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Geotechnological Foundations of Mining Natural-Technogenic Deposits in Donbas

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Abstract. The purpose of this study is to substantiate theoretically and technologically both parameters, formation and recovery schemes to use natural-technogenic and capacity resources of the mined coal deposits with the help of a set of geo-modules providing their activation, extraction, and storage depending on seasonable irregularity of energy consumption. Methods. Complex approach has been applied to achieve the purpose. The approach involves collection, systematization, and analysis of actual data concerning filtration as well as physical and mechanical characteristics of enclosing rocks, and seam mining conditions effecting formation of natural and technogenic deposits in addition to analytical and numerical methods to solve hydrogasodynamic, heat and mass transfer equations. The models reflect thermodynamic processes of a geocirculating system performance providing both heating and conditioning of industrial facilities and civic buildings since it accumulates summer heat and winter cold within the disturbed aquifers. Numerical modeling has been applied to simulate formation dynamics and a pattern of heat resource within an aquifer located over the coal seam being burnt depending on its inclination angle, coal mining stage, and aquifuge thickness. Originality. Spatial nonstationary model of heat transfer, simulating filtration direction, velocity of underground water and its temperature while carrier pumping and extracting from an aquifer for heat and cold supply of buildings according to ambient temperature has been developed and tested. Heat transfer mechanism within the flooded rock massif in an abandoned mine, followed by periodical injection and extraction of mine water from different levels, and its heating with the help of natural geothermal heat as well as underground burning of residual coal reserves has been analyzed. Practical implications. Operation parameters of a geotechnological module for reuse of thermal resource of the flooded mine workings while extracting and injecting water from different levels for heat and cold supply of buildings have been substantiated. It has been proved (in terms of the "Novohrodivska 2" mine being during liquidation) that the thermal flow, which is formed while coal burning and heated water pumping, is quite sufficient to meet calorific requirements of a town with 15 thousand inhabitants.

Keywords: coal deposits, hydrothermal resources, thermal energy, geocirculating systems

Геотехнологічні основи розробки природно-техногенних родовищ Донбасу

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Анотація. Метою даної роботи є теоретичне і технологічне обгрунтування параметрів і схем формування та використання природно-техногенного теплового і ємнісного ресурсів відпрацьованих вугільних родовищ за допомогою комплексу геомодулів, що забезпечують їх активізацію, відбір і зберігання синхронно із сезонною нерівномірністю споживання енергоносіїв. Для досягнення поставленої мети застосований комплексний підхід, що включає збір, систематизацію та аналіз фактичних даних про фільтраційні і фізико-механічні властивості вміщуючих порід, і гірничотехнічні умови розробки пластів, що впливають на формування природно-техногенних родовищ, а також аналітичні та чисельні методи рішення рівнянь гідрогазодинаміки і тепломасопереносу. Оцінено динаміку формування і конфігурація обсягів теплового ресурсу в водоносному горизонті, що залягає над вугільним пластом, що спалюється, в залежності від кута його падіння, стадії розробки вугілля і потужності водотриву. Обгрунтовано геотехнологічний модуль, що забезпечує ефективне освоєння теплового ресурсу затопленої шахти за рахунок відбору та закачування вод різних горизонтів для тепло- і холодопостачання будівель відповідно до температури зовнішнього повітря, а також його періодичну активізацію шляхом підземного спалювання залишкових вугільних запасів. Розроблено і протестовано просторову нестаціонарну модель перенесення тепла, що відтворює напрямок фільтрації, швидкість і температуру підземних вод при нагнітанні і відборі теплоносіїв з водоносного горизонту для опалення та охолодження будинків з урахуванням температури зовнішнього повітря. Досліджено механізм теплопереносу в затопленому гірському

масиві ліквідованої шахти, що супроводжується періодичним закачуванням і відбором шахтних вод різних горизонтів, а також їх нагріванням природним геотермічним теплом і підземним спалюванням залишкових запасів вугілля. Обґрунтовано параметри експлуатації геотехнологічного модуля для багатократного використання теплового ресурсу затоплених гірничих виробок шляхом відбору і закачування шахтних вод різних горизонтів для тепло- і холодопостачання будівель. На прикладі ліквідованої шахти «Новогродівська 2» доведено, що тепловий потік, який утворюється при спалюванні вугілля і відкачування нагрітих вод практично повністю покриває теплові потреби населеного пункту з 15 тисяч жителів.

Ключові слова: вугільні родовища, гідротермальні ресурси, теплова енергія, геоциркуляційні системи

Research problem statement. Significant technogenic reorganization of geological structures being mined as well as critical environmental situation is typical for old coal-mining regions. Taking into account the severe problem of energy carrier deficit, the situation signifies technological inferiority of the industry in terms of use of natural and technogenic resources concentrated within the worked-out areas (Ermakov, 2001; Gavrilenko, 2003; Falshtynskyi, 2017). Incoordination of different stages of exploration, extracting as well as scaling down of mining operations, especially in the context of coal deposits, are the main reasons of the current situation. Neither techno-economic nor geotechnical predictions of the efficient development of mine fields pays sufficient attention to the prerequisites concerning formation of associated commercial components and a collectors, the hydrothermal resource of which is considered negative at the stage of coal seam development; moreover, it is not taken into account at the stage of the mining termination.

Adequate quantitative assessment is required to determine formation conditions and a potential of technogenic hydrothermal deposits, as well as technological substantiation for integrated development of energy intensive resources of coalfields and mining enterprises during liquidation, which can satisfy current thermal requirements of the country. Thus, coordination of development stages of coal deposits on the unified theoretical foundation with characterization of geotechnological modules concerning the use of natural and technogenic energy resource and capacity properties of the worked-out rock massif and adjacent areas is both topical and strategically important theoretical and practical problem.

The paper presents theoretical and engineering substantiation of parameters as well as schemes to form and use natural-technogenic thermal and capacity resources of the worked-out coal deposits with the help of a system of geo-modules providing their activation, extraction, and storage depending on seasonable irregularity of energy consumption.

Substantiation of models for accumulation of heat carriers within aquifers. A system of underground heat accumulation is profitable if only its mining con- ditions and operating schedules avoid mutual effect of heat envelopes of wells; in this context, thermal losses should not be more than 25% (Dickinson, 2009; Sadovenko, 2015). Taking into consideration complex nature of physical processes and recommendations of the world theory and practice (Andersen, 1985; Inkin, 2018), the geotechnology application must be substantiated by numerical modeling of filtration and heat transfer within an aquifer used as a collector of heated and cold water.

The equation of filtration during injection and pumpout in water forced mode has the following form:

$$\frac{\partial}{\partial x}\left(Km\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(Km\frac{\partial H}{\partial y}\right)+Q_\Sigma-\frac{K_1}{m_1}\left(H_1-H\right)-\frac{K_2}{m_2}\left(H-H_2\right)=S_s\frac{\partial H}{\partial t},$$
(1)

where K and m are filtration coefficient and aquifer thickness respectively; K_1 and m_1, K_2 and m_2 are identical parameters of its roof and bottom respectively; H, H_1 and H_2 are pressures within an aquifer, in overlying and underlying aquifers, respectively; and Q_Σ is time-variant total intensity of water extraction and injection by means of wells

$$Q_\Sigma=\sum_{i=1}^{N}Q_i\delta\left(x-x_i,y-y_i\right),$$

where Q_i is i^{th} well capacity; x_i, and y_i are its coordinates; and S_s is compressibility of the seam.

Two-dimensional (in horizontal plane) heat migration within underground water is described by means of the equation:

$$\frac{\partial}{\partial x}\left(\lambda m\frac{\partial T}{\partial x}-\rho_w C_w v_x mT\right)-\frac{\partial}{\partial y}\left(\lambda m\frac{\partial T}{\partial y}-\rho_w C_w v_y mT\right)+$$
$$+mq_\Sigma-q_b-q_t=m\left[n\rho_w C_w+(1-n)\rho_{sk}C_{sk}\right]\frac{\partial T}{\partial t},$$
(2)

where λ is heat transfer coefficient of aquifer rocks; ρ_w, ρ_{sk} are densities of water and rock matrix; T is underground water temperature; q_t and q_b are thermal flows from an aquifer to its roof and bottom; C_w, C_{sk} are specific densities of underground water

and rock matrix; q_Σ is intensity of heat sources and heat sinks distributed within a seam

$$q_\Sigma = \sum_{i=1}^{N} q_i \delta(x - x_i, y - y_i),$$

where q_i is intensity of ith heat source (heat sink) corresponding to a location of ith well for water injection (extraction).

In the context of water injection and extraction through a well, thermal flow intensity is determined using the formula

$$q_i = C_w \rho_w Q_i \Delta T_i,$$

where $\Delta T_i = T_i - T_0$ is during water injection; $\Delta T_i = T(x_i, y_i, t) - T_0$ is during water extraction. In this context, T_i is the temperature of water being injected through i^{th} well; $T(x_i, y_i, t)$ is temperature of water being extracted from i^{th} well; and T_0 is current temperature of underground water.

Thermophysical properties of water are determined for the area of an aquifer near the well.

Thermal flows, passing through the seam roof and bottom, are determined using the formulae

$$q_t = -\frac{\lambda}{n} \frac{\partial T}{\partial z}\Big|_{z=m}; \quad q_b = \frac{\lambda}{n} \frac{\partial T}{\partial z}\Big|_{z=0}.$$

After dividing both parts of equation (2) by a product $n C_w \rho_w$ it is possible to proceed to the equation

$$\frac{\partial}{\partial x}\left(\frac{\lambda m}{C_w \rho_w n} \frac{\partial T}{\partial x} - \frac{v_x m}{n} T\right) - \frac{\partial}{\partial y}\left(\frac{\lambda m}{C_w \rho_w n} \frac{\partial T}{\partial y} - \frac{v_y m}{n} T\right) +$$

$$+ \frac{m q_\Sigma - q_b - q_t}{C_w \rho_w n} = m R_T \frac{\partial T}{\partial t}, \quad (3)$$

where $R_T = 1 + \dfrac{1-n}{n} \cdot \dfrac{\rho_{sk} C_{sk}}{\rho_w C_w}$ is a coefficient being similar to so-called coefficient of delay in terms of mass transfer equation within underground water; and n is porosity.

Numerical model, based on equations (1) and (3) with nonstationary sources and sinks of water and heat, makes it possible to describe transient processes of heat transfer with random arrangement

of several wells, various temperatures of water being injected and extracted, nonhomogeneous structure, and variable thickness of the aquifer. It is impossible to solve analytically such a boundary heat transfer problem.

Thermal balance evaluation within aquifer rocks over underground gas generator. Substantiation of rational parameters of heat energy extraction should involve the modeling of propagation of geothermal fields being formed within an aquifer in the process of coal burning.

Reasonable formulation of a boundary condition in terms of temperature at the aquifer bottom over reaction channel is of crucial importance. To determine underground water temperature, three-dimensional shallow-thickness module in a form of a parallelepiped is singled out within the share of the aquifer. The module is located directly over a heated separating seam (i.e. aquifuge) where thermal exchange is taking place (Fig. 1) (Sadovenko, 2015). Heat balance within the module is established on the basis of equality of heat amount (U_Σ) incoming the block or leaving it during time interval τ, and amount of heat consumed to warm up both underground water and rocks within the block (U_{heat}).

Changes in temperatures of water and rocks within the block can be determined with the help of a heat balance equation (Sadovenko, 2012)

$$U_\Sigma = (q_0 + q_1 - q_2 - q_3)\tau = U_{heat} T_1 - T_0) \cdot B; \quad (4)$$

and $\quad q_1 = AT_w; \quad q_2 = A \cdot \dfrac{T_1 + T_0}{2}; \quad (5,6)$

$$q_3 = D \cdot (\frac{T_1 + T_0}{2} - T_w); \quad D = \frac{\lambda \Delta x \Delta y}{\Delta z}, \quad (7,8)$$

$$A = \Delta y \cdot \Delta z \cdot v \cdot C_w \rho_w; \quad (9)$$

$$B = \rho_w C_w V_w + \rho_{sk} C_{sk} V_{sk}; \quad (10)$$

where T_0, and T_1 are temperatures of water and rocks within a volumetric grid with $\Delta x \Delta y \Delta z$ dimensions at the beginning of time interval τ, and at its end respectively; v is filtration velocity; V_w, and V_{sk} are volumes of water and rocks within the block; q_0 is thermal flow from a reaction channel; q_1 and q_2 are convective thermal flows along the filtration flow direction; q_3 is conductive thermal flow from this block to the block located above; λ is thermal conductivity of the aquifer; ρ_w, C_w, and V_w are density, thermal capacity, and amount of water within the block; ρ_w, C_w, and V_w are density, thermal capacity, and amount of rocks within the block.

Substituting expressions (5) – (10) in (4), we obtain an equation for time temperature series

$$T_i = \grave{O}_{i-1} + \frac{q_0 - (A + D) \cdot (T_{i-1} - T_w)}{B + (A + D)\tau/2} \cdot \tau,$$

where T_i is temperature within the volumetric grid during i^{th} averaging period.

tectonic disturbance is a fault with an amplitude of more than 9 m. Stratigraphic cross-section of coal rocks consists of several blocks (A, B, C, D), which are deposited from older to younger ones. Block D, which consists of silt shales, has a thickness from 5 to 30 m, and block C with a thickness of 30-45 m is mostly represented by sandstones, which alternate with aleurolite and clay sediments. Blocks A and B are the roof of the coal seam and are predominantly represented by aleurolite and sandstone inter layers.
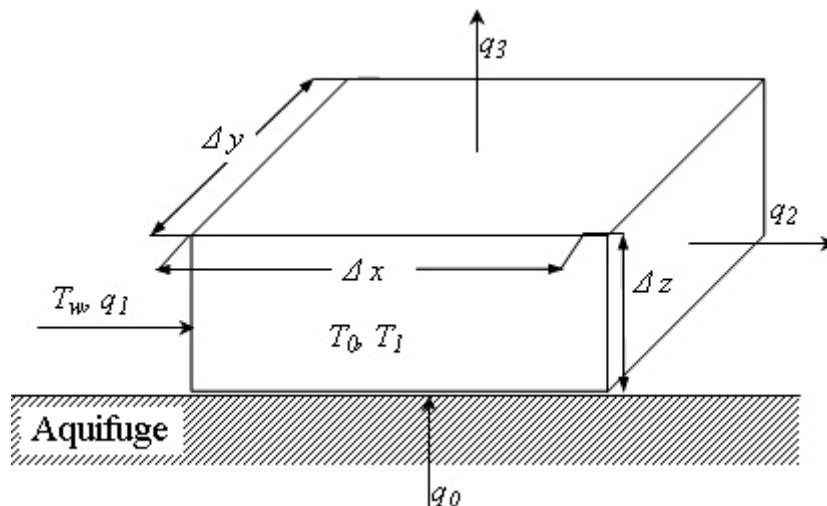

Fig. 1. Heat balance scheme within aquifer block over a reaction channel roof

Evaluating the model accuracy while epignosic problem solving. The developed parametrically modeled technique, aimed at the activation of water-saturated rock massif of the flooded mine, has been tested using the published actual data of a large-scale industrial experiment on underground coal gasification (Rocky Mountain area, the USA) (Berdan, 1993). In the context of the experiment, the effect we used was considered as a side problem.

According to recommendations, suggested in (Sadovenko, 1991, 2015; Rudakov, 2011), layout of the studied area Hanna – 1 (Berdan, 1993) with 500 x 500 m dimensions is approximated by means of a grid with 25 x 25 m pitch, and its 5-time decrease near burning modules making it possible to register accurately a pattern of thermo- and piezo-isohyps (Fig. 2).

According to the data of geological structure, filtration is considered as a multilayer stratum where average thickness of a coal seam is 10 m, average thickness of an aquifuge is 7 m, and average thickness of an aquifer is 15 m. Seam Hanna – 1was subjected to underground burning. The seam thickness is 10 m and depth of seam roof deposition is from 100 to 300 m. Coals of the seam don't heave, are bituminous, have large amounts of volatile components and coal interlayers with 40-75% ash content. Their only

An aquifer is located within the boundaries of blocks A and B, which is confined to coarse-grained sandstones, located between layers of aleurolites. Rocky Mountain, located within the area and extending from the south-east to the north-west, is a barrier for water movement; it is specified as impenetrable hydrodynamic boundary. Detailed information on feeding and discharging area of the aquifer is not available. Then, boundary conditions of the first type are defined for the remaining contour of Hanna – 1with water head values, which simulate actual hydraulic gradient of underground water (i.e. 0.006).

Burning cavities are internal boundaries of the model. The cavities are also displayed with the help of boundary conditions of the first type with a hydrodynamic head value being equal to absolute elevation of a coal seam floor. The placement of these boundaries is performed by tracing the contours of worked-out areas on the calculated layers. While modeling the operation of UCG (underground coal gasification) modules, internal boundary conditions were switched off after the blow stopped to be supplied.

Fig. 3 presents a comparison of full-scale data and simulated data concerning changes in underground water temperature in wells located near modules
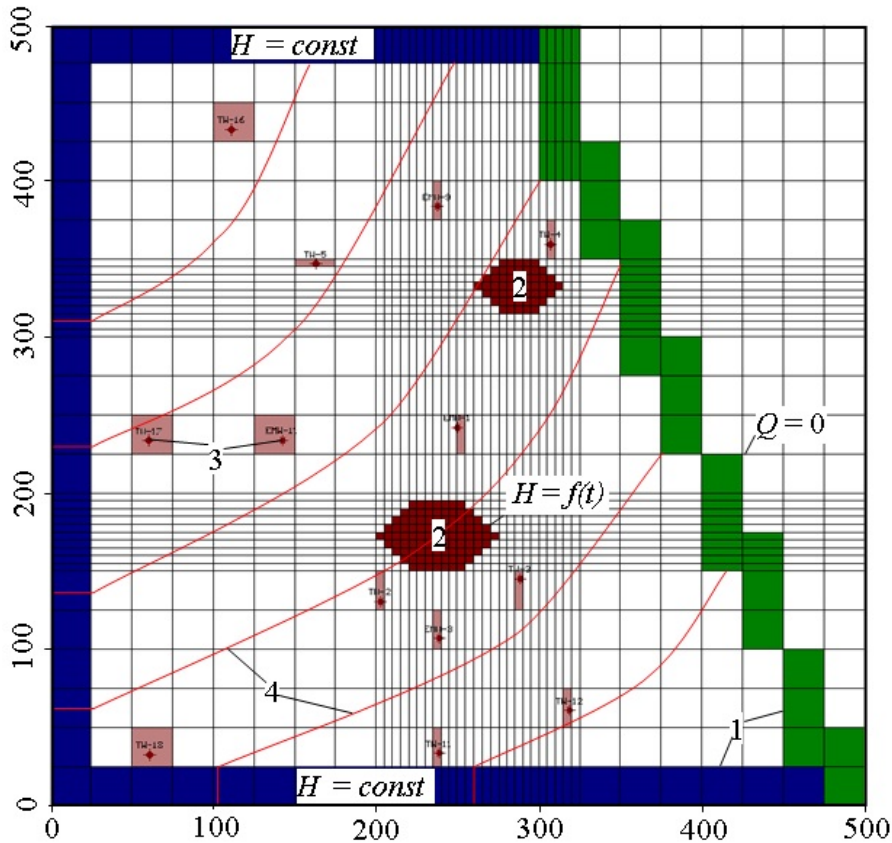
Fig. 2. Schematization of Hanna – 1 area model in terms of ModFlow software solution: 1 – hydrodynamic boundaries; 2 – IAF modules; 3 – wells; 4 – piezo-isohyps

for coal burning. Analysis of the graphs shows that maximum relative calculation error is not more than 5%, which confirms the results reliability. The data provide support for the heat transfer model adequacy, and possibility to apply it in the context of practical tasks concerning evaluation of thermal resource of aquifers in the process of underground coal seam burning.

Parameterizing the development, activation, and use of thermal potential in terms of the "Novohrodivska 2" mine being during liquidation. The mine field is geologically and structurally located within the southwestern wing of the Kalmius-Toretska hollow and is confined to the footwall of a large regional tectonic disturbance – Selidovsky thrust fault. Mid-Carboniferous sediments (C_2^6 and
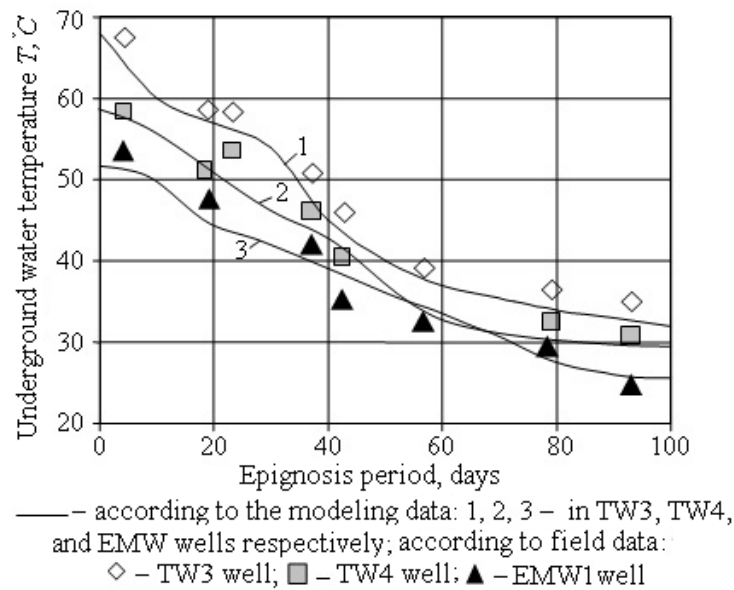

Fig. 3. Dynamics of changes in underground water temperatures within Hanna – 1 area

C_2^5), overlapped by Paleogene-Neogene sands and Quaternary loamy soils (Trigub, 1978, Sadovenko, 2019) are present in a structure of the area. Series C_2^5 contains a large amount of sandstones and a small amount of coal (Krasnopolsky, 2006) in the lower part. Coal seams and interbeds of variable thickness are concentrated in the middle part. "Novohrodivska 2" mine developed the coal seam k_8 out of the seams of series suitable for industrial development to the mark –370.3 m, with average water inflows into mine workings of 100 – 120 m³/h and frequent water influxes from overlying sandstones and limestones. This character of groundwater inflow is caused by the presence of thick aquifers in the k_8 seam roof confined to carstified limestone L_1 and sandstones L_1sl_1 and l_1sl_3. From the side of soil, the seam was saturated from sandstones that are 5 – 10 m away from it.

Series C_2^6 within the field of the "Novohrodivska 2" mine is the most coal-saturated and contains seven coal seams and interbeds. Only the l_1 "Shestychetvertovy" seam out of these seven was industrially developed. It should be noted that water-saturated sandstone l_1sl_3, located directly in the seam l_1 caused significant water inflow (200 – 250 m³/h) in mine workings. Balance reserves of coal are estimated at 17355 thousand tons, and industrial reserves – 12644 thousand tons, which corresponds to losses of 4711 thousand tons. Off-balance reserves of series C_2^6, mainly concentrated in seams l_4 and l_5 are estimated at 3215 thousand tons. Accounting the losses and off-balance reserves allows concluding that more than 8 million tons of coal are concentrated at the present time within the boundaries of the "Novohrodivska 2" mine during liquidation.

The low-amplitude discontinuous disturbance within the "Novohrodivska 2" mine is caused by the influence of mid-amplitude faults (Novohrodivska and Hrodivska) extending from the south-west to the south-east. A total of 15 low-amplitude discontinuities were found in k_8 and l_1 coal seams, which determined the disturbance coefficient (the ratio of a sum of products of amplitudes of discontinuities by their length to the studied area) of the mine field – 0.93 (Krasnopolsky, 2006, Trigub, 1978).

The hydrogeological conditions of the "Novohrodivska 2" mine field are closely connected to its geological structure (Trigub, 1978, Ruban, 2005). Thus, two aquifers can be pointed out to be located within deposits of Quaternary sediments that are first from the day surface. One of which is the horizon of Holocene alluvial sediments (*aH*), it is confined to modern alluvial formations and fills the valley of the Solona river and bottoms of ravines flowing into it.

Its water-bearing rocks are represented by sandy silts, loamy soils, and clay sands with a thickness from the first meters to 10 m. The depth of groundwater levels varies from 0.5 to 3 – 4 m. The water content of the horizon is low, the values of filtration coefficients are usually hundredths or tenths m/day. The second aquifer horizon of Quaternary aeolian-deluvial loamy soils is developed on watershed areas and is confined to loamy soils with a thickness of 5 – 20 m, that are located on the top of an aquiclude of Pliocene–Lower Quaternary red-brown clays. This aquifer is developed almost everywhere in the northern part of the mine field. It is fed from atmospheric precipitation, and is discharged through the crossflow to the underlying Paleogene-Neogene sands and evaporation. The prevailing depth of the groundwater level varies from 10 to 20 m. Their mineralization varies from 2.5 to 6.0 g/dm³, the hardness – 18 –50 mmol/dm³ (Ruban, 2005, Sadovenko, 2019). The composition of water is often sulphatic, less often – chloride-hydrocarbonate-sulphatic and calcium-magnesium-sodium.

Aquifer of Paleogene-Neogene sands (P_3-N_1) is confined to fine-grained sands overlying on weathered Mid-Carboniferous sediments. Thickness of sands within the "Novohrodivska 2" mine reaches 40 m, decreasing to 0.5 – 2 m in its north-eastern part and wedging out in the south-eastern direction. In the area of basset under Cenozoic deposits of coal seams l_1 and k_8, Paleogene-Neogene sands are often completely drained. The water content of this horizon is low: well inflow rates are usually 1.5 – 2.0 m³/h at descensions of 3 – 10 m, inflows to shafts – 5 – 6 m³/h. The chemical composition of groundwater is often chloride-hydrocarbonate-sulfatic, less often – calcium-magnesium-sodium, their mineralization varies from 1.1 to 5.0 g/dm³, the hardness – from 4 – 5 to 30 – 36 mmol/dm³.

Mid-Carboniferous aquifer complex C_2 and its horizons are confined to sandstones and limestones, depositing among clay and carbonaceous shale (Krasnopolsky, 2006, Trigub, 1978). In the weathering zone, which is developed to a depth of 50 – 60 m below the surface of Carbon deposits, all lithological varieties of rocks are flooded to some degree. Sandstone thickness averages 10 – 20 m, in some cases reaching 40 – 50 m. Sandstones L_1sl_1 and l_1sl_3 are the most sustained in terms of thickness and seam strike in the considered territory. Their filtration coefficients vary widely; from $n \times 10^{-4}$ to the first m/day and decrease regularly with depth. Porosity in the interval from ±0 to –400 m decreases from 20.6 to 14.5% respectively.

The chemical composition of underground water of coal deposits within depths reached by the mine

is predominantly chloride or hydrocarbonate-sulphatic or calcium-sodium with mineralization from 1 to 3.5 –4.5 g/dm³. Water is generally hard (total hardness of up to 34.4 mmol/dm³), foaming with a large amount of solid boiler sediment when boiling. The aquifer complex is fed from the flow of groundwater from the overlying Paleogene-Neogene sands, and is less often associated with bassets of black coal rocks to the surface. In mine fields the leading role in feeding belongs to absorption of surface discharge.

Mine water of the "Novohrodivska 2" mine, as well as water of adjacent mines, was characterized by sulphatic magnesium-calcium-sodium composition and mineralization of 3.1 – 3.4 g/dm³ during the operation period. In this case, the flooding of a

significant volume of workings of k_8 and l_1 seams (around 4 million m³) practically did not affect their chemical composition. At the present time, the mine water has mineralization of 3.3 – 3.7 g/dm³ and contain the following basic microcomponents (mg/dm³): lithium – 0.039 – 0.05; bromine – 0.01 – 0.022; lead – 0.017 – 0.05; manganese – 0.55 – 1.82. It should be noted that the content of almost all components does not exceed the MPC (maximum permissible concentration). After discharge to the surface and settling in the Maslovsky pond-clarifier, located in the upper reaches of the Solony stream, the mine water practically does not change its composition. However, at a distance of 100 m downstream, after the municipal wastewater from the Novohrodivka treatment plants
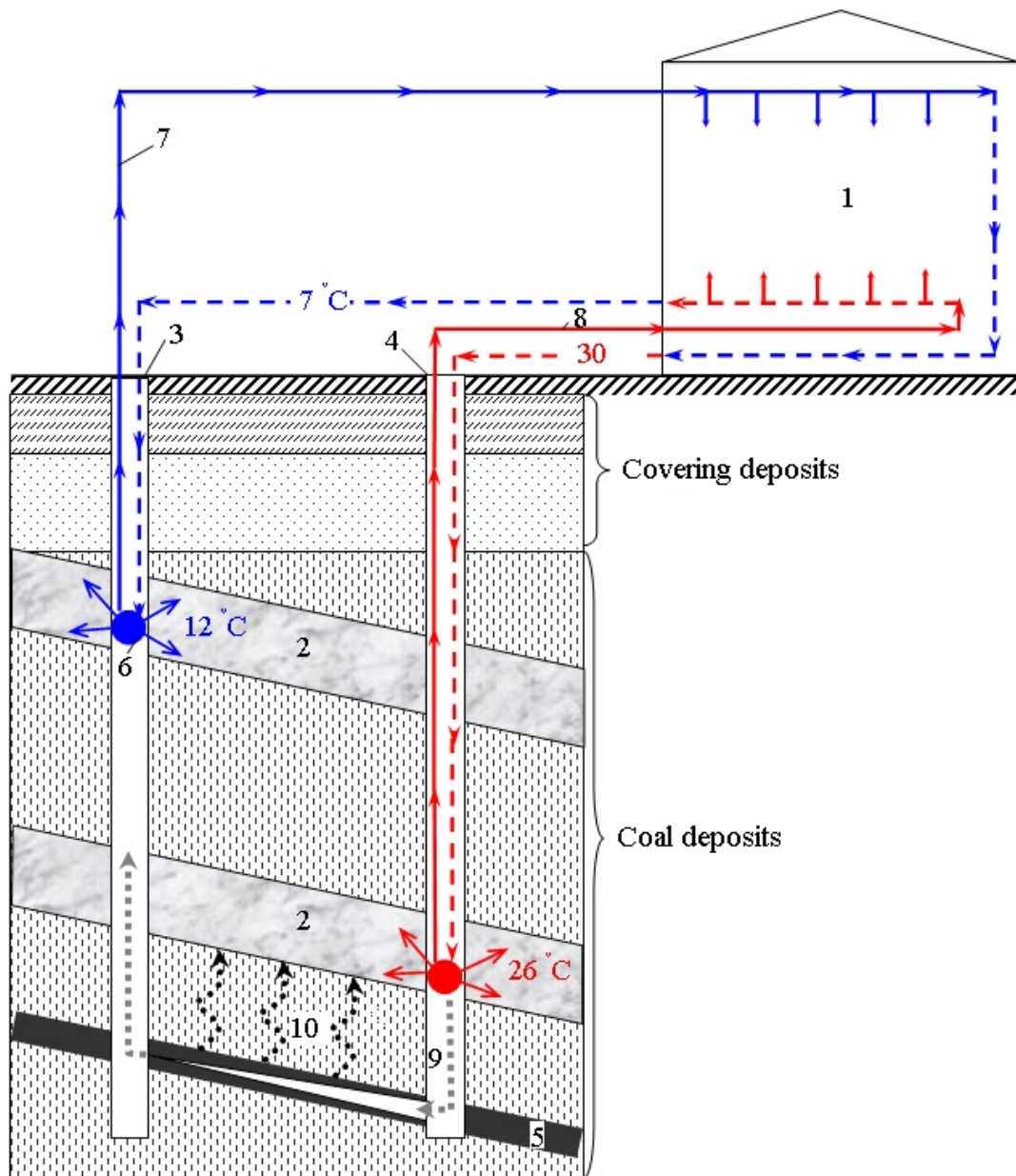

Fig. 4. Technological scheme of geomodule within the territory of "Novohrodivska 2" mine field: 1 - a building; 2 - productive stratum with the flooded mine workings; 3, and 4 – "cold well" and "warm well"; 5 - off-grade coal seam; 6 - packer; 7, and 8 - a path of mine water flow from "cold well" and "warm well"; 9, and 10 - the directions of blow (gas) flow and thermal flow while coal burning
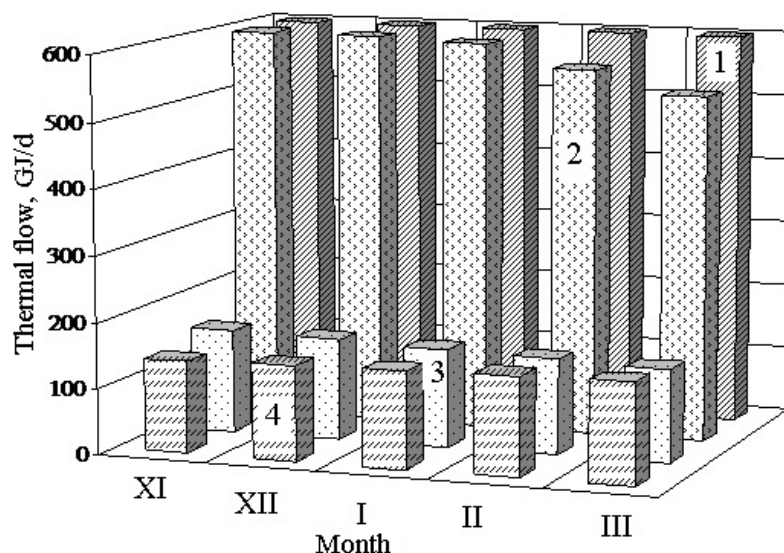
Fig. 5. Geomodule efficiency at the territory of the "Novohrodivska 2" mine: 1 – 3 - a thermal flow, required to heat up Novohrodivka town, generated by the geomodule according to the first and second technological schemes respectively; 4 - thermal capacity equivalent required by a pump to heat up buildings with the help of mine water (variant one) as a source of low-potential energy

enter the stream, water salinity and hardness in it decrease to 2.2 – 2.7 g/dm³ and 15.0 –21.7 mmol/dm³ respectively (Trigub, 1978, Ruban, 2005).

Preliminary calculations have helped to determine that the total amount of the thermal energy, accumulated by the water from the flooded workings of the "Novohrodivska 2" mine, is 1300 TJ (Sadovenko, 2014; Sotskov, 2017). Its use with the help of geomodule can be considered in terms of two technological variants (Fig. 4). One of them is connected with the development of natural thermal resource of a mine ("cold well"); another one is connected with its extra activation at the expense of underground burning of residual coal ("warm well") (Inkin, 2016; Falshtynskyi, 2017).

Analysis of the diagrams in the Fig. 5 explains that thermal resource, generated by the geomodule in terms of variant two, is quite sufficient to meet the thermal requirements of Novohrodivka town during its heating season. That gives a ground to consider the technological scheme as the most advanced one while using resources of the "Novohrodivska 2" mine being during liquidation. If the geomodule operates in terms of variant one, when mine water is used as low-potential energy in thermal pumps, the energy, consumed by them to heat up buildings, is 150 GJ/day. It is four times less than that of the required thermal flow. Efficiency of the first technological scheme may be improved through replacing expensive thermal pumps by such heating solutions as heat-insulated floor system.

Conclusions. Long-term coal mining as well as mine liquidation in Ukraine has resulted in the formation of natural and technogenic environment in the territo-

ries of coal-mining regions; the environment contains substantial reserves of energy resources in a form of residual coal and off-grade coal, warm mine water as well as warm underground water. The disturbed rock massif involves significant capacity resource capable of accumulating heat carriers in the amounts sufficient to smooth up seasonable irregularity of energy consumption.

The developed models of filtration and heat transfer within water-saturated rocks are the key tools of the research. The models reflect thermodynamic processes of geocirculating system performance providing both heating and conditioning of industrial facilities and civic buildings since it accumulates summer heat and winter cold within the disturbed aquifers.

Numerical modeling has been applied to simulate formation dynamics and a pattern of heat resource within an aquifer located over the coal seam being burnt depending on its inclination angle, coal mining stage, and aquifuge thickness. The model has been identified basing on epignosis simulation of industrial experiment concerning underground coal burning in the context of Rocky Mountain deposit (the USA). Relative calculation error does not exceed 5%.

Geo-technical module, providing the efficient development of a thermal resource of the flooded mine has been substantiated. It operates due to extraction and injection of water from different levels for heat and cold supply of buildings depending on ambient temperature with its periodical activation by means of underground burning of residual coal. It has been proved in terms of the Donbas "Novohrodivska 2" mine being under during liquidation that a thermal flow of 500-580 GJ/day formed while coal burning

and heated water pumping out is quite sufficient to meet calorific requirements of a town with 15 thousand inhabitants.

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