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A METHOD TO EVALUATE THE PERFORMANCE OF AN OPEN LOOP GEOTHERMAL SYSTEM FOR MINE WATER HEAT RECOVERY

Purpose. To develop a method to evaluate hydrodynamic and thermal parameters of an open loop geothermal system with the discharge into surface water bodies as well as to test the method under real site conditions considering different technology options, geotechnical and thermodynamic factors.

Methodology. We employed the relations of hydraulics and thermodynamics, performed an engineering review of open loop geothermal systems for mine water heat recovery, studied hydrodynamic and mining conditions of the colliery "Novohrodivska" No. 2. The developed technique includes evaluating the temperature of rocks around flooded workings, the length of the hydraulic path and flow resistance of workings.

Findings. The evaluated temperature of mine water entering on-ground heat exchangers ranges at 17.8 ± 0.25 °C, and the system thermal output is 1070 ± 21 kW. Water temperature in flooded workings due to dilution with infiltration during the operation period of 25 years is expected to fall by 0.6–1.0 °C, which decreases the thermal output by 5.6–8.3 %. The estimated cooling of water during its rise in the shaft does not exceed 1 °C. The criterion of the geothermal system energy efficiency decreases from 1.8 when pumping close to the mine water level to 1.05 when pumping 460 m below the ground; the heat pump coefficient of performance (COP) reaches 5.0.

Originality. The flow characteristics and hydraulic flow lengths at different horizons, the temperature of rocks around workings were found to be the dominant factors for the thermal output under steady flow. The pumping depth was proved to significantly affect the energy efficiency of the system.

Practical value. The proposed method allows quantifying the energy criterion of an open loop geothermal system with the discharge into surface watercourses, which enables optimizing system performance indicators.

Keywords: *mine water, geothermal systems, thermal flux, hydraulic model, thermal capacity*

Introduction. In line with the UN Sustainable Development Goals, coal consumption is currently declining in many countries, which is accompanied by mine closure. Following the global trends, Ukraine intends to abandon many thermal power plants, with reducing coal production. Under these conditions, the sustainable use of energy resources of closed mines with the ongoing environment restoration of post-coalmining areas becomes highly important.

Mine water heat recovery in flooded workings is getting more widespread in former coalmining areas in Europe and the USA within the global transition to "green energy". By 2018, 28 geothermal systems were under operation at closed mines around the world at a thermal output of 0.35–4.6 MW; a large number of facilities have been installed in the Ruhr area of Germany [1, 2].

In Ukraine, there are still single examples of mine water heat recovery for heating and hot water supply [3]. The system of heat recovery from mine water has been installed at the colliery "Blahodatna" in the Western Donbas under scientific and technical support of Dnipro University of Technology in early 2011. It uses water at a temperature of up to 17 °C with a flow rate of up to 200 m^3/h and reaches a thermal output of 0.8 MW, thus, saving fossil fuel at the cost equivalent to tens of thousands of US dollars annually [4, 5].

Overview of existing technologies. Existing open loop geothermal systems [2, 6] include pumping mine water to recover heat on the ground followed by the discharge of thermally used water into: a) surface watercourses, b) settling ponds; c) wells, d) shafts, e) horizontal workings that crop out the surface.

The most common of these systems provide for the discharge into surface watercourses (case "a"), with water being withdrawn from the flooded mine through the shaft and delivered further to the on-ground heat exchanger connected to the heat pump [7]. After heat recovery, mine water is discharged into surface water bodies, mostly after treatment. The examples of such system are the shaft of the Barredo colliery in Mieres, Asturias, northern Spain [8], where water quality is acceptable and there is no need for treatment, and the Kephaus colliery in Yorkshire, UK [9], where heat is recovered before water treatment. However, open loop systems often require additional costs for cleaning the pumps, pipelines and heat exchangers from solid sludge appearing due to chemical reactions with iron hydroxides or manganese oxides [10].

Because of required pumping to maintain a hydrodynamically safe mine water level across the post-mining areas, these systems became quite widespread. In some cases, pumping from the shaft maintains the safe level also in neighboring active or closed mines, hydraulically connected to the drained one. Thus, the energy spent on mine dewatering may not be formally included in the cost balance while assessing such system performance.

For these reasons, geothermal systems with discharge into surface water bodies under the conditions of the Donbas can be recommended for the collieries with low water salinity to reduce treatment costs and minimize the environmental impact, and for those that drain also neighboring underground workings and adjacent areas.

The systems with the discharge into settling ponds (case "b") recover heat with the exchangers installed directly in the pond. In this case, the circulating fluid recovers heat energy from the pond water. This system's advantage is the large low-grade heat resource available in the pond during the summer. However, heat recovery from the pond becomes ineffective under low ambient temperatures in the winter season, as well as due to additional energy costs for on-ground water transportation to the settling pond. Thus, under the climate conditions of the Donbas such systems can be efficient only during the summer period at the mines with closely located settling ponds.

If the discharge into surface water bodies is not permitted due to environmental constraints such as exceeding the sanitary limits of toxic compounds, the pumped water can be re-injected through wells after thermal use back to the underground workinhgs (case "c"). On the one hand, water resources are not depleted, water and salt balances are maintained, treatment and disposal costs are minimized. On the other hand, this requires drilling and maintenance of back-injection wells and creates the risk of thermal "short circuit" between the pumping and discharge points if reinjected water is heated insufficiently before withdrawal. Such schemes have been installed near the cities of Shettleston, Glasgow, Lumfinance, Fife in Scotland (the United Kingdom) [11] and Heerlen in the Netherlands [1, 2]. Under the the conditions of the Donbas, these systems can be recommended for the collieries with additional shafts or big diameter wells for reinjecting thermally used water; underground workings must be hydraulically connected with the main shaft to provide heating water along its underground flow path.

The systems with reverse discharge to the same shaft (case "d") recover heat from surrounding rocks along the circulation path. In this case, the costs to transport thermally used water are significantly reduced; however, such a system has several technical constrains associated with water volume in the shaft and the flowpath length sufficient to heat the discharged cooled water. This system application under the conditions of the Donbas can be recommended for the collieries with low drainage flow rate, the considerable zone of flooding and a high geothermal gradient.

The systems with reverse discharge into horizontal workings (case "e") deliver thermally used water into the shaft with the installed pump. As opposed to case "d", water does not move down in the shaft, instead, it flows through an upper horizontal gallery, which crops out near the watercourse. In the same vein as in case "d", the costs of cooled water transportation can be significantly reduced. Due to the undulating topography with flat inter-river valleys on most of the Donbas area, the collieries with such underground geometry and workings are of quite limited distribution and more typical of mountainous areas.

All reviewed systems can be installed in closed mines of the Donbas only after detailed feasibility studies including the balance of the produced heat energy and electricity cost needed for running heat pumps and water circulation. In cases "a" and "b" without direct reinjection to the mine the hydrogeological constrains (maintaining a safe mine water level below the bottom of upper aquifers used for drinking water supply) should also be taken into account in system performance and environmental impact assessments. The circulation rate for the systems with reverse discharge (cases "c" through "e") can be optimized considering the demand on thermal energy among local consumers.

Hydraulic and thermal parameters of geothermal systems can be evaluated by special software (COMSOL Multiphysics, Pipe Flow) [12, 13]; however, numerical models often run across computational difficulties in modeling heat transfer under coupled hydraulic flow and seepage in mined out rocks. A simpler analytical model may turn to be a good alternative to sophisticated tools that require very detailed data and high qualification of users.

Purpose. Since open loop geothermal systems with discharge into surface water bodies are very common and allow maintaining a safe mine water level, this study aims to develop an analytical method to evaluate hydraulic and thermal parameters of these systems' performance and test the method under conditions of the real site considering different technology options, geotechnical and thermodynamic factors.

Hydraulic and thermal model. We assume that before the operation begins, a certain water level has come to stay in the shaft at the elevation below the local erosion base, which is in line with applicable regulations and enables preventing from waterlogging of soils (Fig. 1).

The pump is installed in the shaft, water moves to the on-ground heat exchanger where heat is recovered and then used for heating buildings, greenhouses, pools located nearby, hot water supply, and for other needs. Thermally used water is, generally, subject to treatment followed by the discharge to streams and rivers.

As a result of pumping from the shaft, the mine water level sinks, with forming a drawdowns area around the hydraulically connected workings. Pumped warm water from flooded workings is gradually diluted with colder infiltration seeking from the upper strata. Simultaneously, colder water entering the workings is gradually heated by geothermal flux depending on the contact surface "rocks – mine water". Groundwater within the mining area is mainly recharged due to infiltration and partly the inflow from neighboring mines. Therefore, the rate of pumping from the shaft should slightly exceed the infiltration inflow plus horizontal inflows to prevent from flooding. The water level in the flooded mine is assumed to have come to stay before geothermal system operation begins.

We consider a hydraulically isolated mine, with negligeable inflows from neighboring mines through weakly permeable pillars. Then, the water level in the shaft is calculated based on the balance equation written for the mine

$$Q_{gw}+Q_{mw}+Q_{\inf}-Q_0=\frac{\omega_{sh}\Delta H_{sh}}{\Delta t}, \quad (1)$$

where Q_0 is the pumping rate, m^3/d; Q_{gw} is the groundwater inflow from the upper aquifer, m^3/d; Q_{mw} is the inflow from

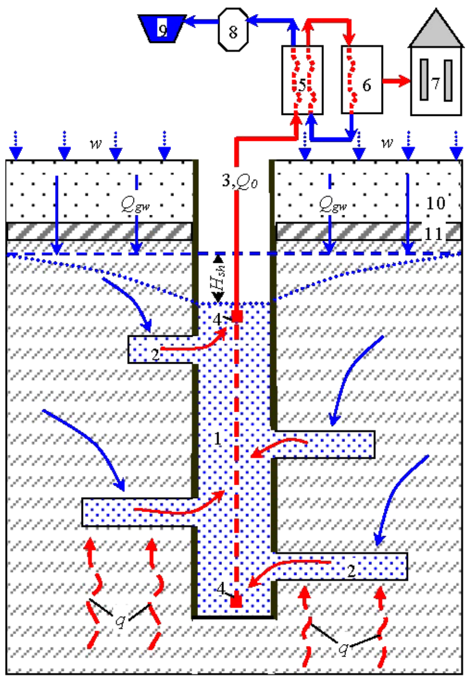

Fig. 1. Design of an open loop geothermal system with mine water discharge into surface water bodies:

1 – shaft; 2 – flooded workings; 3 – pipe for mine water transportation; 4 – pump locations in the shaft; 5 – heat exchanger; 6 – heat pump; 7 – thermal energy consumer; 8 – treatment facilities; 9 – surface watercourse; 10 – upper free flow aquifer; 11 – aquitard; w – infiltration; H_{sh} – change in water level in the shaft; q – geothermal flux; Q_0 – discharge from the shaft; Q_{gw} – groundwater inflow from the upper aquifer to the shaft flooded workings to the shaft, m^3/d; Q_{inf} is the infiltration inflow from the mining area, m^3/d; ΔH_{sh} is the change of the level H_{sh} in the shaft during the time interval Δt, m; ω_{sh} is the cross-sectional area of the shaft, m^2.

Regarding sufficient hydraulic permeability of the shaft casing, the groundwater inflow from the upper free flow aquifer can be estimated by the formula

$$Q_{gw} = \pi K_f \frac{\left(H_{Rm} - z_b\right)^2 - \left(H_{sh} - z_b\right)^2}{\ln\left(R_m / r_{sh}\right)},$$

where K_f is the aquifer conductivity, m/d; H_{sh} is the water level in the shaft, m; H_{Rm} is the groundwater level at the outer boundary of the draining zone of the shaft, simulated as a single well, m; z_b is the bottom level of the aquifer, m; R_m is the radius of the draining zone of the shaft in the upper aquifer, m; r_{sh} is the shaft radius, m. The radius of the draining zone R_m can be estimated by the formulas of Kusakin or Siehard [14].

The infiltration inflow is evaluated as

$$Q_{inf} = S_m w_{inf},$$

where w_{inf} is the infiltration rate or conductivity of the aquitard under the free flow aquifer, m/d.

The mine water inflow to the shaft through the layered stratum can be evaluated by Kamensky's formula [15]

$$Q_{mw} = 2\pi \sum_{i=1}^{n} K_{w,i} m_{w,i} \frac{H_{Rm} - H_{sh}}{\ln\left(R_m / r_{sh}\right)},$$

where $K_{w,i}$ is the conductivity of the i^{th} layer, m/d; $m_{w,i}$ is its thickness, m.

The water level in the shaft is dynamically stabilized when the withdrawal becomes equal to the inflow from workings being filled with infiltration and water from neighboring mines. In calculations by (1), the maximum possible drawdown in the shaft $\Delta H_{sh,\max}$ and the change in the level due to inflow from adits and infiltration ΔH_{miw} over a period Δt is calculated as follows

$$\Delta H_{sh,\max} = \frac{Q_0 \Delta t}{\omega_{sh}}; \quad \Delta H_{mw} = \frac{\left(Q_{mw} + Q_{\inf}\right)\Delta t}{\omega_{sh}}.$$

With increasing drawdown, ΔH_{mw} grows up to a limit $\Delta H_{sh,\max}$. Then, the water table fluctuates at an elevation $H_{st,0}$, and the withdrawal is balanced by the inflows from the adits.

Since water at different mining horizons has different temperatures, it is necessary to consider the relationship between the inflows to the shaft from the workings located at different depths.

We consider the withdrawal at a constant flow rate from the shaft connected to the workings from two mining horizons (Fig. 2). Hydraulic flow in case of o three or more mining horizons is modelled similarly.

The inflows from the adits connected to the mining horizons "1" and "2" can be calculated based on the equations governing pressure loss along underground workings. Following this approach, the workings are interpreted as large diameter pipes, with the flow being governed by the hydraulic equations written for a complex open pipeline network [16].

The estimated average flow velocity in workings at the pumping rate Q_{mw} of a few thousand m^3/d does not exceed a few mm/s so that the velocity head below 10^{-6} m can be neglected. We also assume that water in all flooded kings is in hydrostatic equilibrium under almost the same pressure.

For two adits three potential positions of the pumping point can be considered assuming

$$Q_{mw} = Q_1 + Q_2. \tag{2}$$

Case "a": the pumping point is positioned above the upper adit ($z_p > z_1 > z_2$). The pressure loss equation is derived from the system

$$\begin{cases} \dfrac{Q_{mw}^2}{K_{sh}^2} l_{1p} + \dfrac{Q_1^2}{K_1^2} L_1 = \Delta z_1 \\ \dfrac{Q_{mw}^2}{K_{sh}^2} l_{1p} + \dfrac{Q_2^2}{K_{sh}^2} \Delta z + \dfrac{Q_2^2}{K_2^2} L_2 = \Delta z_2 \end{cases}, \tag{3}$$

where K_{sh} is the discharge characteristic of hydraulic flow in the shaft, m^3/d; K_1 and K_2 are the discharge characteristics of hydraulic flow in horizons "1" and "2", respectively, m^3/d; $l_{1p} = |z_p - z_1|$ is the distance between the pumping point to the adit that passes water from workings of horizon "1", m; $\Delta z = z_2 - z_1$ is the distance between adits "1" and "2", m; Δz_1, Δz_2 are pressure head differences between the pumping point and the far ends of workings of horizons "1" and "2", m.

Simplifying (3), we derive the quadratic equation with respect to Q_2

$$\frac{\left(Q_{mw} - Q_2\right)^2}{K_1^2} L_1 = Q_2^2 \left(\frac{\Delta z}{K_{sh}^2} + \frac{L_2}{K_2^2}\right). \tag{4}$$

Solving (4) together with (2), we first find Q_2 and then the inflow Q_1 from horizon "1".

Case "b": the pumping point is positioned between the upper and lower adits ($z_1 > z_p > z_2$). In a similar way we derive the equation

$$\left(Q_{mw} - Q_2\right)^2 \left(\frac{l_{1p}}{K_{sh}^2} + \frac{L_1}{K_1^2}\right) = Q_2^2 \left(\frac{l_{2p}}{K_{sh}^2} + \frac{L_2}{K_2^2}\right). \tag{5}$$

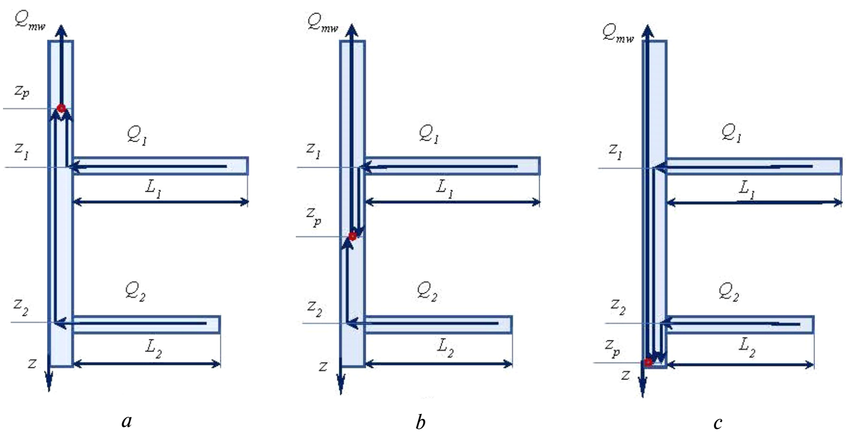

Fig. 2. Options for positioning the pump in the shaft at the depth z_p:

$a - z_p > z_1 > z_2$, $b - z_1 > z_p > z_2$, $c - z_1 > z_2 > z_p$. Flow directions are shown by arrows, the red dot is the pumping point (place of water withdrawal). Notation: Q_1, Q_2 are inflows from adits "1" and "2", m^3/s; z_1, z_2 the elevations of adits "1" and "2", m; z_p the elevations of the pumping point, m; L_1, L_2 the average lengths of hydraulic flow in adits "1" and "2", m

Solving (5), we find the inflow from the lower adit Q_2, and then Q_1. Here $l_{2p} = |z_p - z_2|$ is the distance between the pumping point to the adit passing water from horizon "2", m.

Case "c": the pumping point is positioned below the lower adit ($z_1 > z_2 > z_p$). Similarly to case "a" we derive and solve the equation governing hydraulic flow through the workings of two horizons

$$\left(Q_{mw} - Q_2\right)^2 \left(\frac{\Delta z}{K_{sh}^2} + \frac{L_1}{K_1^2}\right) = Q_2^2 \frac{L_2}{K_2^2}. \quad (6)$$

The discharge characteristics of hydraulic flow can be calculated as follows [16]

$$K_{sh} = C_{sh}\omega_{sh}\sqrt{R_{sh,h}}; \quad K_1 = C_1\omega_1\sqrt{R_{1,h}}; \quad K_2 = C_2\omega_2\sqrt{R_{2,h}}, \quad (7)$$

where C_{sh}, C_1, C_2 are Chezy coefficients for the shaft and workings, $m^{0.5}/s$; ω_1, ω_2 are the average cross-sectional areas of workings, m^2; $R_{sh,h}$, $R_{1,h}$, $R_{2,h}$ are the hydraulic radius of the shaft and the average hydraulic radii of workings, m; here "1" and "2" refer to horizons "1" and "2".

The Chezy coefficient for hydraulic flow in pipes can be calculated [16] as

$$C = \sqrt{8g/\lambda},$$

where λ is the dimensionless coefficient for pipes evaluated as $\lambda = 64/\mathrm{Re}$ for laminar flow with Re as the Reynolds' number; empirical formulas proposed for λ in case of transient and turbulent flow can be found, for example, in [17].

If the detailed data on geometry of underground workings within different depth intervals, excavation volumes and their distribution by cross-sectional area are available, (4–7) can be refined by representing flooded workings as a branched open network of complex pipelines with varying discharge characteristics at different sections.

Hydraulic flow in workings while pumping becomes stable at a constant flow rate within a few days. For example, at $Q_{mw} = 2000\ m^3/d$, the average flow velocity in the shaft of a diameter of up to 6 m reaches about 70 m/day. At this velocity, the temperature in the mixing zone of the shaft of up to 400 m becomes almost stable in 5–7 days; in addition, the volume of water in the shaft is replaced in 3–10 days. Therefore, in the case of constancy of the flow rate Q_0 the inflows from two mining horizons Q_1 and Q_2 can be assumed constant, and the temperature of water pumped can be calculated by the formula of mixing

$$T_{mw,p} = \frac{T_{mw,1}Q_1 + T_{mw,2}Q_2 + T_{gw}Q_{gw}}{Q_1 + Q_2 + Q_{gw}},$$

where $T_{mw,1}$, $T_{mw,2}$ are temperatures of water flowing from thehorizons "1" and "2", °C; T_{gw} is the water temperature in the upper aquifer, °C.

The value of $T_{mw,p}$ can be refined considering heat exchange with surrounding rocks [18].

The values of $T_{mw,1}$ and $T_{mw,2}$ are calculated under the assumption that water within the entire volume of underground voids is constantly diluted with seeking down colder infiltration, alongside with that being heated by geothermal flux from below.

Water circulation in a hydraulically isolated mine is driven by the infiltration inflow from above to flooded workings and the outflow due to pumping. The equation of heat balance in workings of a mining horizon for such a circulation can be written as

$$q_{gth,i} - q_{in,i} - q_{out,i} = C_{w,i}\rho_{w,i}V_{w,i}\frac{\Delta T_{mw,i}}{\Delta t}, \quad i = 1, 2,$$

where $q_{gth,i}$ is geothermal heat flux from below to the workings of the mining horizon "i", W; $q_{in,i}$ is the heat loss due to the inflow with a lower temperature from above to flooded workings of the mining horizon "i", W; $q_{out,i}$ is he heat flux to the shaft from the flooded workings of the mining horizon "i" during circulation, W; C_w and ρ_w are heat capacity and density of water, thatwhich are calculated by average salinity and temperature in workings of the mining horizon "i", J/(kg · K) and kg/m^3 [19]; $\Delta T_{mw,i}$ is the change in the average water temperature in workings of the mining horizon "i" over a period of time Δt, °C.

Deep heat flux to the workings can be estimated as

$$q_{gth,i} = S_{hw,i}G_E,$$

where $S_{hw,i}$ is the horizontal alignment of workings of the mining horizon "i", m^2; G_E is the specific geothermal flux, W/m^2.

The horizontal alignment of workings can be estimated based on available mining maps as the product of the total length of workings and their average width. This value can be refined by grouping the workings in terms of geometry into different types with individual average sizes and cross-sectional areas.

The values $S_{hw,i}$ can be increased by 5–10 % to take into account the heat transfer from the layers of rocks around the workings outside the horizontal alignment.

Heat loss in the mining horizon "i" due to the inflow of colder water can be calculated as

$$q_{in,i} = Q_iC_{w,i}\rho_{w,i}(T_{in,i} - T_{mw,i}), \quad (8)$$

where $T_{in,i}$ is the temperature of inflowing water, °C; $C_{w,i}$ and $\rho_{w,i}$ are evaluated at the temperature $T_{in,i}$.

The value of $T_{in,i}$ can be approximately defined as the temperature of rocks T_r on the top of the mining horizon "i" at $z = z_{i,t}$, $T_{in,i} = T_r(z_{i,t})$, and the temperature T_r at a depth z can be evaluated by the equation

$$T_r(z) = T_{nl} + \Gamma(z_{nl} - z), \quad (9)$$

where T_{nl} is the soil/rock temperature at the depth of the so-called neutral layer, below which the annual fluctuations can be neglected, °C; z_{nl} is the absolute elevation of the neutral layer top, m; Γ is the geothermal gradient, °C/m.

The heat flux from workings to the shaft is calculated by the formula

$$q_{out,i} = Q_{mw,i}C_{w,i}\rho_{w,i}(T_{mw,i} - T_{sh,wa}), \quad (10)$$

where $T_{sh,wa}$ is the average water temperature in the shaft, °C; $C_{w,i}$ and $\rho_{w,i}$ are evaluated at the temperature $T_{mw,i}$.

The temperature change of mine water ΔT_{mw} when it moves to the surface is calculated by the formula

$$\Delta T_{mw} = \Delta T_{mw,sh} + \Delta T_{mw,pw} + \Delta T_{mw,pa},$$

where $\Delta T_{mw,sh}$ is the change in temperature of water flowing up in the shaft to the pumping point, caused by heat exchange through casing with surrounding rocks, °C; $\Delta T_{mw,pw}$ and $\Delta T_{mw,pa}$ are the changes in temperature of water moving in the pipe to the surface along the interval with the contact to mine water outside and air, respectively, °C.

These values are calculated by the formulas

$$\Delta T_{mw,sh} = \frac{q_{sh}}{C_{w,sh}\rho_{w,sh}Q_0}; \quad \Delta T_{mw,pw} = \frac{q_{pw}}{C_{w,pw}\rho_{w,pw}Q_0}; \quad \Delta T_{mw,pa} = \frac{q_{pa}}{C_{w,pa}\rho_{w,pa}Q_0}, \quad (11)$$

where heat capacity C_w and water density ρ_w are evaluated at appropriate temperatures; the heat fluxes are calculated as

$$q_{sh} = \frac{T_{mw,sh} - T_{r,sh}}{R_{\Sigma,sh}}L_{sh}; \quad q_{pw} = \frac{T_{w,pw} - T_{mw,sh}}{R_{\Sigma,pw}}L_{p,w}; \quad q_{pa} = \frac{T_{w,pa} - T_{a,sh}}{R_{\Sigma,pa}}L_{p,a}, \quad (12)$$

where $T_{mw,sh}$ and $T_{r,sh}$ are the average temperatures of water in the shaft and the rocks around it between the deepest working horizon and the pumping point, °C; $T_{w,pw}$ and $T_{w,pa}$ are the average temperature of water in the pipe, through which it moves to the surface along the interval with the contact to mine water and air outside, respectively, °C; $R_{\Sigma,sh}$ is the total thermal resistance of heat transfer from water to surrounding rocks through the shaft casing, m·K/W; $R_{\Sigma,pw}$ and $R_{\Sigma,pa}$ are the total thermal resistance of heat transfer from the pipe to the water and air in the shaft, respectively, m · K/W

$$L_{sh} = z_p - z_2; \quad L_{p,w} = z_{mwl} - z_p; \quad L_{p,a} = z_s - z_{mwl},$$

where z_{mwl} is the mine water table elevation, m; z_s the ground surface elevation, m.

Thermal resistances in (12) can be calculated following the method outlined in [19]. A more detailed assessment of heat loss during the transportation of warm water can be made using convective heat transfer models discussed in [18].

The maximum thermal output of a geothermal system q_{gts} and the heat loss Δq_{gts} are calculated with the account for cooling during water transportation to the surface by the formulas

$$q_{gts} = Q_0 C_w \rho_w (T_{mw,p} - \Delta T_{mw,sh} - \Delta T_{mw,pw} - \Delta T_{mw,pa} - T_{\min}); \quad (13)$$

$$\Delta q_{gts} = Q_0 C_w \rho_w (\Delta T_{mw,sh} + \Delta T_{mw,pw} + \Delta T_{mw,pa}). \quad (14)$$

Eqs. (8, 10, 11, 13, 14) account for the changes in density and heat capacity of water depending on its temperature and salinity.

To assess the geothermal system's energy efficiency, it is necessary to calculate the balance between the energy spent and the produced thermal energy. This can be done using the energy criterion ξ_E proposed by the authors in [20], thatwhich is defined as the ratio between the thermal energy recovered, considering heat losses during water transportation and the thermal equivalent of electricity needed for circulation and energy conversion. This criterion enables optimizing the system performance parameters.

The electricity consumed by the open-loop geothermal system is calculated based on the flow rate and depth, water density, and pump parameters. The energy for heat conversion is calculated by dividing the system thermal output by the coefficient of performance (COP) that depends on the temperature of mine water and the heat transfer fluid circulating in the heating system. The thermal equivalent of the total electric power is calculated by dividing the electrical energy by the thermal power plant efficiency [20].

Results. We tested the developed method under the conditions of the colliery "Novohrodivska" No. 2 situated in the Krasnoarmeyskiy (Pokrovskyi) coal district of the Donetsk region. According to the geological zoning, it belongs to the Donetsk coalmining area and is located within the Krasnoarmeyskiy monocline disturbed by the branches of Novohrodivskyi throw and Selidov thrust as local tectonic structures.

The colliery was put into operation in 1951 to process coal seams k_8 and l_1. It is vertical and isolated; it borders in the north with Novohrodivskyi throw No. 1 that separates the studied colliery from the colliery "Novohrodivska" Nos. 1–3; in the west it borders with the bed outcropping of the k_8 seam under Paleogene-Neogene sediments; in the east it borders with hypsometric contour of the k_8 seam at –350 m a.s.l. The mining operations along the seam k_8 and l_1 reached the depth of 575 m (–370.3 m a.s.l.). There are no reported hydraulic connections with adjacent mines in the flooded strata; the average inflow to the colliery during 1999–2006 fluctuated at 280 m^3/h.

The suggested design of the open loop geothermal system with the discharge into surface watercourses at the colliery "Novohrodivska" No. 2 meets the design shown in Fig. 1. The input data are brought together in Table 1.

We compared two options of positioning the pump: 1) close to the water table above horizon "1" (Fig. 2, *a*); 2) 5 m below the adit connected to horizon "2" (Fig. 2, *c*).

According to groundwater flow calculations, the inflow from the upper aquifer Q_{gw} is estimated at 120.76 m^3/d, the mine water inflow Q_{mw} = 1879.24 m^3/d; the mine water level will slightly fluctuate at z_{mwl} = +176.5 m when pumping. Considering (9) we estimated the average water temperature in the upper aquifer T_{gw} at 10.35 °C, in horizons "1" and "2" before pumping $T_{mw,1}$ = 15.85 °C and $T_{mw,2}$ = 21.85 °C.

Due to uncertainty about the conditions and geometric characteristics of underground workings, we varied the model input parameters to evaluate their effect on the temperature of mine water to be delivered to the heat exchanger and the thermal output of the geothermal system.

The horizontal alignment of workings was estimated by available mining maps for two horizons where coal seams k_8 and l_1 were processed, assuming an average width of horizontal and inclined workings of 3 m.

Table 1

Input data for geothermal system calculation

Parameter	Notation	Value	Unit
Mining area	S_m	$1.8 \cdot 10^7$	m^2
Infiltration rate	w_{inf}	$1.09 \cdot 10^{-4}$	m/d
Pumping rate	Q	2000	m^3/d
Volume of flooded workings in mining horizon "1"	$V_{w,1}$	$4.3 \cdot 10^6$	m^3
Volume of flooded workings in mining horizon "2"	$V_{w,2}$	$3.0 \cdot 10^6$	m^3
Altitude of the ground surface	z_s	+205	m a.s.l.
Altitude of the upper aquifer bottom	$z_{0,b}$	+190	m a.s.l.
The radius of influence of the shaft in the upper aquifer	R	500	m
Highest elevation of flooding the mine	H_R	+185	m a.s.l.
Elevation of the adit connected to the mining horizon "1"	z_1	–50	m a.s.l.
Elevation of the adit connected to mining horizon "2"	z_1	–250	m a.s.l.
Neutral layer temperature	T_{nl}	10	°C
Elevation of the neutral layer surface	z_{nl}	+195	m a.s.l.
Geothermal gradient	Γ	0.03	°C/m
Average mine water salinity	C_m	5	g/dm^3
Shaft radius	r_{sh}	2.75	m
Outer diameter of the shaft	$d_{sh,out}$	6	m
Inner diameter of the shaft	$d_{sh,in}$	5.5	m
Shaft cross-sectional area	ω_{sh}	23.75	m^2
Thickness of the shaft casing	d_c	0.25	m
Thermal conductivity of the shaft casing	λ_c	1.5	W/(m · K)
Outer diameter of the pipe for mine water transportation in the shaft	$d_{p,out}$	0.16	m
Inner diameter of the pipe for mine water transportation in the shaft	$d_{p,in}$	0.14	m
Thermal conductivity of pipe material	λ_p	0.4	W/(m · K)
Heat transfer coefficient "water – shaft casing"	$\alpha_{c,w}$	52	W/(m^2 · K)
Heat transfer coefficient "water – plastic pipe" outside the pipe	$\alpha_{p,w}$	33	W/(m^2 · K)
Heat transfer coefficient "air – plastic pipe" outside the pipe	$\alpha_{p,a}$	5	W/(m^2 · K)

The quantitative analysis of Table 2 allows to drawing the conclusion that the discharge characteristics, the length of hydraulic path in the mining horizons, and the depth-dependent rock temperature are the dominant factors for the system's thermal output under steady flow mode. The depth of withdrawal does not change the pumped water temperature significantly; however, it plays the critical role in terms of the overall energy efficiency of the geothermal system.

Within the examined range of input parameters, the expected thermal output reaches 1070 ± 21 kW at the temperature of water entering on-ground heat exchangers of 17.8 ± ± 0.25 °C. These figures correlate to the performance indicators of the geothermal system at the mine "Blahodatna" mentioned in the review above [4, 5].

The estimated cooling of mine water during its upward transportation in the pipe and shaft for the examined parameter range does not exceed 1 °C; this causes a decrease in thermal output by 2–3 % compared to the output calculated at the temperature of water withdrawn in the pumping point. When positioning the pump below the adit of the lower mining horizon the water from upper horizons is slightly warmed up when moving downward.

After long-term circulation within this system, one should expect a gradual decrease in pumped water temperature due to its dilution in workings with cooler infiltration. The expected cooling for the operation period of 25 years ranges from 0.6 to 1.0 °C, which may cause a decrease in thermal output by 5.6–8.3 %.

The criterion for the geothermal system energy efficiency significantly depends on the pump depth L_{pw}. Near to the water table (L_{pw} = 55 m) ξ_c reaches 1.81, which means that the recovered thermal energy exceeds the energy of coal to generate the required electricity by 81 %. At the deeper position of the pump (L_{pw} = 460 m), the energy criterion falls to 1.05 due to higher costs for running pumps, which indicates the system unprofitability. Therefore, under conditions of the studied colliery positioning the pump closer to the water level above mining horizon "1" at z_p = +150 m a.s.l. allows saving electricity costs for circulation without significant heat losses when transporting mine water upwards.

The evaluated COP was found not depending significantly on the pump depth due to relatively low flow resistance in the shaft. The COP varies at 5.0, which is sufficiently high and correlates with the heat conversion factors achieved by some geothermal systems operated at similar temperatures at flooded mines abroad.

Conclusions. Based on the analysis of technology options of open loop geothermal systems that recover mine water heat, it was shown that the systems with the discharge to surface water bodies – quite common in the world practice – are quite applicable under the conditions of the Donbas. They combine thermal energy production with maintaining a safe water level across the mining sites and neighboring areas to prevent from soil waterlogging and high groundwater level.

By applying governing equations of hydraulic flow and thermodynamics we developed an analytical method to estimate indicators of geothermal system performance, evaluating the temperature of rocks and water in flooded workings, the hydraulic path of water and flow resistance of workings. We tested the method under the conditions of the colliery "Novohrodivska" No. 2 currently being flooded. Discharge characteristic, flow pathlength and flow resistance of mining horizons have been assessed to be the dominant factors for the expected thermal output. The depth of withdrawal plays the critical role for the system energy efficiency.

Within the examined range of model parameters, the temperature of water entering the on-ground heat exchangers is estimated at 17.8 ± 0.25 °C and the thermal output at 1070 ± 21 kW. The water temperature in workings is expected to decrease due to dilution with infiltration after the operation period of 25 years by 0.6–1.0 °C; this will reduce thermal output by 5.6–8.3 %. The estimated cooling of water during its upward transportation in the pipe does not exceed 1 °C, but it may reduce the thermal output by up to 3 %.

The energy criterion ξ_E of the geothermal system under the conditions of the colliery "Novoghrodivska" No. 2 first depends on the pump depth; ξ_E decreases from 1.81 when positioning the pump close to the water table to 1.05 when positioning below the deepest adit. Thus, the pump is recommended to be positioned at a possibly higher point to minimize the electricity consumption needed for circulation. The COP may reach 5.0, which correlates to other geothermal systems operated at closed mines abroad at similar tempera-

Table 2

Evaluated indicators of geothermal system performance

Parameter	Calculation variants							
	1	2	3	4	5	6	7	8
L_1, m	1700	2500	1700	2500	1700	2500	1700	2500
L_2, m	3000	2500	3000	2500	3000	2500	3000	2500
$S_{w,1}$, m^2 $S_{w,2}$, m^2	390 000 270 000	390 000 270 000	780 000 540 000	780 000 540 000	390 000 270 000	390 000 270 000	780 000 540 000	780 000 540 000
z_p, m a.s.l.	+150	+150	+150	+150	–255	–255	–255	–255
Q_1, m^3/day	1072.2	939.7	1072.2	939.7	1072.0	939.5	1072.0	939.5
Q_2, m^3/day	807.0	939.5	807.0	939.5	807.2	939.7	807.2	939.7
$T_{mw,p,0}$, °C	17.94	18.34	17.94	18.34	17.94	18.34	17.94	18.34
$T_{mw,p,25}$, °C	16.97	17.36	17.26	17.66	16.97	17.36	17.26	17.66
ΔT_{mw}, °C	0.37	0.5	0.37	0.5	0.25	0.29	0.25	0.29
L_{pw}, m	55	55	55	55	460	460	460	460
$q_{gts,0}$, kW	1048.8	1073.2	1048.8	1073.2	1059.5	1091.8	1059.5	1091.8
$\Delta q_{gts,25}$, kW	961.6	985.2	987.9	1012.0	971.5	1003.8	998.6	1030.7
COP_0	4.98	5.02	4.98	5.02	4.99	5.05	4.99	5.05
COP_{25}	4.83	4.87	4.87	4.91	4.85	4.90	4.89	4.94
$E_{el,0}$, kW	583.1	590.8	583.07	590.83	1003	1013	1003	1013
$E_{el,25}$, kW	553.7	561.9	562.8	571.02	973.5	984.7	983	993.6
$\xi_{c,0}$	1.79	1.81	1.79	1.81	1.05	1.08	1.05	1.07
$\xi_{c,25}$	1.73	1.75	1.75	1.77	0.99	1.02	1.01	1.03

tures; this parameter deviates by 1 % within the examined parameter range and is expected to decrease by 3 % in 25 years due to dilution with colder infiltration.

Further studies in this area may include refining the proposed method by paying more attention for geometry of workings, improving the accuracy of estimations of heat exchange by using differential equations of convective heat transfer.

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Методика оцінки показників геотермальної системи відкритого типу з використання тепла шахтних вод

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Мета. Розробка методики оцінки термогідродинамічних показників геотермальної системи відкритого типу зі скидом шахтних вод у поверхневі водотоки, а також її тестування для умов реального об'єкту з урахуванням різних технологічних варіантів, геотехнічних і термодинамічних чинників.

Методика. Використано співвідношення гідравліки й термодинаміки, проведено інженерний аналіз геотермальних систем відкритого типу, що відбирають тепло із шахтних вод, досліджені гідродинамічні й гірничо-технічні умови шахти № 2 «Новогродівська». Розроблена методика включає визначення температури порід, що оточують затоплені виробки, довжини гідравлічної течії та гідравлічного опору гірничих виробок.

Результати. Оцінена температура води, що подаватиметься до теплообмінників на денній поверхні та становитиме 17,8 ± 0,25 °С, а теплова потужність системи – 1070 ± 21 кВт. Прогнозоване охолодження води у виробках розглянутої шахти за рахунок розбавлення інфільтраційною водою протягом періоду експлуатації геотермальної системи у 25 років становитиме 0,6–1,0 °С, що відповідає зниженню її теплової потужності на 5,6–8,3 %. Оцінене охолодження шахтної води при її підйомі у стволі не перевищуватиме 1 °С. Енергетичний критерій ефективності геотермальної системи зменшується від 1,81 при відборі близько до рівня шахтних вод до 1,05 при відборі на глибині 460 м за коефіцієнта перетворення теплового насоса, що досягає 5,0.

Наукова новизна. Домінуючими чинниками, що визначають потужність відкритої геотермальної системи при усталеному режимі течії, є витратна характеристика й довжина гідравлічної течії на різних горизонтах відпрацювання, та температура порід, які оточують затоплені виробки. Глибина відбору води виявилася впливовим чинником для енергетичної ефективності геотермальної системи.

Практична значимість. Запропонована методика дозволяє визначати енергетичний критерій геотермальної системи відкритого типу зі скидом шахтних вод у поверхневі водотоки, що дає можливість оптимізувати параметри експлуатації системи.

Ключові слова: *шахтні води, геотермальні системи, тепловий потік, гідравлічна модель, теплова потужність*

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