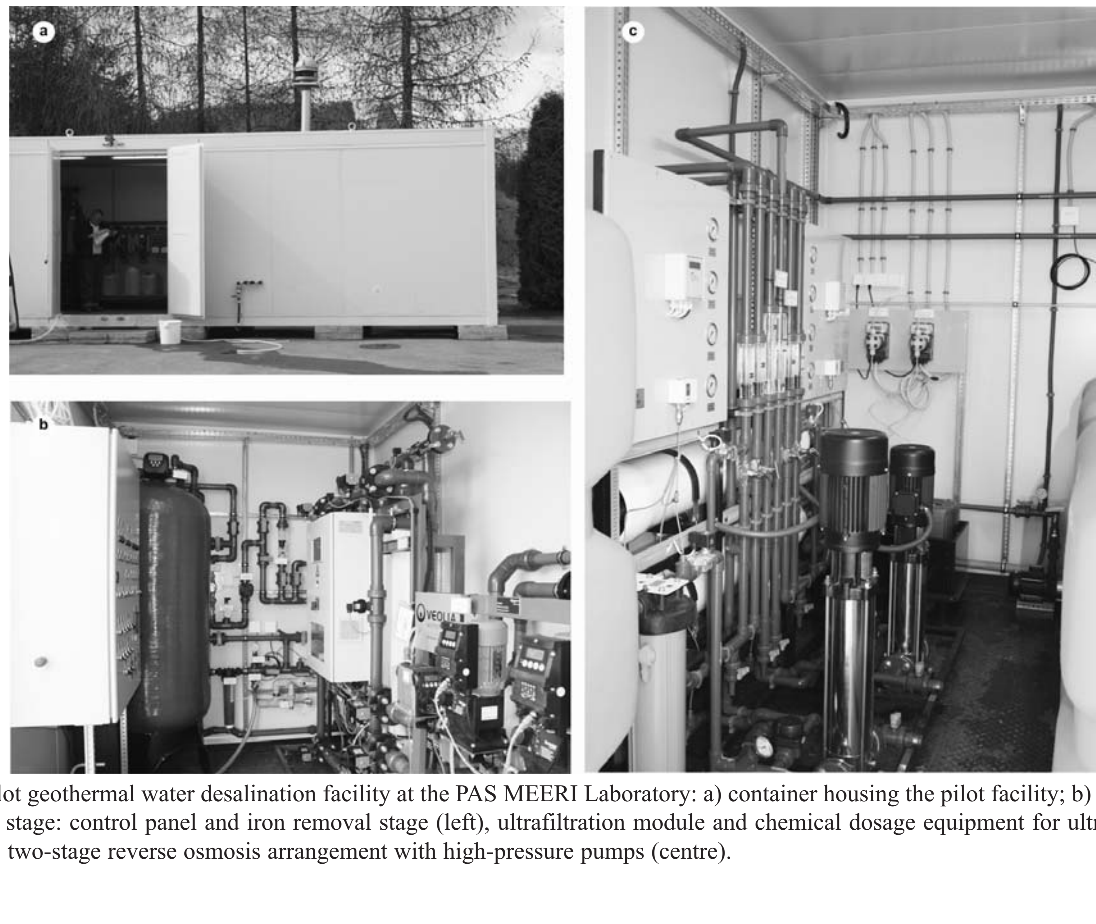

Fig. 5. Pilot geothermal water desalination facility at the PAS MEERI Laboratory: a) container housing the pilot facility; b) water pretreatment stage: control panel and iron removal stage (left), ultrafiltration module and chemical dosage equipment for ultrafiltration (right); c) two-stage reverse osmosis arrangement with high-pressure pumps (centre).

Table 2. Chemical composition of geothermal water and the water output from successive stages in the desalination process.

Parameter	Geothermal water	After Iron removal and UF	After RO-1	After RO-2*
Nitrates, g/m^3	<0.50	<0.50	<0.50	<0.50
Boron, g/m^3	9.46	9.45	6.07	0.16
Chlorides, g/m^3	527.0	520.0	13.4	13.4
Aluminium, g/m^3	0.015	0.005	0.005	0.005
Manganese, g/m^3	0.041	0.040	0.002	<0.001
pH	7.2	6.87	5.38	9.49
Conductivity, S/cm^3	3550	3230	195	104
Sulphates, g/m^3	938.2	915.18	8.10	6.40
Sodium, g/m^3	545.1	543.9	21.0	19
Iron, g/m^3	4.0	0.013	0.009	0.008
Magnesium, g/m^3	42.71	41.7	0.24	<0.10
Hardness, eq/m^3	13.5	13.5	0.076	<0.02
Alkalinity, eq/m^3	4.45	4.45	<0.01	<0.01
Sulphites, g/m^3	0	0	0	0
Phosphates, g/m^3	0.03	0.03	<0.006	<0.006

(potassium permanganate $KMnO_4$). After filtering out major contaminants and removing iron, the water is fed to the ultrafiltration (UF) module. UF membranes are used to remove microsuspensions (<0.03 μm), colloids, bacteria, and viruses. The facility is fitted with two ultrafiltration modules with UFC M5 (X-Flow) polyethersulphone hydrophilic capillary membranes. The water passes through the ultrafiltration module under reservoir pressure. Since artesian pressure is used in the iron removal and ultrafiltration stages, circulation pumps are not required. For the facility in question, this is tantamount to reducing electrical power consumption by ca. 0.7-0.9 kW.

The reverse osmosis (RO) stage consists of the following modules (pressure pipes): RO-1 – two modules, RO-2 – one module. Each module includes one reverse osmosis membrane (Fig. 5c). DOW FILMTEC BW30HR–440i membranes have been used for test purposes. These are thin-film polyamide composite membranes. According to the manufacturer's specifications, the maximum temperature of the raw water fed to the membranes must not exceed 45ºC, the maximum pressure is 4.1 MPa, admissible pH range is from 2 to 11 and the maximum Silt Density Index (SDI) is 5. Tests were conducted within the pressure range from 1 to 1.5 MPa.

The quality of the feed and desalinated water were continuously monitored through online measurement of the variable physical parameters of water: temperature and specific electrolytic conductivity. The pH reaction was measured using the electrometric method directly after collecting water samples from the installation. The chemical composition of water samples was tested at an accredited laboratory (PCA-AB 1050) using the inductively coupled plasma mass spectrometry (ICP-MS) method. Chloride ion content and water alkalinity were determined by titration in accordance with accredited testing procedures. Tests concerning the total count of microorganisms at 22ºC after 68 hours were conducted at an accredited laboratory (PCA-AB 595) as per PN-EN ISO 6222:2004.

Discussion of the Results

The results of facility operation are presented in Table 2 and in Fig. 6 using the retention coefficient concept (the difference in the value of the parameter in question, e.g. ion concentration or conductivity, in raw and treated water divided by the value for raw water and expressed as a percentage). The technological arrangement used made it possible to reduce iron content from ca. 4 to 0.013 g/m^3 (Table 2). Water electrolytic conductivity and its hardness after UF were only reduced by ca. 10% (Fig. 6), but this process reduced colloidal substance content by half. The silt density index (SDI) for "raw" geothermal water subject to desalination ranged from 4.6 to 5; following the UF process, it ranged from 2 to 2.8. Aluminium content also was reduced significantly (by 30% to 60%). This is advantageous from the point of view of protecting RO membranes from fouling.

RO-1 membrane permeability with a 78% desalinated water recovery rate amounted to ca. $5.25 \cdot 10^{-6}$ $m^3/(m^2 \cdot s)$; with respect to mineralization, the retention coefficient was 93% (Fig. 6).

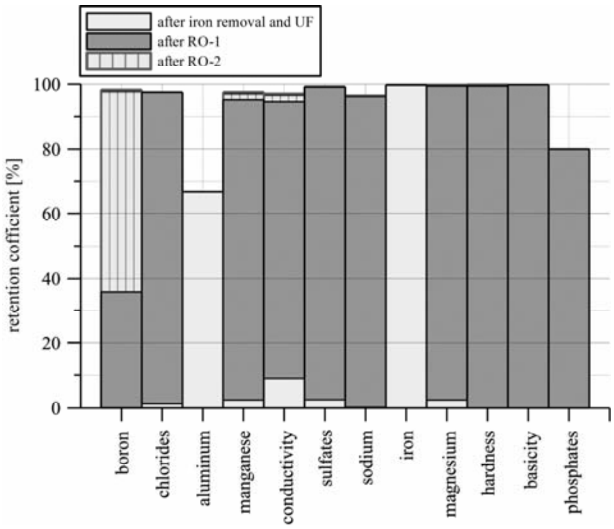

Fig. 6. Retention coefficient in % for key parameters.

Following first-stage reverse osmosis desalination, total water hardness was not reduced to a satisfactory extent (Table 2), despite the fact that retention coefficients for calcium (95%) and magnesium (99%) were high (Fig. 6). By using the second stage reverse osmosis procedure, water that met the set requirements was obtained (Table 1). RO-2 membrane permeability with a 78% desalinated water recovery rate amounted to ca. $7.9 \cdot 10^{-6}$ $m^3/(m^2 \cdot s)$; with respect to mineralization, the retention coefficient was 95% compared to raw water (geothermal water from the Bańska IG-1 well).

In order for the permeate obtained to be used for filling and replenishing heating circuits, an anti-corrosion adjustment is required, in particular pH stabilization and degassing. Adjustment of pH to a value around 10 (through NaOH dosage) before the second RO stage permits a high boron retention coefficient (96%) to be obtained; boron can only be effectively removed from water in an alkaline environment [13]. However, reducing the content of this ion is not required, and therefore pH adjustment may be introduced following treatment of the water.

The PN-85/C-04601 Polish Standard does not specify any requirements concerning the admissible concentrations of, *inter alia*, chloride and sulphate ions, i.e. anions that affect water corrosivity, mostly pitting corrosivity. These ions form soluble compounds with metals and thereby inhibit the formation and precipitation of metal oxides. The use of the membrane technology discussed here in the desalination of geothermal waters made it possible to achieve high retention coefficients – 84% after RO-1 and 97% after RO-2 for chlorides and 99% for sulphates already after RO-1.

Bacteriological tests of desalinated water demonstrated that the total number of microorganisms after 68 hours for a water temperature of 22ºC amounted to 9 units per 1 ml. The admissible number of microorganisms in water for filling and replenishing heating circuits is not included in standards, but it should be noted here that 100 microorganism units per 1 ml of water are admissible for potable water.

During the desalination process, the water becomes oxygenated, and therefore it must be degassed by chemical means or in a vacuum degasifier before it is finally fed into the heating circuit. Chemical water deoxygenation consists of adding strong reducing agents that bind oxygen. The usual agent is sodium sulphite (Na_2SO_3), since this is the cheapest and simplest method. Sodium sulphite binds dissolved oxygen as follows:

$$2Na_2SO_3 + O_2 \rightarrow 2Na_2SO_4 \quad (1)$$

The sodium sulphate (Na_2SO_4) thus formed causes water salinity to increase; moreover, taking the elevated pressure and intensive thermal load of heat exchange surfaces into account, it may be prone to decomposition, thus increasing water SO_2 content [19]. In practice, excessive dosage of sodium sulphite is frequent, and for this reason PN-85/C-04601 regulates its concentration range.

In the authors' view, a better solution is to use a vacuum degasifier, which may play a dual role: degassing water following the desalination process within the RO arrangement and degassing the network water that has been subject to secondary oxygenation (through leaking fittings and pump glands). With this in mind, the vacuum degasifier may be fitted in a bypass of the return pipeline. This makes it possible to systematically eliminate secondary oxygenation; additionally, where it is necessary to replenish the circuit with water, a seamless transition to the mode in which network and additional water are degassed is possible at the same time. It should be emphasized that the degassing system is more efficient at higher temperatures, and treated water obtained by using the solution described is warmer than that yielded by standard solutions.

Taking into account the ultimate application of treated geothermal water (i.e. replenishing network water losses in the heating circuit), the higher temperature of treated water is another advantage of the solution proposed. Standard network water treatment systems yield water with a temperature that usually ranges from 10ºC to 18ºC, depending on the season and the source of raw water. Treated water fed to the heating circuit must be heated to the operating temperature prevailing within the distribution system. The water treated using the solution proposed (Fig. 4) has a higher temperature of ca. 30-35ºC. For the required water volume of 1-1.5 m^3/h, this saves up to 30 kW in thermal power. This is a small amount (0.2% of geothermal power) when the power rating of the energy source for the entire system is taken into account, but nevertheless constitutes another advantage of the method put forward.

Conclusions

The tests and analyses conducted have demonstrated that geothermal water treated using membrane processes has a secondary application – it can be used to replenish water losses in heating circuits and to fill such circuits. This allows its fuller and more comprehensive use. This may be of special significance in areas where there is a deficit of fresh water. One such area is the Podhale Basin, where the facility discussed in the article is situated. It uses geothermal water sourced by the largest Polish geothermal heating installation. The water used to replenish the losses is currently treated using ion exchange water softeners and vacuum degasifiers. It is suggested that the missing water be replaced with treated geothermal water. The membrane processes can be used within the framework of a double hybrid arrangement, including ultrafiltration and two independent reverse osmosis stages connected in series to treat water with a temperature of 35ºC. As a result of the tests conducted it was found that treated water met the requirements set forth in the standard.

The authors point out the advantages of treating geothermal water in that it is hotter and has a higher natural pressure as compared to treating standard water with standard methods. In the solution analyzed, the higher pressure reduces the electrical power input required for the circulation pumps by 0.7 to 0.9 kW, while the higher temperature reduces the average power required to heat the water that replenishes the heating circuit by ca. 30 kW. Moreover, the fact that the water to be treated is warm improves the efficiency of the treatment processes, particularly ultrafiltration, reverse osmosis, and degassing, which is confirmed by the observations and tests described in the literature. A definite improvement in the energy balance could be expected if hotter water (i.e. before passing through heat exchangers) were to be used in the treatment process, but a technological barrier exists here that constrains this process, since the ultrafiltration and reverse osmosis membranes currently available only permit the treatment of water with a temperature of up to 40-45ºC.

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