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Utilizing Geothermic and Geothermal Energy for Heat and Power

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Abstract

Our paper characterizes Polish resources for geothermic and geothermal energy and describes their extraction and utilization. We also present perspectives on development of energy conversion installations utilizing geothermal energy for heating purposes. Existing geothermal heating plants and geothermal installations currently under construction together, with those planned for future (including geothermal power plants) are discussed.

Keywords: geothermic energy, geothermal energy, geothermal heating plant

Geothermic and Geothermal Energy

Temperature differences between the hot interior of the Earth and its cold surface, estimated at the level of 3,000-6,200°C, renders the flow of geothermic heat with average density of about 63 mW/m². However, this value is not uniform throughout the globe [1, 2]. For example, within the Polish Lowlands there is differentiation of the heat flux density in the range of 38 to 105 mW/m² (Fig. 1) [3].

Temperature change is caused by the radial flow of heat in the crust, i.e. the so-called geothermic gradient. The local values of rock temperatures that cause geothermic gradient depend on geological building of the Earth's crust and the average temperature on the surface of the Earth. Energy accumulated in the hot rock formations (so-called hot, dry rocks – HDR) and salt diapers is called geothermic energy. If we fill the gaps in rocks (and other fluids), such water is called geothermal water, and energy contained therein is geothermal energy.

It can be assumed that down to a depth of 10 km below the Earth's surface temperature T in the crust varies linearly with depth H, in line with the relation:

$$T = A + BH \text{ [K]} \tag{1}$$

...where:
B – geothermic gradient, K/km,
A – mean temperature at Earth's surface, K.

A mean value of geothermic gradient is about 30 K/km [2-5].

An unanimous classification of geothermal resources cannot be found in literature. Most often the criterion of recognition assumed is temperature fluid being the heat carrier, but such a classification according to temperature is neither unanimous nor precise (Table 1) [6].

Geothermal waters in Poland can be divided into warm waters (low-temperature, 20-35°C), hot ones (medium-temperature, 35-80°C), very hot ones (high-temperature, 80-100°C) and superheated ones (> 100°C) [2, 7].

The total resources of geothermal energy are abundant, but only a small part can be utilized in practice, which stems from actual technical possibilities and the economy of acquiring energy from the Earth's interior.

Due to the way in which geothermal energy is acquired, its resources are recognized as:

- hydrogeothermal resources, where the source of heat is natural underground water resources exploited by means of drilled wells,

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Table 1. Classification of geothermal resources according to temperature [6].

Geothermal resources:	Muffler and Cataldi	Haenel et al.	Benderitter and Cormy	Hochstein	Gunnlaugsson, Axelsson
Low-temperature	<90°C	<150°C	<100°C	<125°C	<190°C
Medium-temperature	90-150°C	-	100-200°C	125-225°C	-
High-temperature	>150°C	>150°C	>200°C	>225°C	>190°C

- petrogeothermal resources, i.e. energy of dry hot rocks, which is acquired by introducing water into hot rock massif through drilling wells.

Poland has abundant resources of geothermal waters with low and medium enthalpy estimated at 6,600 km^3 [5], and the water contained therein has temperature in the range 25-130°C. Geological conditions of existence of geothermal resources in Poland, together with potential resources of contained thermal energy, have been generously discussed in the works by Sokołowski, Górecki, and Ney [2, 3, 5, 6]. Classified and calculated by Górecki [3] values of resources of geothermal energy resources in Polish Lowlands split into temperature ranges have been presented in Table 2.

Ways of Extraction of Geothermal Energy

The decisive factors on exploitation of geothermal resources are: favourable natural conditions of rocks, i.e. adequate depth of cover and good permeability as well as quality of geothermal heat carrier, its temperature, mineralization, heat efficiency, operation time, etc.

Table 2. Resources of geothermal energy in Polish Lowlands according to Górecki [3].

Formation	Temperature of water basin [°C]	Static extractable resources [J]	Disposable energy resources	
			[J/year]	[t.o.e./year]
Cretaceous layers	to 40	$1.66 \cdot 10^{19}$	$0.96 \cdot 10^{17}$	$2.18 \cdot 10^{6}$
	40 – 60	$1.46 \cdot 10^{19}$	$1.44 \cdot 10^{17}$	$3.27 \cdot 10^{6}$
	60 – 80	$1.19 \cdot 10^{19}$	$1.23 \cdot 10^{17}$	$2.80 \cdot 10^{6}$
	80 – 100	$0.24 \cdot 10^{19}$	$0.19 \cdot 10^{17}$	$0.43 \cdot 10^{6}$
	Total	**$4.55 \cdot 10^{19}$**	**$3.82 \cdot 10^{17}$**	**$8.68 \cdot 10^{6}$**
Jurassic layers	to 40	$0.51 \cdot 10^{20}$	$1.69 \cdot 10^{17}$	$3.84 \cdot 10^{6}$
	40 – 60	$1.66 \cdot 10^{20}$	$6.20 \cdot 10^{17}$	$14.09 \cdot 10^{6}$
	60 – 80	$1.55 \cdot 10^{20}$	$5.48 \cdot 10^{17}$	$12.45 \cdot 10^{6}$
	80 – 100	$0.44 \cdot 10^{20}$	$2.52 \cdot 10^{17}$	$5.73 \cdot 10^{6}$
	above 100	$0.20 \cdot 10^{20}$	$1.42 \cdot 10^{17}$	$3.23 \cdot 10^{6}$
	Total	**$4.36 \cdot 10^{20}$**	**$17.31 \cdot 10^{17}$**	**$39.34 \cdot 10^{6}$**

t.o.e. – tons of oil equivalent, 1 t.o.e. = $4.44 \cdot 10^{10}$ J

Assuming as a criterion of division the state of aggregation of the geothermal heat carrier and its temperature the sources of geothermal energy can be divided into:

- sources of hot and warm water, extracted by means of drilled wells, used primarily in the heating industry as well as in heat and power industry,
- sources of steam, extracted by means of drilled wells and used in geothermal power plants for production of electricity,
- so-called salt heaves, from where energy is acquired by means of the brine or neutral liquids with respect to salt (for example hydrocarbons),
- hot rocks, from which energy is extracted by means of circulating water under high pressure through the system of natural or purpose-made gaps in the rock massif; such energy is utilized in heating plants and/or geothermal power plants.

Possibilities of utilization of geothermal water resources are quite extensive, whereas the methods of its acquisition are preconditioned by several factors. The most important thing to consider is that the ratio of mineralization of geothermal waters the systems of energy extraction can be considered as single and double wells.

Single-well systems find applications in cases of geothermal water featuring a small rate of mineralization, i.e. below 1 g/dm^3 (Fig. 2a). The system consists of a single extraction well, through which geothermal water is extracted to the surface and then directed to geothermal heat

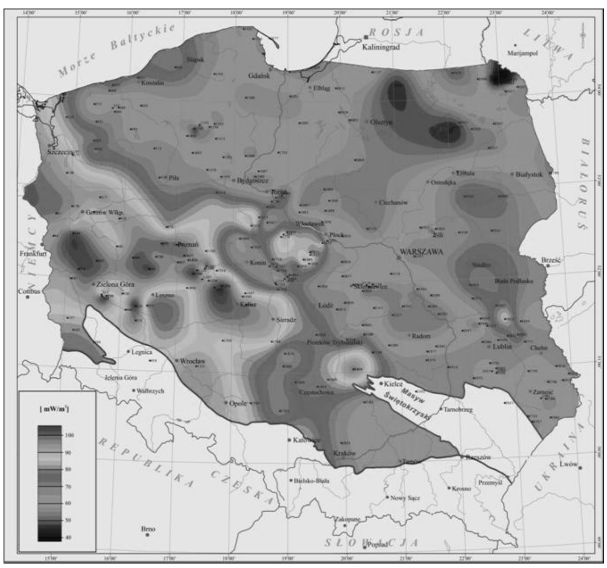

Fig. 1. Distribution of heat flux density in Polish Lowlands [3].

exchange. Once cooled there it is delivered to the storage reservoir in order to use it for other purposes.

Two-well extraction systems (Fig. 2b) find application in the case of geothermal waters featuring a high rate of mineralization and consist of two wells (dublet). One well serves as an extraction well where water is taken from the geothermal bed. The second one, an injection well, is where water, after reduction of its temperature in the heat exchanger, is pumped back to the basin.

Other different designs of extraction systems of geothermal energy are discussed in detail in [2, 4, 7-10].

Utilization of Geothermal Energy in Heating Installations

Geothermal water can be used in heating systems as a sole source of thermal energy or in combination with other sources of energy. The first design is justified if a sufficient amount of geothermal water is at a disposal with temperature above 100°C. Using water with lower temperatures, the heat plant is usually supported by an additional heat source, where different systems of combination are available with respect to several factors.

In practice the most often used are three fundamental concepts:

- Installations using only heat exchangers. In such an installation the network water is heated by means of heat contained in geothermal water.
- Installations with application of heat exchangers and peak-load boilers. In such an installation the network water is heated by means of heat contained in geothermal water and further heated up, if necessary, in a peak-load boiler.
- Installations with application of heat exchangers and heat pumps. Acquisition of geothermal energy is taking place in heat exchangers transferring geothermal heat to the return network water with simultaneous utilization of a heat pump. Such an installation can also be supplemented by a peak-load boiler.

The amount of received geothermal energy depends on parameters of geothermal water as well as network water and type of heat exchanger.

Volume of extracted geothermal energy in a heat exchanger depends on the characteristics of a geothermal basin and characteristic network combined with heat receivers. The rate of heat $\dot{Q}_g$ [kW] possible for extraction from geothermal water can be determined from:

$$\dot{Q}_g = \dot{V}_g \rho_g c_g (T_{gw} - T_{gz}) \quad (2)$$

...where:

$\dot{V}_g$ – flow rate of geothermal water [m^3/h],
ρ_g – density of geothermal water [kg/m^3],
c_g – specific heat of geothermal water [kJ/(kgK)],
T_{gw} – temperature of extracted geothermal water [K],
T_{gz} – temperature of injected geothermal water [K].

An important quantity from the point of view of utilization of geothermal heat is the temperature of extracted geothermal water, which defines its quality.

The characteristics of the basin can be presented in a form of relevant distributions illustrating possibilities of extraction of geothermal energy, both using the two-hole and single-hole systems. The fundamental characteristic is the diagram illustrating the rate of heat of extracted geothermal energy, dependent on volumetric rate of extracted water, its temperature and degree of cooling of geothermal water in the heat exchanger (Fig. 3).

An important factor influencing the effectiveness of utilization of geothermal energy is time (during a year) of the system operation and geothermal energy extraction [2, 4, 6].

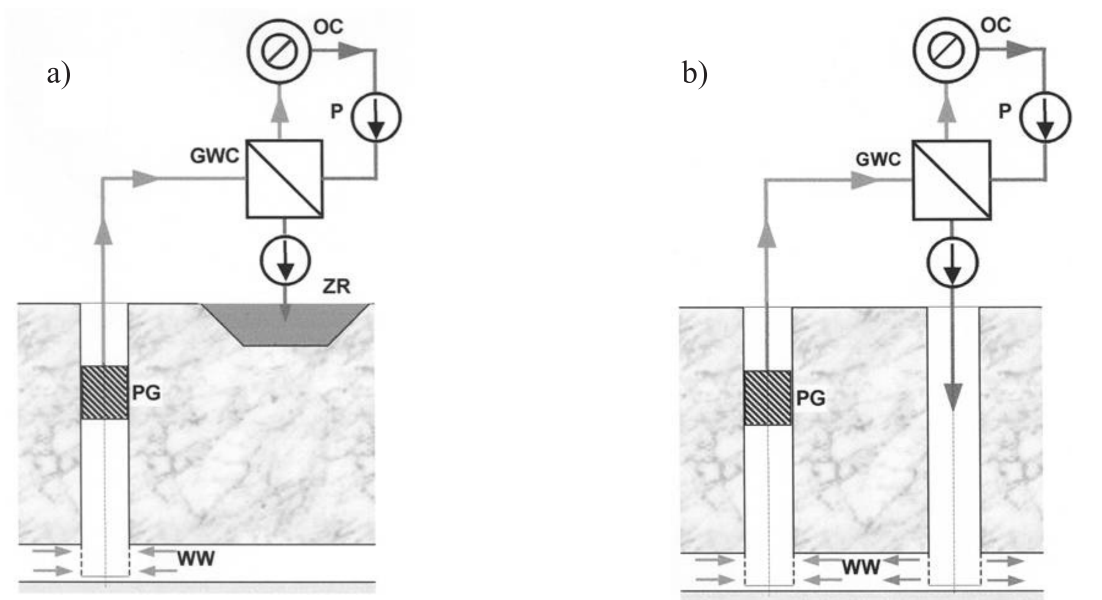

Fig. 2. Systems for extraction of geothermal water: a) single well, b) double well.
GWC – geothermal heat exchanger, OC – heat receiver, PG – deep-well pump, P – pump, WW – aquiferous layer, ZR – storage reservoir.

Table. 3. Basic data of geothermal heat plants operating in Poland.

Characteristic parameter	Bańska Niżna	Pyrzyce	Mszczonów	Uniejów	Słomniki by Kraków	Stargard Szczeciński
Year of commission	1994/2001	1996	1999	2001	2002	2005
Water temperature [°C]	82/86	61	40	67-70	17	86.9
Depth of basin [m]	2,000-3,000	1,500-1,650	1,600-1,700	~2,000	300	2,67
Mineralization [g/l]	3.0	120	0.5	6,8-8,8	-	120
Flow rate [m^3/h]	120 + 550	2x170	60	68	53	300*
Heat capacity (total from geothermal and additional resources) [MW_t]	42	50	12	4.6	1.1	14

*assumed flow rate of geothermal dublet.

The most effective and simplest way to manage geothermal resources is their application for heating purposes. In cases when temperature and/or the stream of extracted geothermal water is not sufficient for heating water in a heating installation, then the peak-load boilers or heat pumps are introduced to support the heat source, with the objective of increasing water temperature to the required level. As noted, the geothermal installations feature a significant variety of possible designs that stem from the necessity of individual adjustment of the geothermal well to the needs and parameters of heat-receiving installations [2, 4, 7, 10].

Demanded by recipients, heat is variable in time. This regards particularly the demand for heat for surface heating, which is mainly a function of external temperature. The basis for determination of that heat is the ordered diagram. It is helpful, among other factors, in setting the concept and design of the heat source utilizing the energy of geothermal water. In development of geothermal installations, three basic systems are possible.

- Monovalent system, where entire energy is extracted from geothermal installations and the source power is adjusted to the maximum heat demand.
- Bivalent systems, where the geothermal source is supported with conventional boilers, heat pumps, thermal-power modules. In such a system the additional heat resource supplies the required amount of heat only in the peak demand period.
- Combined system, where part of heat recipients is supplied from a geothermal installation and the remaining part from a conventional boiler.

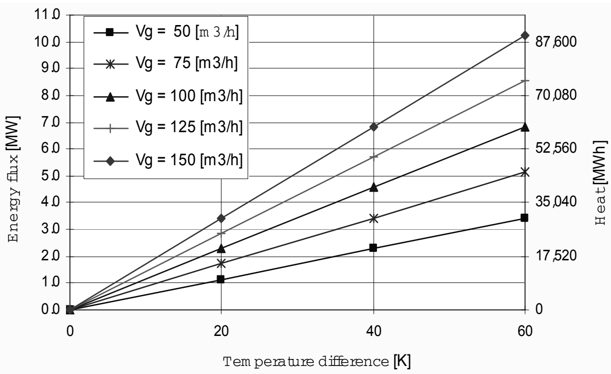

Fig. 3. Possibilities of extracting of geothermal energy from a geothermal deposit.

Specific solutions depend on local geothermal conditions and possibilities of management of seasonal surplus of geothermal heat, occurring outside the heating season.

Existing Geothermal Heating Plant

Despite significant potential, the exploitation of geothermal resources for heating purposes in Poland started only in the 1990s. Previously, geothermal resources were used in balneology and recreation, and a series of spas utilized hot springs for medical applications [6, 7].

Several heating installations based on energy of hot underground resources have been constructed in Poland since 1993 (Fig. 4; see basic technical parameters in Table 3).

The first Polish geothermal heating plant was commissioned in 1994 in Bańska near Zakopane [8, 11]. Water at 86ºC, extracted at a rate of 120 m^3/h (Fig. 5), is delivered to the geothermal heat exchanger and then (following the rejection of heat) pumped to the same water-bearing layer. At the time, network water, heated in the exchanger, supplied heat for heating purposes and preparation of hot water to about 200 dwellings and public utility buildings, as well as to the PASci geothermal laboratory.

At present the installation forms part of a large heating system commissioned in 2001 (Fig. 6), with the objective of mating the heating needs of Zakopane and surrounding villages [8, 11]. A fundamental source of energy in that new system is a new geothermal heating plant utilizing water with temperature of about 86°C and maximum flow rate of 550 m^3/h. An integral part of the installation is the peak-load boilers situated in Zakopane, equipped with two medium-temperature water boilers and Combinet Heat and Power units (CHP).

A gas-geothermal heat plant commissioned in Pyrzyce in 1996 with capacity of 50 MW was the first large instal-

Fig. 4. Location of existing installations utilizing geothermal resources in Poland.

lation in Poland that utilized a geothermal well for heat production with maximum capacity of 13 MW and peak-load boilers. Implemented in the heat plant system are absorption heat pumps driven by energy produced in high-temperature boilers (Fig. 7) [12].

Another geothermal heating plant was commissioned in 2000 in Mszczonów [13]. Water with temperature of 40-42°C is extracted at 60 m^3/h and features a small rate of mineralization (0.5 g/l), which enables its final utilization as drinking water and in effect no pumping back is necessary. The heat plant applies low-temperature gas boilers with capacities of 2.4 MW each, playing the role of peak-load boilers. The source of energy for the heat pump with 2.7 MW capacity is a high-temperature boiler with capacity of 1.9 MW.

In 2001 a heating plant was commissioned in Uniejów that utilizes water with temperature ranging from 67 to 70°C, extracted from a depth of over 2,000 m under pressure pod 0.4 MPa. Water with mineralization of 6.8-8.8 g/m^3 has therapeutic properties, which in future should permit its use for balneological and recreational purposes [6].

In 2002 a plant in Słomniki began utilizing energy contained in water with temperature of +17ºC, extracted from a depth of 300 m [14]. At the moment installation has not been exploited. The last investment is a heating plant in Stargard Szczeciński, which due to temperature of water (86.9ºC) extracted from the depth of 2,672 m, consists of merely the geothermal dublet and a heat exchanger with capacity of 14 MW. The heat contained in geothermal water is transferred to network water circulating in the heating installation of the town.

Apart from heating plants in which geothermal energy is utilized, geothermal water is being used for healing and

Fig. 5. Water intake (extraction well) of PASci geothermal heating plant in Bańska Niżna.

Fig. 6. A new geothermal heating plant in Bańska Niżna.

recreational purposes at such locations as Lądek Zdrój, Zakopane, Bukowina Tatrzańska (Fig. 4).

Geothermal Power Plants

For some time now in Poland, studies of the possibility of utilization of geothermal energy for production of electricity which would allow for a full exploitation of existing sources, including outside the heating season, have been conducted.

Construction of the surface installation of a geothermal power plant depends primarily on temperature and properties of extracted geothermal fluid. Among installations situated on the ground two principal designs can be selected, [6, 15]:

- Power plants with direct utilization of steam (Fig. 8a) or evaporation of geothermal water with high pressure and temperature in the expander-separator (Fig. 8b). Their feature is that used water is at the same time the working fluid in the cycle of the power plant. That type of design can be used when temperature of geothermal water is at least 120°C.
- Two-fluid power plants (Fig. 9), where geothermal water is used for evaporation and eventually superheating of appropriate low-boiling-point fluid circulating in the secondary loop of an installation and supplied to the steam turbine. In such cases utilization of geothermal water with lower temperature is possible.

Only deep bore-hole resources of geothermal waters in Poland have temperature exceeding 120°C. In operating installations in the extreme case temperature does not exceed 86°C. Therefore, it ought to be assumed that the only realistic solution in construction of geothermal power plants with the so-called organic Rankine cycle is to utilize low-boiling-point fluids. The chemical industry offers a relatively large number of substances to choose from with respect to critical temperature, location of triple point, and working pressure range to become a potential working fluid in the cycle of the power plant (Fig. 10).

A sample schematic of the steam plant operating with so-called dry fluid is presented in Fig. 11. The plant consists of the geothermal heat exchanger, turbine with electricity generator, steam cooler, condenser, circulation pump, heater, and evaporator. Saturated steam is directed to the steam turbine, where isentropic expansion takes place to the

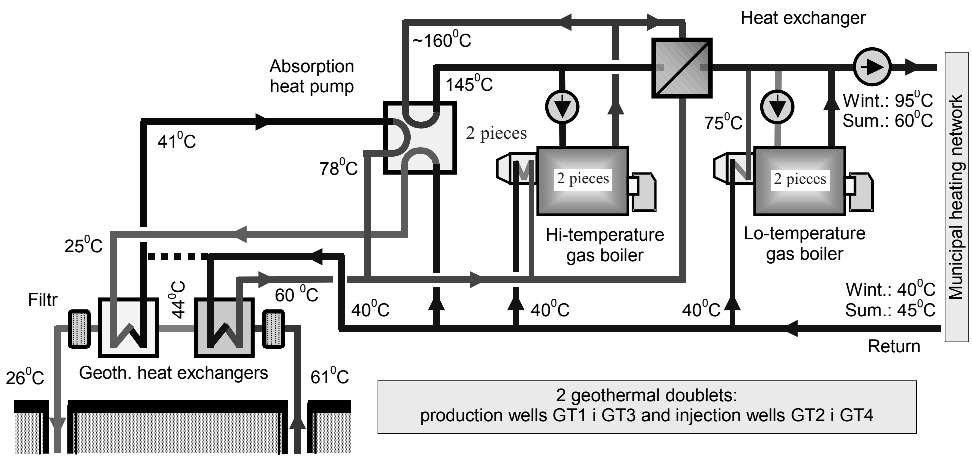

Fig. 7. A simplified schematic of the geothermal heating plant in Pyrzyce.

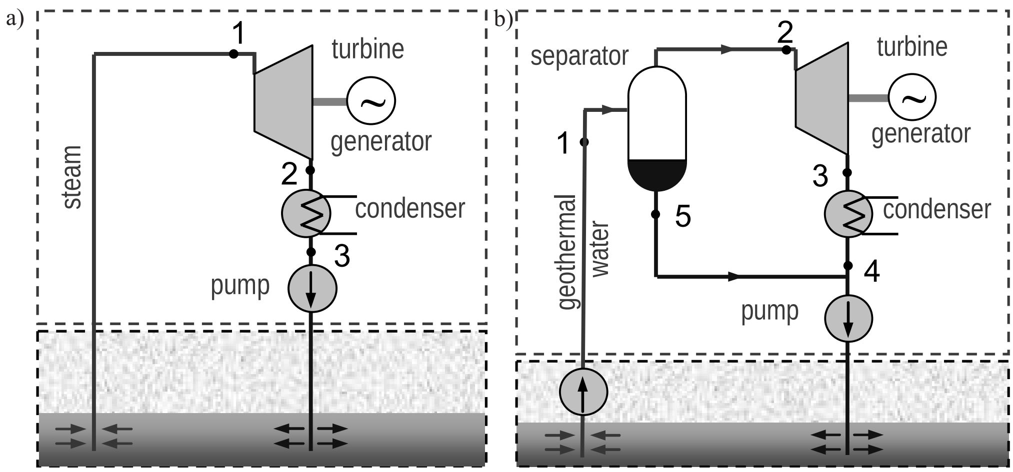

Fig. 8. Schematic of geothermal power plant installation with direct utilization of saturated steam (a) and single-stage decompression of geothermal water (b).

pressure in condenser. Next, steam is directed to the condenser and the condensate of organic fluid is directed to the heater and evaporator.

Sample results of calculations of efficiency $\eta_{C\text{–}R}$ and power $N_{C\text{–}R}$ of the Clausius-Rankine cycle for a plant presented above is shown in Fig. 12.

Summary

The oldest way to utilize geothermal resources in Poland is their application in medical purposes. But we have noticed a significant increase of interest in utilizing geothermal resources for energy purposes.

Taking into account significant resources of geothermal waters as well as existing reports on possibilities of their utilization in numerous towns in Poland. It seems that in the near future the number of geothermal heat plants will increase. It should also be expected that around such geothermal heating plants there will arise other objects where such energy will be used. These can be objects of recreational profile but also objects for agriculture and industry.

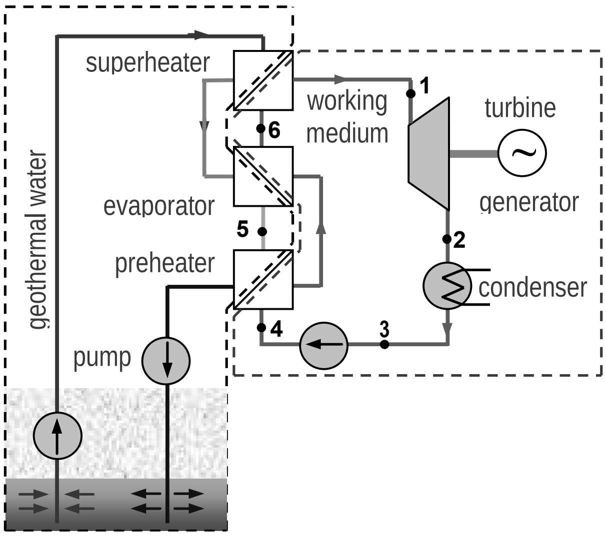

Fig. 9. Schematic of geothermal power plant installation with low boiling point working fluid.

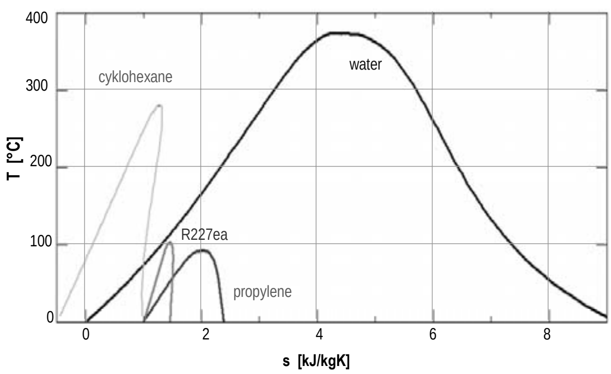

Fig. 10. Shape of the saturation curves on T, s diagram for selected fluids.

Development of the system with differentiated, heat recipients is in line with higher efficiency heat plant operation and more effective utilization of geothermal waters.

Analysis schows that utilizing geothermal energy for production of electricity in power plants operating with low

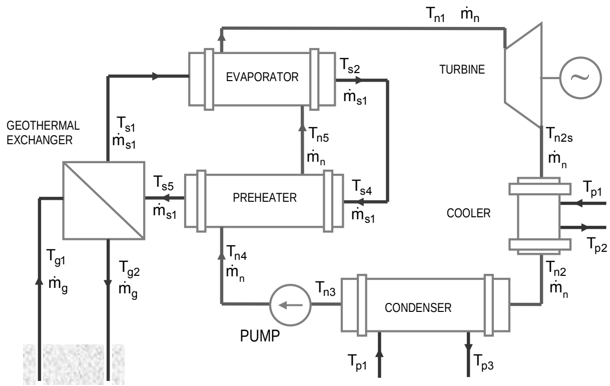

Fig. 11. Schematic of power plant installation with dry organic fluid.

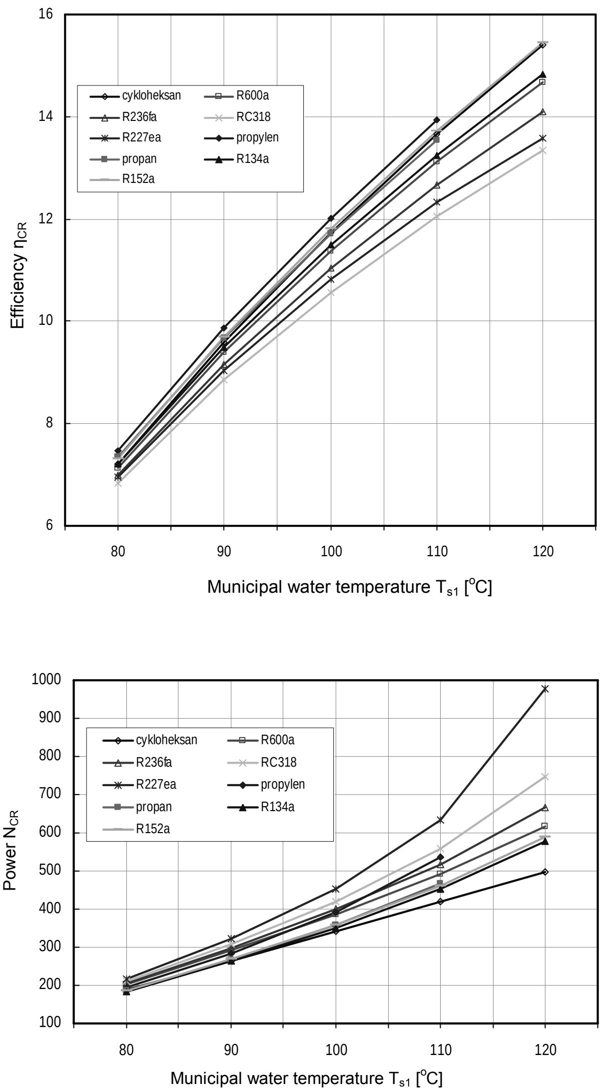

Fig. 12. Efficiency and power of the C-R cycle in function of municipal water temperature for different working media.

boiling point working fluids (according to the so-called C-R cycle) are flexible.

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