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Possibilities for the utilization of highly mineralized water in Central Bulgaria as a source of thermal energy, based on the Austria's experience

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The hydrogeological conditions in Northern Bulgaria are determined by the presence of a large artesian basin. It is constituted by several aquifers, which with depth significantly increase their temperature and total dissolved solids. These waters have been used in the past mainly for balneology and heating, but in the recent years their utilization has decreased significantly. One of the reasons for this is the processes of scaling in the wells and associated facilities. Many countries, including Austria, whose geological and hydrogeological conditions are similar to those in Bulgaria, have experience in its implementation. In the artesian basins, in the mountain depressions and in the pre-Alpine basin, high-temperature reservoirs with high total dissolved solids (TDS) are formed, some of which are used as a source of energy. One example is the hydrothermal power plant 'Frutura'at Bierbaum an der Safen in Styria, which began operation in 2016. The geothermal doublet uses water with a temperature of 124.5 °C - the highest temperature so far of all geothermal wells in Austria and with total dissolved solids (TDS) of 78 g/l. This experience could be used in Bulgaria, mainly in the Central parts of Northern Bulgaria, where highly mineralized waters with high temperatures are present. For this purpose, the data on the main artesian aquifers were summarized, with the main focus being on the most water-rich ones – the Upper-Jurassic-Lower-Cretaceous. In order to locate suitable areas for utilization of geothermal energy, their spatial position, temperature and chemical composition are characterized. A regional assessment of the amount of heat energy has been made.

Keywords: hydrogeothermal plants, scaling, corrosion, artesian basin, geothermal resousces Austria, Bulgaria

INTRODUCTION

Thermal waters have widespread, but uneven distribution around the world. They are formed under different conditions and this directly affects their quantities, qualities and utilization. Based on information from 87 countries, a summary of the amount of geothermal energy used in the world is made [1]. The heat energy used in 2020 was 1,326.96 TJ/yr. In the last years the role of renewable energy sources has been increasing also in Bulgaria, but the utilization of the energy potential from thermal waters is still largely untapped. The main interest is directed to the hot waters formed in the fractured hydrothermal systems in Southern Bulgaria. During the joint work on the implementation of the Project "Scaling and corrosion in hydrogeothermal plants and wells in Austria and Bulgaria - a comparison", along with the main tasks, attention was paid to the similarities and differences in the use of geothermal energy.

The purpose of this study is to identify opportunities for using the experience of Austria in the exploration and operation of highly mineralized waters from aquifers in artesian basins, with respect to similar areas in Northern Bulgaria.

CONDITION AND USE OF GEOTHERMAL ENERGY IN BULGARIA

In Bulgaria, the formation of thermal waters is closely related to the geological-tectonic conditions. Rocks of different origin, lithologic and petrographic composition, ranging from Precambrian to Quaternary, are common on the territory of the country. Although there are different perceptions of the tectonic structure of the country [2, 3, 4, 5, 6], two radically different zones can be distinguished in its territory, predetermining different conditions for the formation of both fresh [7] and thermal waters [8, 9, 10] (Fig.1). The southern part of the country is entirely related to the Alpine-Himalayan orogeny, characterized by tectonic structure, with folded structures, imposed graben depressions, filled with Quaternary and

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Pliocene deposits with porous aquifers. Fissured and karst waters with active circulation are predominant. The presence of faults predetermine the formation of fissured water systems. Northern Bulgaria is located on the Moesian platform, which predetermines the formation of a large artesian structure, with storey-arranged aquifers, descending mainly in the north direction. Hydrodynamic, geothermal and hydrochemical patterns are observed with descending of aquifers in depth.

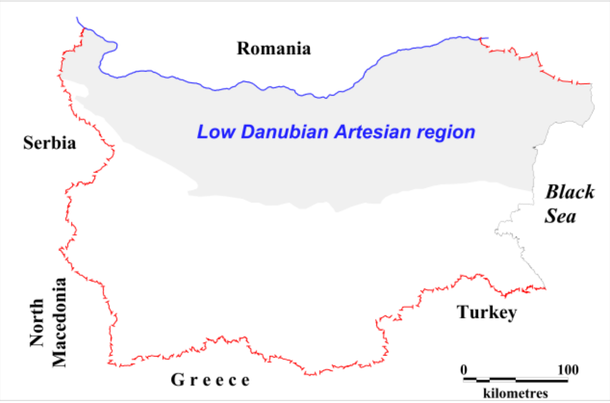

Fig.1. Distribution of the artesian waters in Bulgaria

The different geological-structural and hydrogeological conditions also have an impact on the distribution of the thermal field in the country - an important factor for the formation of thermal waters. According to [11, 12, 13, 14], with a high degree of certainty, one could assume an increase in the temperature at the same depth from north to south direction in Southern Bulgaria, and within the Moesian platform from west to east. Neotectonic activation, which greatly affected the Rhodope Mountains, was apparently related to mantle activity and the arrival of mantle asthenospheric materials from depth within the Earth's crust. This may explain the appearance of a number of anomalous points with heat flux values above 120 mW/m^2 and 440 mW/m^2, mainly due to hydrothermal activity at the mentioned points. In Northern Bulgaria aquifers of considerable thickness and wide area distribution play an important role in the distribution of the thermal field.

The nature of thermal water sources in Northern and Southern Bulgaria is different. In Northern Bulgaria, thermal aquifers are being revealed with a number of boreholes that have been drilled mainly for oil and gas exploration within the reach of the Low-Danube artesian basin. Their depth ranges from several hundred meters to more than 5,000 meters. The temperature of the waters depends on the depth of intersection of the respective aquifer, and in their deepest parts the temperature reaches over 100 °C [15]. Data from the chemical analysis of aquifers in northern Bulgaria have been published by Yovchev and Ryzhova (1962), Monakhova (1964, 1975) [16, 17, 18]. The values of the total dissolved solids (TDS) range from less than 1.0 g/l in the shallower parts of the aquifers to more than 150.0 g/l in their deepest parts.

In southern Bulgaria, thermal waters are attached to fissured-fractured confined groundwater systems. Their drainage is most often done by natural springs, but in the twentieth century a number of boreholes were drilled in the areas around the springs and in areas of supposedly not discharged on surface thermal waters. The depths of the wells are significantly smaller than in Northern Bulgaria, only in some cases they are up to 2000 m. The prevailing water temperatures are up to 60 °C, only in some cases they are above 70 °C. The highest temperature in southern Bulgaria is in Sapareva Banya where water with 103 °C is revealed. Thermal waters are fresh, predominating of those with a TDS below 1 g/l, and only in some cases -2-3 g/l.

The current state of thermal water exploitation in Bulgaria is reviewed by Hristov et al. 2019, Hristov, Gerginov, 2019 [19, 20]. Of all the existing thermal water fields and water sources, 102 are state-owned, the rest are provided for municipal management for a period of 25 years. About 72% of the total resources are with relatively low temperatures - up to 50 ºC on the surface. The flow rates of most exploited water sources vary from 1 l/s to 20 l/s, with a TDS below 1.0 g/l. Thermal waters in Northern Bulgaria with higher TDS are not exploited. Despite the relatively good hydrothermal capacity of 9957 TJ/year (2765,855 MWh), the use of thermal water is still only 25-30% of the total amount of renewable energy. The installed heat output increases from approximately 83.10 MWt in 2014 to 99.37 MWt in 2018.

CONDITION AND USE OF GEOTHERMAL ENERGY IN AUSTRIA

As in Bulgaria, the territory of Austria is characterized by rocks of different age, lithology and petrographic composition, which are in complex relationships with regard to its tectonic conditions [21]. The main regional structure is the Alpine-Himalayan orogeny, which occupies more than 3/4 of the country's territory. This is a typical folded structure built of various Mesozoic, Paleozoic and older rocks. Pre-mountain lowered sections are usually filled by molasses and flysch complexes. To the north and east, the mountain structures switch into the Vienna and Styrian basins, which are parts of the Middle Danube lowland. Hydrogeologically, three main structures are separated in Austria - the Eastern Alps, the Pre-Alpine basin and the Czech basin [22].

The Eastern Alps are characterized by the spread of fresh fissured and karst waters with intense circulation and good drainage conditions. At times, in some depressions, artesian basins with relatively higher water abundance are formed.

The Pre-Alpine basin is characterized by the presence of distinct smaller artesian basins (Molasse, Vienna, Styrian, Pannonian) with its characteristic storey-arranged aquifers. They are characterized by an increase in temperature and TDS in depth.

The Czech massif is relatively low water-abundant and is characterized by the presence of fissured waters in the weathered zones of the rocks.

As in Bulgaria, two main types of thermal water can be separated in Austria - those attached to fissured water systems (mainly in mountainous regions) and to layered aquifers in the artesian basins (Fig.2). A total of over 210 thermal and thermal mineral water fields have been identified [23].

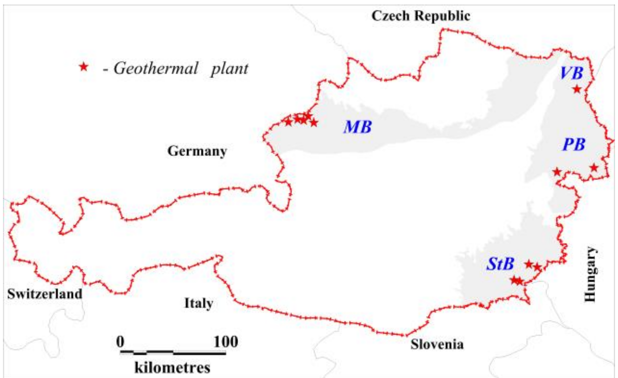

Fig.2. Distribution of artesian waters in Austria (MB - Molasse basin, VB - Vienna basin, PB - Pannonian/Danube basin, StB - Styrian basin)

Three major provinces could be separated:

- Acidic waters, attached to large tectonic disturbances in areas of relatively young magmatism located along the distribution of crystalline rocks and their eastern boundary with the Pre-Alpine basin - most of the known natural springs.

- The second group is mainly hydrocarbon thermal waters in the area of the youngest tectonic movements in the Alps.

- In the artesian basins, in the intermountain depressions and in the pre-alpine basin, highly-temperature and highly mineralized water reservoirs are formed.

In some parts of the Northern Limestone Alps, sodium and sulfate springs, attached to salt and gypsum deposits, are also presented.

Although there is a long tradition in the use of renewable energy in Austria, the share of geothermal heat production is estimated at around 1.6% [24]. Geothermal conditions in Austria are different across the Alpine region, on the one hand, and the main sedimentary basins, on the other. In the eastern part of Austria, increased heat flux densities above 100 mW/m^2 (Pannonian, Styrian basin) can be observed.

Local anomalies in the Molasse and Vienna basins are related to hydrothermal systems of local and regional importance. Inside the alpine orogen, the heat flux density is usually reduced due to the thickening of the Earth's crust. Particularly in the Northern Alps, the long-ranged infiltration systems for meteoric water lead to a further reduction in the heat flux density to below 50 mW/m^2. Natural springs with temperatures up to 46 °C are used for balneological purposes. The thermal waters of the Vienna and Styrian artesian basins are much more widely used.

The exploitation of natural thermal waters has a long tradition in Austria. The waters were used for balneology and recreation mainly. The use of thermal water as an energy source has been increasing since 2014 - in addition to the numerous resorts. Currently, 10 hydrogeothermal power plants are operating in Austria. They are located in the Molasse and Styrian basins, where the most favorable conditions for hydrogeothermal use in terms of heat flow, capacity of water-bearing structures and groundwater chemistry composition are presented. However, the water from these two regions is quite widely exploited and offer limited available resources - around 100 MWth according to Goldbrunner, Goetzl [24].

The exploitation of high mineralization thermal waters in artesian aquifers is associated with the processes of scaling and corrosion of pipes and installations [25, 26, 27, 28, 29, 30]. The water sources used have a temperature in the range of 39 to 115 °C, half of which are above 80 °C and are attached to artesian aquifers, some of which with very high TDS.

HYDROTHERMAL POWER PLANT ‘FRUTURA’ AT BIERBAUM AN DER SAFEN IN STYRIA

The waters with the highest temperature and mineralization that are used in Austria are those from the hydrothermal power plant ‘Frutura’ at Bierbaum an der Safen in Styria, which has started exploitation in 2016 (Fig.3). For the heating of greenhouses, a reinjection system of two boreholes was constructed in 2016 [24]. Initially, the boreholes were drilled for oil and gas exploration. The pumping well is 3,300 m deep, revealing the Malm-Valanginian aquifer. It pumps out water at a flow rate of 60 l/s with a temperature of 124.5 °C (the highest temperature so far of all geothermal wells in Austria). The water is Na-Cl type with a TDS of 78 g/l. The reinjection borehole is located at about 1800 m distance and so are the borehole heat exchangers. The currently installed heat output is 15 MWt, which is used for greenhouses. On some parts of the heat exchangers halite is deposited, which is periodically removed.

Pumping well

Reinjection borehole and hydrothermal power plant

Halite scaling on the borehole heat exchangers

Location (Goldbrunner, Goetzl, 2019).

Fig.3. Hydrothermal power plant ‘Frutura’ at Bierbaum an der Safen in Styria

STATE AND POSSIBILITIES OF USING HYDROTHERMAL ENERGY IN CENTRAL NORTHERN BULGARIA

Conditions for the formation of higher temperature thermal waters exist in northern Bulgaria within the reach of the Lower Danube artesian basin [8, 9, 10]. Water-bearing rock complexes have a wide surface area in horizontal direction and varying lithological composition and stratigraphic vertical range. Several aquifers are formed which are storey-arranged. The basin is characterized by hydrodynamic, hydrochemical and hydrogeothermic zoning, both vertically and horizontally [16]. In the aquifer recharge zones, the waters are fresh, with active water exchange and low temperature. In depth, the temperature gradually increases, the type of their chemical and gas composition changes.

With the largest area distribution and importance is the Upper Jurassic-Lower Cretaceous aquifer. It is attached to a thick carbonate complex, where the rocks, including in depth being cracked and unevenly karstified [31]. In the southern parts, there is a gradual transition of carbonate to flysch sediments, which also changes their collector properties. The aquifer is hardly outcropped on the surface, except for some spots directly or under a thin quaternary cover in the highest, crest parts of the North Bulgarian vault (Northeastern Bulgaria). From there, the carbonate rocks descend in depth in all directions. To the East, towards the Black Sea and south of the North Bulgarian vault- in the Varna Depression, the Upper Jurassic - Lower Cretaceous aquifer descends from its recharge area (in the outcrops in the North Bulgarian vault) to the west and south.

The waters are cold in the recharge zone and increase their temperature up to 30-55 °C along the Black Sea Coast The predominant TDS of thermal waters is in the range of 0.4-0.8 g/l, where only at the Northern Black Sea waters with TDS of 1-4 g/l are present. To the West, as the aquifer descends, the temperature gradually increases, reaching more than 100 °C in the deepest western parts. At the same time, the TDS increases, reaching values of few dozens of g/l.

The object of the present study is the part of the Upper Jurassic-Lower Cretaceous aquifer, located in Central Northern Bulgaria, in the zones where the temperature increases and there would be relatively more potential consumers of geothermal energy.

The area under consideration is about 8000 km^2, with the Iskar River as western; the Danube River as northern; the Yangtara River as eastern; and the tectonic boundary separating the Moesian Platform as southern boundary. The basic information about its the geological, hydrogeological and geothermal conditions was used during the prospecting for oil and gas, summarized in 1983 in the monograph "Geology and oil and gas perspectives of the Moesian Platform in Central North Bulgaria” under the editorship of A. Atanasov and P. Bokov [32].

The predominant thickness of the water-bearing rocks is 700 - 900 m, which in the South increases to 1500 m, and then sharply decreases due to the transition of the rocks from carbonate to flysch facies. The aquifer lies on the Middle-Jurassic aquitard or the Lower-Middle- Jurassic aquifer complex and is covered by the Lower Creatious aquitard complex. The relief at the top of the aquifer (Fig.4) in its north-eastern parts is relatively smooth, but smaller structures with positive and negative character are observed (elevation of its top -700 - -1300 m a.s.l.). In the Southwest, a gradual descending is observed, with a maximum depth of over 3000 m. The horizon is characterized by filtration heterogeneity, with values of conductivity varying from about 40 to over 3000 m^2/d, with a decrease in values with the aquifer descending from the east to the west. The waters of the aquifer are confined and in most cases the water level is below the terrain. The temperature of the waters increases in depth, ranging from below 40° to 100 °C (Fig.4). The geothermal gradient within the aquifer, due to its high water abundance, is low - from 1 to 2°/100 m. Only in the deepest parts of the horizon, where the water exchange is slow, the gradient is above 2.5°/100 m. The aquifer is characterized by slightly salty to salty thermal waters with a tendency to increase in the TDS from north-northeast to south-southwest [33]. The lowest value of TDS is 1.55 g/l and the highest - 22.3 g/l (Fig.5). The hydrogen index is in the range of 6 to 10, with predominant values between 7 and 8. The predominant types of water are chloride-sulphate-sodium-calcium and chloride-sulphate-sodium. In the west, with depth, the water changes into sodium chloride type.

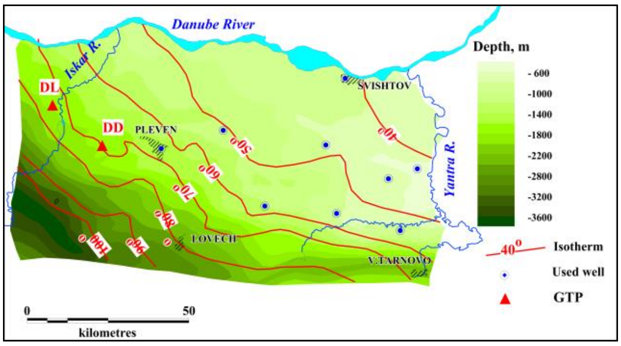

Fig.4. Map of temperatures in depth of the upper part of the Upper Jurassic-Lower Cretaceous aquifer and locations of used in the past boreholes and geothermal plants (GTP): DD - Dolni dabnik, DL – Dolni Lukovit

DISCUSSION

The conducted analysis of the quantities and qualities of thermal waters in Central Northern Bulgaria, as well as their thermal energy, show that there are possibilities for their use in the area. Unfortunately, this potential is hardly utilized.

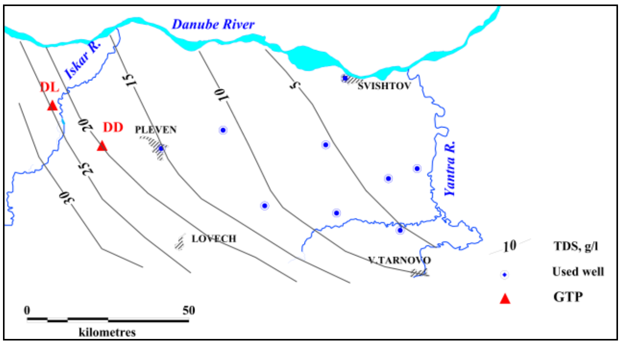

Fig.5. Map of TDS distribution of the Upper Jurassic-Lower Cretaceous aquifer and locations of used in the past boreholes and geothermal plants (GTP): DD - Dolni dabnik, DL – Dolni Lukovit

In the past and at present time for balneology, greenhouses, hygienic needs and heating, only thermal waters from some single wells, located in the eastern, shallower part of the aquifer have been used. Their temperature varies from 44 to 58 °C and have TDS from 2.8 to 12 g/l. In the 1990s, tests in the western part of the aquifer were conducted to evaluate the possibility of using geothermal energy in several sections. Subsequently, two geothermal plants were built, which operated for a short period - from 1987 to 1989. The geothermal plant in Dolni Dabnik was designed in 1986. For this purpose, a pumping well was used, which reveals thermal water with temperatures of 70-71 °C in the Upper Jurassic/ Lower Cretaceous aquifer in the interval 1794 - 2693 m. The re-injection of 8 °C cooled water was carried out in a well, located at a distance of 1750 m, revealing the same aquifer in the range 1808 - 2705 m. A backup injection well at a distance of 1270 m was also planned. The plant was equipped with iron heat exchangers, but it was intended to replace them with titanium. The plant's design capacity was around 30 l/s, but due to the change in its political and economic status during its operation in Bulgaria, which led to a significant decrease in energy consumers. Initially, 8 l/s were used for the heating of administrative buildings, and later its operation was canceled and the buildings and facilities were abandoned. The situation with the other geothermal plant - near the village of Dolni Lukovit is similar. The designed flow rate was 7 l/s, with a temperature drop of 13 °C (from 66 °C to 53°C). At present, the plant is also not fully used and only operates during the colder months for heating of buildings. The distance between the pumping well and the injection wells was 5 km. In both plants there were problems with scaling.

The examples given above, as well as the experience of Austria, show that the Upper Jurassic/-Lower Cretaceous aquifer in the studied area is promising for the use of geothermal energy. An indicative regional assessment of the aquifer's thermal energy was made, according to the methodologies given by Galabov [34].

At a natural resource of the aquifer of 1380 l/s, with a reduction of the temperature up to 40 °C, the heat output amount is 115 MW_{th} and up to 15 °C - 259 MW_{th}. With the use of re-injection, the energy potential is significantly higher. For its estimation, a representative area around the town of Pleven, with an area of 1600 km^2, was selected. The choice is based, on one hand, that there are potential energy users in the area and, on the other, the suitable geological, hydrogeological and geothermal conditions. In the area under consideration, the upper part of the Upper Jurassic-Lower Cretaceous aquifer is at absolute elevations between -1200 and -2500 m, at an average thickness of about 1000 m, the water level is at an average depth of 120 - 125 m and the conductivity is about 40 m^2/d. The water temperature in the upper part of the horizon is between 60 and 90 °C, and in the lower part with 10-20 °C higher. The TDS is in the range of 10 to 25 g/l. The estimated calculations were conducted at a temperature drop of 30 °C according to the following scheme: 800 thermocouples were evenly located over the area under consideration, with an estimated operating flow rates of each pumping well of 10 l/s with groundwater table decline of about 13 m. The estimated value for the heat capacity is 1000 MW_{th}.

CONCLUSIONS

Although geothermal energy is not being sufficiently utilized in Austria, there are positive trends in its use, including the construction of a number of new hydrogeothermal plants, including in the artesian basins, where significant amounts of high-temperature groundwater bodies are present. Serious studies have focused on the processes that hinder the exploitation of geothermal energy. A review of the hydrogeological and geothermal conditions in Bulgaria shows that Austria's positive experience can be applied, especially in Northern Bulgaria. This is confirmed by the use of thermal and mineral waters in the past. For example, in Central Northern Bulgaria, only about 35-40 l/s of thermal water was used for heating and balneology in the late 1980s, while at present these quantities are minimal, mainly only for hygienic purposes and partially for balneology. Unfortunately, the existing and efficiency proven geothermal power plants at Dolni Dabnik and Dolni Lukovit, have been abandoned. In this respect, it would be useful for the administrative authorities and businesses to be aware of the possibilities of optimal utilization and use of this renewable energy potential.

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