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THE TENDENCIES TO USE REMAINING RESERVES OF THE CLOSED-DOWN COAL ENTERPRISES

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The analysis of energy consumption in Ukraine reveals the growing need for wider use of alternative sources including those accumulated in abandoned mines. Regarding to the rapid growth of various applications during last decades geothermal energy is considered worldwide as one of promising energy sources, with the significant share and prospects of heat pumps. The monograph describes the concepts of combined use of ground source heat pumps, the resources of abandoned mines, and various geotechnologies including underground combustion of residual coal seams, mine drainage, water flow regulation in mining and post-mining areas, underground hydropower plant, mine and ground water treatment, and water supply.

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Introduction

The analysis of energy consumption in Ukraine reveals the growing need for wider use of alternative sources including those accumulated in abandoned mines. Regarding to the rapid growth of various applications during last decades geothermal energy is considered worldwide as one of promising energy sources, with the significant share and prospects of heat pumps. The monograph describes the concepts of combined use of ground source heat pumps, the resources of abandoned mines, and various geotechnologies including underground combustion of residual coal seams, mine drainage, water flow regulation in mining and post-mining areas, underground hydropower plant, mine and ground water treatment, and water supply.

A feasibility study was accomplished for a geological structure in Central Ukraine as the hypothetical underground gas storage (UGS) facilities. The gas flow equations were used for estimating UGS nonsteady performance taking into account the gas losses caused by leakage through a low-permeable overlying bed during pumping, storing gas, and its extraction. An assessment was made for changes of the gas volume and pressure in the aquifer during pumping and extraction. The results of laboratory studies on triaxial testing soils and rocks were used to quantify permeability and porosity in the aquifer under pressure ranging within the intervals typical for UGS.

The developed four geotechnical designs are economically feasible because of combining low-grade heat recovery or/and power generation with addressing economical and environmental challenges, primarily, in mining areas.

1. Actualization of prospects of thermal usage of groundwater of mines during liquidation

According to different programs of restructuring the coal industry, the number of mines planned for liquidation in Ukraine is constantly increasing. In accordance with estimates, a significant number of closed mines will appear in its territory in the near future, that constitute a significant threat to the environment and require substantial expenses to maintain their hydrodynamic safety, as well as to eliminate involuntary unemployment [12, 57]. Thus, for example, the closure of the N.I. Stashkova Mine in the Western Donbass in 2021 will lead to flooding of a developed space and a threat of rapid rise of mine water level to the daylight surface [5]. In addition, many nearby settlements will experience an acute shortage of heat in the conditions of constantly growing prices of energy carriers. At the same time, a considerable resource of mine water with temperature of up to 20°C will be concentrated in the flooded mine workings, which are currently practically not used.

Foreign scientific and practical experience in the utilization of mine water heat from flooded mine workings [40, 68] shows the applicability and profitability of this technology. Currently, there are a lot of local projects in which the heat of water from closed mines is used to heat one- or two-storey buildings (Germany, France, and England). The most large-scale is a Dutch project, which is called MinewaterProject. In the city of Heerlen, the water of a mine, which had been flooded for almost 30 years, now heats the area with 350 buildings, over 200 of which are residential buildings. At the same time, pumping out of mine water is accompanied by technical difficulties associated primarily with high mineralization of water and the presence of various substances in it, which requires usage of special equipment and the organization of an environmentally safe water usage cycle.

Profitability of usage of warm mine water for heating and hot water supply increases dramatically when using heat pumps. Thus, at Blagodatna mine of Pavlohradcoal DTEK PJSC, pumping out of mine water in an amount of 200 m^3/h with a conversion coefficient of heat of 3.5 provided annual savings of about $60 thousand [54]. At the same time, heat pump operation does not create harmful emissions into the environment, which is especially important for coal mining regions. However, the usage of heat pumps in mines is not widespread due to large capital expenses on their installation and maintenance. In connection with this, the purpose of this paper is to justify a cost-effective technological scheme for development of a thermal resource of Stashkova mine after its closure ensuring the maintenance of a favorable energy and ecological-hydrogeological regime in the region.

When developing a technological scheme for usage of mine water heat, it must be kept in mind that after a mine is closed and flooded, filtration flows in a rock massif are characterized by an increase in velocity and flattening of levels near natural channels due to a multiple increase in permeability of disturbed rocks. This leads to underflooding and subsidence of the day surface. Flows of low-potential heat from a technogenic aquifer are drained through natural channels containing environmentally harmful components. In this connection, it is expedient to produce heat from mine water in combination with technologies for its treatment, which are more economically efficient exactly in the presence of waste low-potential heat.

The main elements of the suggested technological scheme are presented in Fig. 1.1, on the basis of which, a systematic pumping out of water from flooded mine workings of different horizons using water wells is required to prevent flooding of the area around the mine. At the same time, the maximum operating efficiency of wells is achieved by combining their shafts with main workings. The rise of water to the day surface is performed using electrical centrifugal pumps (General Electric, Centrilift, Novomet, etc.), the usage of which is caused by their trouble-free operation in corrosive liquids with dissolved salts, gases and mechanical impurities. In addition, pumps of this type are characterized by simplicity of ground equipment, a long operation period between repairs (2 – 3 years), a large pumping out depth (up to 4 km) and a significant flow rate (up to 10,000 m^3/day).

After the water enters the day surface, it is sent to the inter-pipe space of a heat pump evaporator, where it is used as a low-potential source of thermal energy and is cooled by boiling the refrigerant (working medium, which is low-boiling fluorochlorine-containing hydrocarbons) in the evaporator pipe space. Refrigerant constantly circulates in a closed contour of the pump, undergoing changes in its aggregate state in its devices and transferring heat from a renewable source of mine water to the consumer of average-potential heat due to the expenditure of high-potential energy in the compressor. At the same time centrifugal and heat pumps consume electricity for operation, the amount of which is proportional to the power of a heat flow going to heat buildings. Mine water, cooled as a result of emission of thermal energy to the pump evaporator, enters the storage ponds located in Kosminna, Svidovok and Taranova gullies, from where it is discharged into the r. Samara. It should be noted that in order to reduce the influence of mine water on a quality of water in the river, they should be discharged in portions depending on the hydrogeological regime of the river.

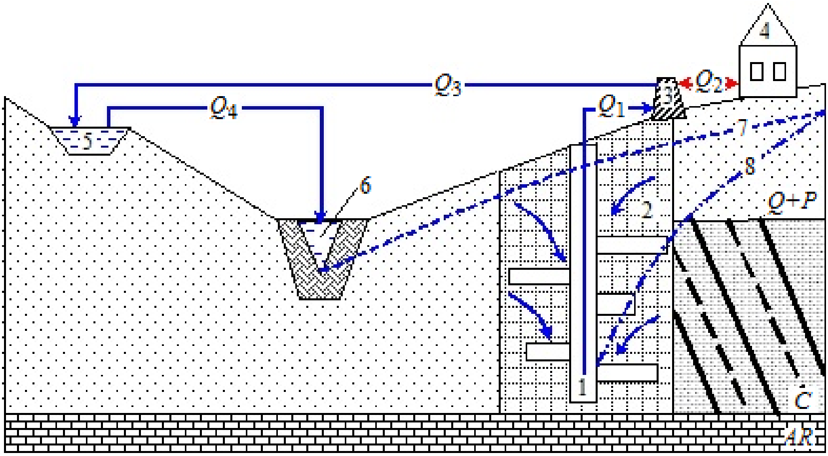

Figure 1.1 – Technological scheme of a geomodule for development of mine water heat: 1 – mine workings; 2 – developed coal massif; 3 – heat pump; 4 – building; 5 – storage pond; 6 – surface water flow; 7, 8 – level of mine water before and after their pumping to the surface; Q_1 – Q_4 – flow rate of mine water from workings, coolant from the pump, wastewater into a storage pond and settled water into a river, respectively.

The suggested technological scheme of mine water usage has a number of obvious environmental (prevention of territory underflooding, reduction of environmental impact) and energy (heating of buildings) advantages. However, it is necessary to carry out a feasibility study of scheme operation effectiveness for its implementation, the tasks of which are as follows:

– assess the maximum possible heat flow occurring from pumping out of groundwater from different horizons of a mine;

– determine the conversion coefficient of heat pumps, depending on the temperature of mine water;

– perform a comparative analysis of usage of mine water in heat pumps with other types of natural low-potential sources of thermal energy;

– establish the profit obtained from the operation of the suggested geomodule by determining the cost of electricity for operation of centrifugal and heat pump, as well as the cost of heat generated by them;

– quantify the prevention of CO_2 emissions due to the usage of heat pumps.

To solve the set tasks, it is necessary to determine the water temperature of various horizons of Stashkova mine concentrated in mine workings. In this case, in the first approximation, it can be assumed that hydrodynamic parameters of seams do not depend on a heat transfer processes [25], and the water temperature and temperature of a rock skeleton coincide at every point. Assume that mine water movement within the mine field occurs along the flooded workings, heat exchange in the computed plane is absent [55], the H axis is directed down. The heat flow q caused by heat of earth interior enters flooded mine workings from the bottom (from the depths). A neutral stratum of rocks, the temperature of which is constant and equal to the average annual temperature in the region (about +9 °C) lies above, 10 m below the day surface. Under these conditions, a differential equation of heat conduction about H axis considering convection is

$$\frac{\partial^2 T}{\partial H^2} - \frac{V}{a} \cdot \frac{\partial T}{\partial H} = 0, \tag{1.1}$$

under the following boundary conditions

$$T = T_1 \quad \text{when} \quad H = H_1;$$

$$q = -\lambda \partial T / \partial H \text{ when } H = H_2 .$$

The general solution of equation (1.1) with given boundary conditions is [19]

$$T = T_1 + \frac{q}{\lambda B}\left[\exp B(H - H_2) - \exp B(H_1 - H_2)\right]; \; B = \frac{V}{a}. \tag{1.2}$$

In this case, the thermal flow of mine water contained in the flooded workings is determined from the expression

$$Q = CQ_1(T - T_{dev}) \tag{1.3}$$

where T_1, H_1 are temperature and distance to the neutral stratum; H is depth of location; a, λ are thermal diffusivity and thermal conductivity of water-saturated rocks; V is vertical velocity of filtration; q is heat flow from the depth; C, T, T_{dev} are volumetric heat capacity and temperature of mine water before and after usage respectively.

The table shows the temperature and the natural thermal potential of mine water contained in mine workings calculated by formulas (1.2) and (1.3). According to the obtained data, the heat flow increases with an increase of the depth of location of seams and the amount of pumped out water. At the same time, the total thermal potential of Stashkova mine is 1.72 TJ/day. It should be noted that in order to maintain hydrodynamic equilibrium, the flow of mine water was assumed equal to the predicted inflow of water into each coal seam, previously determined using mathematical modeling [37, 59]. The depth of seam location was assumed as the average value of an interval of its development. Thermophysical properties of rocks were set as characteristic of the conditions of Western Donbass:

$q = 54$ J/day·m^2; C_w = 4187 kJ/m^3; λ_{av} = 245 kJ/m·day· °C; a_{av} = 0.05 m^2/day; T_1 = 9 °C; T_{dev} = 5 °C; H_1 = 10 m.

In assessing the operational efficiency of the suggested geomodule, it is necessary to calculate the conversion coefficient of the heat pump when using mine water. This indicator is the ratio of its heating capacity to the electricity consumed by it and is determined from the following expression

$$K_T = h \cdot \frac{T_2}{T_2 - T_3}, \tag{1.4}$$

where h – coefficient of pump thermodynamic perfection; T_2, T_3 – condensation point (of heat consumer) and refrigerant boiling point (of low-potential energy source), K.

Table 1.1 – Temperature and thermal potential of water, located in mine workings of Stashkova mine

Seam	Average depth of location, m	Water inflow, m^3/day	Temperature of mine water, ºC	Heat flow, TJ/day
$C_{10}{}^{u}$	125	9600	12.45	0.30
$C_8{}^{u}$	175	4800	13.95	0.18
$C_6{}^{l}$	240	3240	15.90	0.15
C_5	270	22000	16.80	1.09

To determine K_T of the heat pump using formula (1.4), which uses mine water from a specific seam as a low-potential source of thermal energy, it is necessary to set its temperature (table), the coefficient of pump thermodynamic perfection (assumed to be 0.6) and the temperature of a heat consumer (temperature of hot water entering the heating system, from 50 to 70 °C, depending on the outside air). Scientific and practical interest is also in the performance of a comparative analysis of usage of mine water in heat pumps with other types of low-potential sources of thermal energy (groundwater and natural water flows). In order to do this, graphs (Fig. 1.2) of K_T changes depending on a type of source and temperature of a heat consumer were built in Mathcad software package. In the performed calculations, the following parameters were assumed: during the heating period, the temperature of soil and water bodies is 9 and 5 °C, respectively.

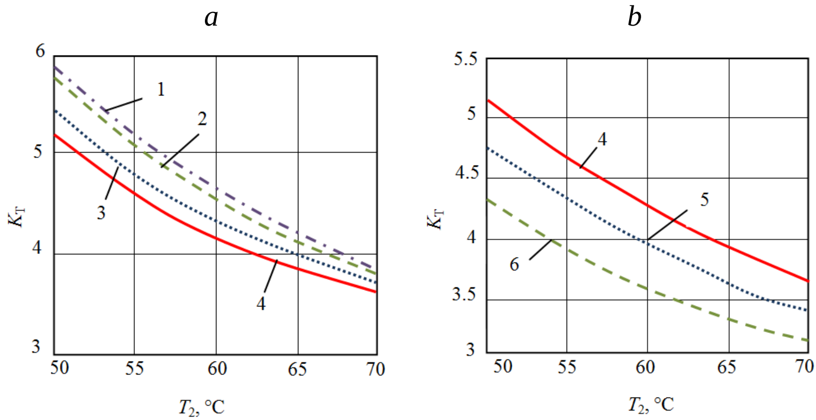

Figure 1.2 – Comparison of a conversion coefficient of a heat pump when using as a source of low-potential energy: 1 – 6 mine water of seams C_5, C_6^l, C_8^u, C_{10}^u, soil and surface water bodies, respectively.

Analysis of the obtained data indicates an increase of a conversion coefficient of the heat pump with increasing depth of pumping out of mine water, as well as its decrease with increasing temperature of the heat carrier supplied to the consumer. This indicates an increase of K_T with a decrease of the temperature difference between the source and the consumer of heat ($T_2 - T_3$), and, accordingly, its decrease with an increase in this difference. This circumstance unambiguously confirms the advantage of usage of mine water in heat pumps in comparison with other natural sources of low-potential energy.

In order to establish the operational efficiency of a heat pump for heating buildings, in addition to determining the conversion coefficient, it is necessary to calculate the consumption of electricity consumed by them, as well as its cost. The following expressions can be used for this.

$$N_{h.p.} = \frac{Q_2}{K_T}, S_{h.p.} = N_{h.p.} \cdot T_E \qquad (1.5, 1.6)$$

where $N_{h.p.}, S_{h.p.}$ – electric energy, consumed by the drive of a heat pump and its cost, T_E – current electricity tariff for enterprises (1 kW·hr = 1.76 UAH).

Fig. 3 indicates the results of calculations by formulas (1.5) and (1.6). Their analysis shows that the amount of electricity consumed by the heat pump increases with increasing temperature difference between the source and the consumer of heat, as well as with the amount of mine water used.

The cost part of a geomodule should also include electricity consumed by a centrifugal pump for pumping out the mine water from mine workings. The following expression can be used to determine its quantity [24]

$$N = k_z \frac{g Q_1 H \rho_v}{\eta_n \eta_p}, \qquad (1.7)$$

where k_z – reserve coefficient, assumed depending on a pump drive; g – free fall acceleration; Q_1 – well inflow; H –depth of a seam location; ρ_v – water density; η_n, η_p – pump and heat transfer efficiency.

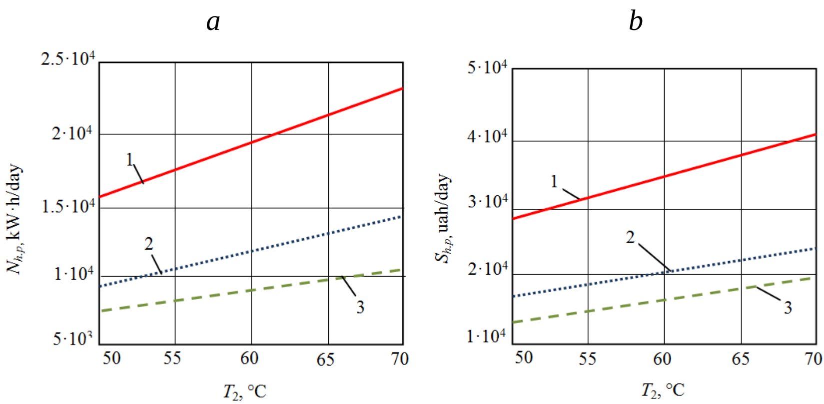

Figure 1.3 – Consumption (a) and cost (b) of electric energy consumed by a heat pump when using: 1 – 3 mine water of seams C_{10}^u, C_8^u and C_6^l respectively.

It should be noted that the operational cost of the geomodule (*Z*) is defined as a sum of a cost of electricity that supplies the centrifugal and heat pumps, and the profit (*P*) is defined as the difference between the cost of thermal energy produced by the geomodule and the electrical energy consumed by the pumps. Fig. 1.4 shows the values of these indicators. When performing the calculations, the tariffs for heat energy currently in Ukraine were assumed (4.18 GJ ≈ 1416 UAH).

As can be seen from the obtained results, the profit from operation of the geomodule is estimated to be tens of thousands of UAH per day, which is very effective in the conditions of modern Ukraine.

However, it must be kept in mind that the obtained results are indicative and do not consider the initial capital costs for drilling wells (in the condition of their absence in the mine field) and industrial equipment (centrifugal and heat pumps, heat supply systems, etc.). However, they can be used in preparation of investment projects and business plans aimed at alternative heat supply systems for buildings.

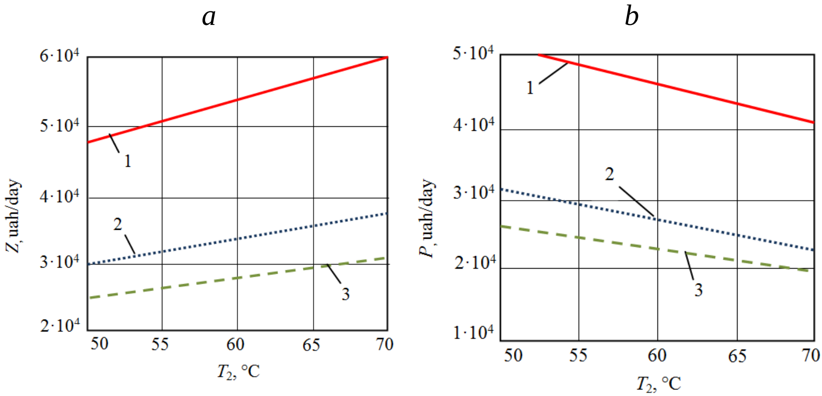

Figure 1.4 – Total expenses for electricity (a) that supplies a geomodule operation and a profit (b) gained from its operation. See designations in Fig. 1.3.

Scientific, practical, and economic interest is the construction of complex graphs of a magnitude of the predicted profit, when the suggested geomodule is in operation. For this, Fig. 1.5 shows the changes in this parameter depending on the amount of mine water pumped out from a depth of 200 m and the temperature of a heat consumer, and fig. 6 shows the value of the same indicator depending on a depth of pumping out and the temperature of a consumer with a well inflow rate of 5000 m^3/day.

According to the tasks formulated in this paper, in addition to the economic indicators of the suggested geomodule, it is necessary to determine the environmental expedience of its usage. This can be performed by establishing the prevention of CO_2 emissions when using heat pumps for heating buildings instead of traditional energy sources (coal, oil products and natural gas).

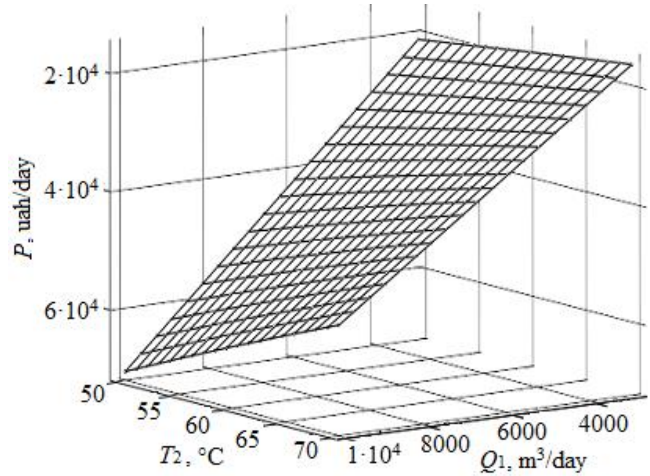

Figure 1.5 – Predicted profit from geomodule operation depending on the amount of mine water pumped out and a temperature of a heat consumer.

To solve the problem, use the method of calculating emissions of greenhouse gases [6. 22, 34], according to which the calculation of CO_2 emissions (tonnes/day) for each type of fuel is performed by the formula

$$E = Q \cdot K_1 \cdot K_2 \cdot K_3 \tag{1.8}$$

where K_1 – coefficient of oxidation of carbon in a fuel (coal – 0.98, oil products – 0.99, gas – 0.995); K_2 – coefficient of carbon emissions (coal – 25.58 tonnes/J, oil products – 20.84 tonnes/J, gas – 15.04 tonnes/J); K_3 – coefficient of conversion of carbon into carbon dioxide (3.66).

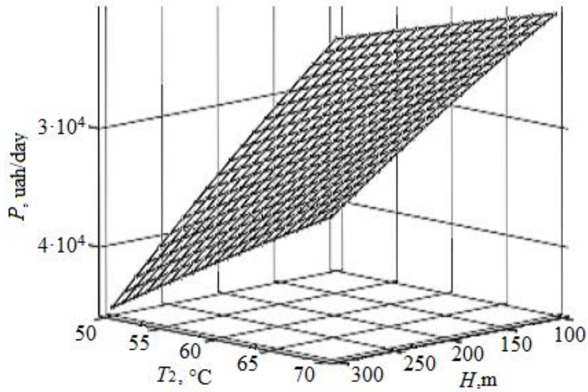

Figure 1.6 – Predicted profit from geomodule operation depending on a depth of pumping out of mine water and the temperature of a heat consumer.

Fig. 1.7 shows the results of calculations performed by the formula (1.8). At the same time, the reduction of CO_2 emissions was determined both for the daily period of time (a) and for the entire heating season (b, November – March ≈ 150 days). An analysis of the obtained data shows that the amount of reduction of CO_2 emissions largely depends on the consumption of mine water and taken as an alternative source of heat supply. On average, when the geomodule is working at Stashkova mine at full capacity (when using mine water from all 4 layers for heating), this value is 120 tonnes/day, which corresponds to preventing 18,000 tonnes of CO_2 from entering the atmosphere during the heating season and clearly indicates the environmental expediency of the suggested geotechnology.

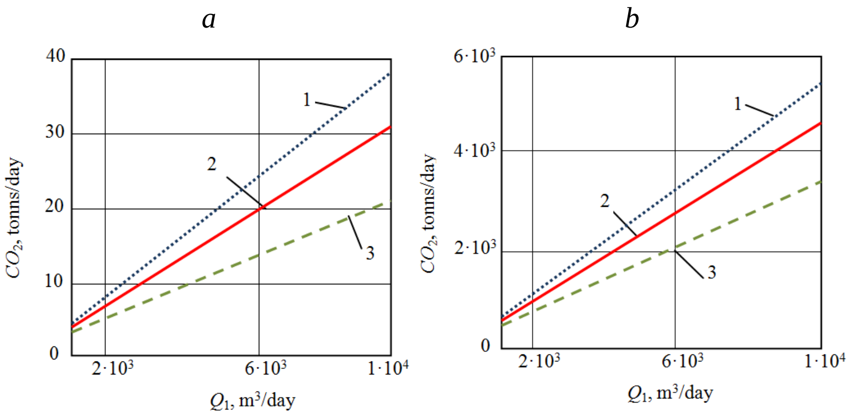

Figure 1.7 – Prevention of CO_2 emissions per day (a) and season (b) during geomodule operation compared to other alternative options of heat supply: 1 – 3 – coal, oil products and natural gas.

Conclusions. Analysis of operation of energy industry and the current ecological situation in coal mining regions of Ukraine indicates the need to preserve non-operational and unprofitable mines. The main problems arising from this are related to regulation of groundwater level, both in liquidated and neighboring operational mines. In addition, after the closure of mines in areas of coal enterprises, limited reserves of other types of natural energy carriers lead to a cessation of heating of buildings and a need to find alternative sources of thermal energy. At the same time, closed mines possess its considerable technogenic resource concentrated in mine water.

For the purpose of a complex usage of a thermal resource of water from flooded mine workings, a geotechnical scheme is justified, which makes it possible to economically expediently stabilize energy consumption and ecological situation in coal mining regions by combining technologies for heat generation, mine drainage, water regime control and mine water treatment in a single module. In accordance with calculations performed in Mathcad software package, the usage of mine water as a source of low-potential energy in heat pumps in comparison with other alternatives (groundwater and surface watercourses) gives their greater heat conversion coefficients (5.2 – 5.8 at T_2 = 50 °C and 3.2 – 3.9 at T_2 = 70 °C).

Evaluation of economic efficiency of the suggested geotechnological scheme was performed by determining the profits from its operation. This indicator was calculated as the difference between the cost of thermal energy generated by the geomodule and the electric power consumed (centrifugal and heat pump). It was established that the profit from operation of the geomodule, depending on a horizon of mine water pumping out and the temperature of a heat consumer, varies from 20 to 55 thousand UAH per day. In addition, the usage of this geomodule for heating buildings instead of traditional energy carriers (coal, oil products and natural gas) significantly reduces emissions of CO_2 into the atmosphere (up to 120 tonnes/day when using mine water from all horizons for heating).

Further development of this work is expedient by increasing the accuracy of the used calculation scheme by considering changes in water temperature during the movement and the impact of operation of several wells at once. In addition, a more detailed economic assessment of the suggested geotechnological scheme, based on the establishment of capital expenses for its creation and modern investment criteria, is needed.

2. Geotechnical Schemes to the Multi-purpose Use of Geothermal Energy and Resources of Abandoned Mines

Last decades have been demonstrating the grow thing geothermal energy share in the world energy resource balance [31]. This process is also typical for Ukraine with some domestic features depending on economical, climatic, and geological factors. The most common ways of using geothermal resources in Ukraine are deep boreholes and ground source heat pumps; besides, mine and municipal sewage waters can be leveraged as a technically achievable resource. Some of these sources have much bigger potential especially in the areas changed as a result of industrial activities and intensive building.

Rock temperature within the Ukraine's territory on the depth of 1000 m varies from 20 to 70°C, and on the depth of 3000 m it ranges from 40 to 135 °C. Heat flux density ranges from 25-30 to 100-110 mW/m^2 [35]. The maximums of temperature and heat flux were measured in mountainous areas in Crimea peninsula and Carpathians. Potential geothermal resources amount to 27,3 million m^3/day of thermal waters. Taking into account cogeneration capacity and thermal water specifics these resources can be estimated at 84 million GCalories per year [36]. The big thermal water resources are concentrated in West side of Carpathians (490 MW), Black Sea coastal area (4900 MW), and Crimea (37600 MW).

About 9,3 million houses on homesteads in Ukraine have the total heated area of more than 510 million m^2. They need roughly 160 million MWh for heating and hot water supply annually. In principle, this demand can be met by ground source heat pumps. The total country's potential that can be used by ground source heat pumps amounts 157530 MWh/year, with technically achievable resource being estimated at 71,4%, but only 6,7 % of that is profitable to use nowadays. Major limitations on putting heat pumps into wider practice are high installation costs and long payback time. F. e., the costs for a heat pump device of 4-5 kW power range currently from 3000 to 7000 €; an increase in power to 10-15 kW raises the costs up to 5000-10000 €. Passive cooling mode would be more profitable, which would ensure the savings 90-95% of costs; however this it is possible in summer time only during 100-150 days and is applicable to southern regions of Ukraine. Maximal estimated savings owing to reduction of fuel consumption amount 700-1000 € annually, which is not profitable under the conditions of high interest rates.

Besides, Ukraine has the vast resource of low-potential heat in mining lands. Annually more than 500 million m^3 of mine water are pumped just in Donetsk coal basin and discharged into ponds and rivers. The temperature of this water ranges from 16 to 22 °C depending on the season; the mine waters temperature deeper than 800 m may reach 30–33 °C. The annual low-potential heat loss is estimated at 5 million GCalories [36, 63]. Use of this resource is restricted by many technical problems including high salt content (up to 60 g/l) and the requirement to isolate mine water regarding in order to protect surface and ground water.

There are now probably only a few examples of mine water heat recovery in Ukraine. A heat pump system implemented at the mine “Blagodatnaya” of “DTEK Pavlogradugol” (Central Ukraine) has heat output of 800 kW at mine water flow rate 200 m^3/h [53]. Mine water temperature of 16°C is increased by heat pumps up to 42–45°C. In case of additional using low-potential heat of waste water from baths at 30 °C the rate of heat transformation growths to 7,0–8,0.

The total annual volume of municipal waste waters is estimated at about 3,74 million m^3 (National Report… 2010). The waste water temperature ranges from 12 to 20 °C depending on the season. The annual technically achievable quantity of this kind of heat energy equals to 18 million tons of s. f. However, there are technical difficulties to recover sewage water heat regarding to obsolete underground infrastructures and water supply facilities.

Nowadays the total potential resource of geothermal energy is not used in Ukraine properly (Table 2.1) and is still one of the lowest among the industrialized countries of the world.

Table 2.1 – Use of geothermal resources in 2010 [31]

Country	Capacity, MW	Annual Use, GWh/yr	Annual Use per capita, KWh/(yr person)*	Capacity Factor
Germany	2 485,4	3 546,0	43,35	0,16
Russia	308,2	1 706,7	11,9	0,63
Ukraine	10,9	33,0	0,72	0,35
U.S.A.	12 611,4	15 710,16	49,87	0,14
World	50 583	121 696,0	17,38	0,27

* Calculated using [31]

The analysis of technical and geological conditions reveals the fact that geothermal energy use would often become profitable in case of combination with other geotechnologies or environmental protection measures, particularly in man-changed environments, primarily in mining lands. The multifaceted and multi-purpose engineering solutions could significantly increase the effectiveness of geothermal applications and facilitate putting into practice these technologies in Ukraine; these would be of interest also for the countries that have similar natural conditions and extensive mining.

Multi-purpose geo-technological schemes considered in this paper include

1. Coupled regulation of water flows and low-grade heat extraction at an abandoned mine.
2. Using heat energy of residual coal reserves in flooded mines.
3. Combining an underground hydropower plant (UHPP) with heat pumps.
4. Combining heat recovery and water supply.

This paper describes the principal features of these promising engineering solutions in terms of geotechnological design.

Coupled regulation of water flows and low-grade heat extraction at an abandoned mine

Mined out rocks are commonly quite permeable due to underground mining and generated excavations, man-made fissures and other disturbances [69]. This intensifies ground water flow and results in rising ground water head and flooding the land surface. At the same time, natural river beds are typically draining the shallow aquifer that accumulates low-potential heat fluxes and dissolved toxic compounds applied in mining. In this regard, it is reasonable to combine heat recovery with water treatment and purification technologies e. g. membrane distillation that is efficient economically in the presence of low-grade heat.

The idea of this scheme consists in simultaneous water-regulating drainage, water withdrawal for treatment and heat pumps by the same gravity-driven drainage system [52]. The major elements of the technological scheme are shown in Fig. 2.1. Here

Q_1 is the discharge of mine water withdrawn by the drain and delivered to pre-treatment facilities,

T_1 is the temperature of mine water withdrawn by the drain,

Q_2 is the discharge of mine water withdrawn by the drain and delivered to the consumer(s) for heat recovery and cleaning,

T_2 is the temperature of water heated by heat pumps,

$Q_{2,c}$ is the discharge of water to the natural drain after use,

$T_{2,c}$ is the temperature of cooled water,

K_1, K_2, K_3, and K_4 are hydraulic conductivities of rocks disturbed by mining, naturally permeable rocks, fluvial deposits, and aquitard respectively ($K_1 > K_2 > K_3 > K_4$).

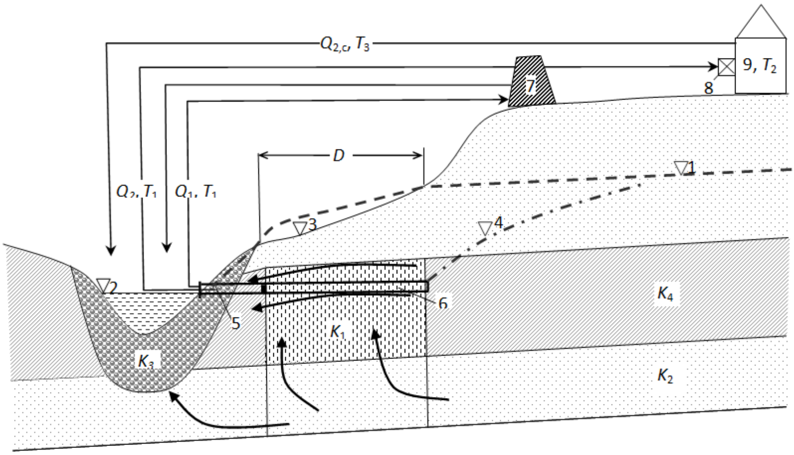

Figure 2.1 – Water flows and heat fluxes in a mined out area: 1 – ground water level in the unconfined aquifer, 2 – water level in the surface water body, 3 – ground surface elevation, 4 – ground water level in the confined aquifer, 5 – the underground drainage gallery, 6 – main haulage road, 7 – water treatment facilities, 8 – heat pumps, 9 – heat consumer (s)

Mine water at the temperature T_1 of about 15–20 ºC is transported to heat pumps at a rate Q_2; then it is heated up to the operational temperature T_2 of 40 to 55 ºC depending on the season and used for heating residential and industrial buildings. Some portion of heated mine water can be used for producing potable water in membrane water treatment units effective in the presence of low-grade waste heat. After cooling to the temperature $T_{2,c}$ of 10 to 12 ºC water is discharged to a natural drain at a rate $Q_{2,c}$. In this case, the specific flux of heat recovered from the drainage system amounts 33.5 MJ/day.

The drained area "D" affected by underground mining requires systematic surface drainage; it can be enhanced by vertical boreholes having self-drainage effect. These boreholes are most effective when combined with long-wall excavations of a closed mine. This way of heat recovery excludes recirculation of water as heat transfer agent transported from flooded excavations to the consumers. Therefore, this design allows preventing from ground water rising; it provides also cleaning of mine drainage water that may contain toxic compounds after seepage through mined out rocks. Such a combination increases the efficiency of heat pump performance.

Using heat energy of residual coal reserves in flooded mines

The available residual coal reserves in flooded mines of Ukraine are estimated at 2 billion tons; most of them are suitable for underground combustion [8]. Besides, there are natural and man-made underground reservoirs (storage capacities) in mining lands where mine water as heat transfer agent can be temporally stored. Due to high thermal capacity mine water can be used for heating and hot water supply. Although the initial temperature of pumped water from deep excavations (more than 800 m below the ground) attains 30–33 °C, the use of this water for hot water supply requires additional heating to the temperature at least of 45 to 55 °C. This can be done either by heat pumps, which is linked with significant investments, or by means of underground coal combustion.

The second option is preferable in the presence of low-grade coal seams or residual coal reserves that are unprofitable to use in one of the conventional ways. The abundance of residual coal in flooded and closed mines makes in-situ combustion of coal an attractive way for heat and hot water supply in post-mining lands. The successful experience of underground coal gasification with extraction of overheated steam at the site in Rocky Mountains, U.S.A. [15, 30] evidenced the prospects of this geotechnology.

The main feature of this scheme consists in using low-grade heat of mine waters of a flooded mine with periodical heating by combustion of low-quality coal seams regarding to seasonal variations of energy consumption. This approach allows heightening the water temperature, eliminating boiler-houses as heat generating facilities for local needs, and, possibly, creating compact modules for specific purposes, f. e. to heat greenhouses.

The hydrothermal module concept and feasibility studies [18, 47, 48, 49] imply using both residual resources of coal and geothermal energy (Fig. 2.2). Here

Q_1 is the gas flow rate from the gasification channel,

q_1 is the heat flux of the gas extracted from the gasification channel,

q_2 is the heat flux from the gasification channel to surrounding rocks,

T_1 is the temperature of the gas in the gasification channel,

Q_2 is the pumping rate of heated ground water withdrawn from the aquifer over the bed confining the gasification channel above,

T_2 is the temperature of ground water above the heated aquitard overlying the coal seams burned,

T_3 is the temperature of withdrawn heated ground water delivered to the consumer.

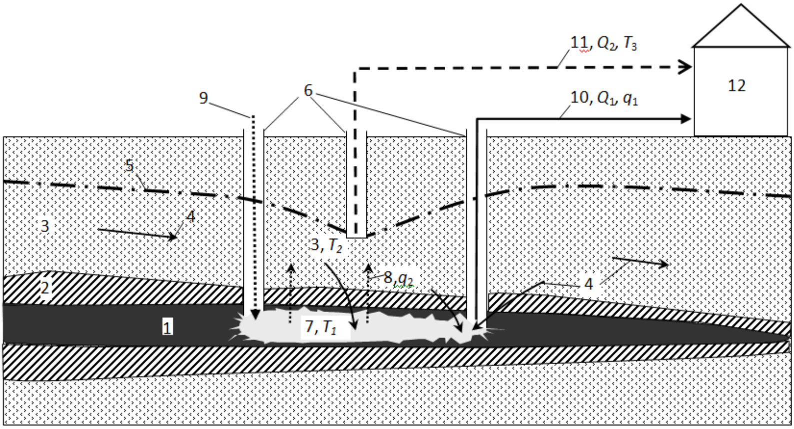

Figure 2.2 – Water flows and heat fluxes in a hydrothermal module: 1 – coal seam, 2 – low-permeable rocks, 3 – aquifer, 4 and 5 – ground water head and flow direction, 6 – wells, 7 – gasification channel, 8 – heat flux to the aquifer, 9 – air blowing, 10 – gas cleaning and transportation, 11 – hot water transportation, 12 – heat consumer

When coal is burned at a temperature T_1 of 900 to 1000 ºC the produced gas is diverted to the surface and then delivered to the consumer(s). The combustible components of the diverted gas bring the heat flux q_1 generated in the gasification channel. The rest part of emerging heat disperses from the channel to surrounding rocks; mostly it is transporting with gas leaks through a low-permeable confining bed to the overlying aquifer and heats ground water. Ground water temperature T_2 may reach 100 ºC under certain conditions depending on the combustion intensity and ground water pumping rate. The hot water delivered to the consumer is cooling and discharged into unused aquifers within the underground gasification site. This technology has to be applied in winter; thus, coal combustion has to be started just before the heating season. The specific heat flux received by the consumer from heated ground water per 1 m^3 of coal burned daily is estimated at 146 MJ/day.

Combining an underground hydropower plant with heat pumps

Electrical power supply networks in mining lands are known to be susceptible to daily overloads; this requires additional power generating facilities working periodically. The energy of water flowing down from upper to lower excavations in a drained mine could be utilised as an additional resource for this purpose. This became feasible as a result of draining and flooding of adjacent mines and significant changes of ground water heads in comparison to the pre-mining hydrogeological regime. This resource is reasonable to use in combination with heat pumps and underground excavations served as heat storage reservoirs in adjacent flooded mines. Performance of a single UHPP in a partially flooded mine has been discussed in details in [47].

The proposed combination of the UHPP and heat pumps is demonstrated in Fig. 2.3. Here

Q_1 is the rate of pumping the water withdrawn from deep excavations and discharged to the retention pond,

T_1 is the temperature of mine water pumped,

Q_2 is the flow rate of the water delivered to heat pumps in winter,

T_2 is the temperature of the water delivered to heat consumers,

$Q_{2,c}$ is the discharge of cooled water to mine excavations,

$T_{2,c}$ is the temperature of cooled water to be discharged to mine excavations,

Q_3 is the emergency discharge of water from the retention pond to the turbines of the UHPP in case of peak consumption of electricity,

Q_4 is the discharge of the water from the retention pond to the surface water bodies or watercourses,

Q_5 is the discharge of the water pumped from the mine in case of flooding of an adjacent active mine.

During the periods of the minimum electricity consumption the UHPP operates in the pumping mode, delivering water to the surface at a rate Q_1 and the temperature T_1 of 30 to 33 ºC to the retention pond. The maximum load on the power supply system is attained when pumps are operated in the hydraulic turbine mode and generate electricity. The turbine pump is rotating under the pressure of drainage water with a discharge Q_2, taking water from the sediment pond on the ground surface. Implementation of this proposal requires increasing the capacity of water tanks and the pumping rate, as well as installation of reversible hydraulic turbine engines with an electric machine capable of running either as an engine or a generator.

During the heating season from November to March a portion of mine water at the temperature T_1 is transported directly to heat pumps with the discharge Q_2; then it is heated to the operational temperature T_2 (45–55 ºC) sufficient for heating and hot water supply. Cooling of the water circulating in buildings lowers its temperature to $T_{2,c}$ = 10–15 ºC; then water is discharged to the mine. Specific heat flux at a flow rate of 1 m^3 per day recovered from mine water for heating buildings averages 83,6 MJ/day. Under the risk of flooding mine drainage operates in the emergency mode at a higher pumping rate Q_5, which allows controlling the safe elevation of the ground water level.

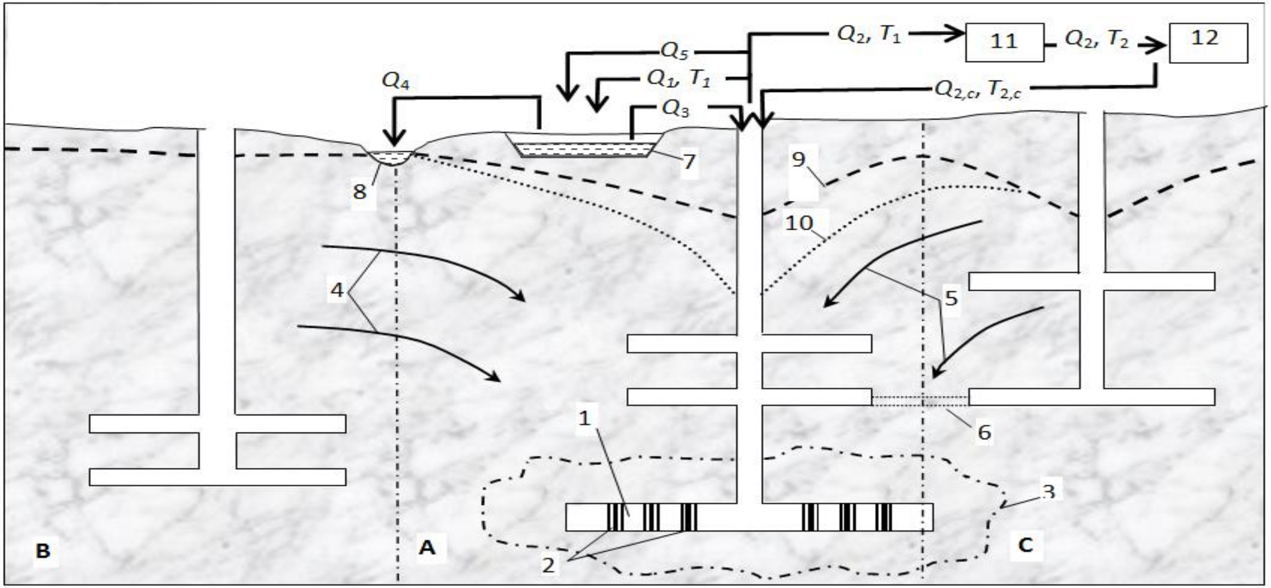

Figure 2.3 – The principal scheme of using mine water heat and generating power in the underground hydropower plant on the area of three mines that are (A) mine with the UHPP, (B) flooded mine, and (C) active mine. 1 – underground excavations, 2 – water permeable dams, 3 – zone of hydrodynamic impact of UHPP on water outflow, 4,5 – ground water flow to the mine with the UHPP from a flooded and active mine, 6 – connecting excavations, 7 – retention pond, 8 – surface water body, 9, 10 – ground water level under normal and emergency operation of the UHPP, 11 – heat pumps, 12 – heat and power consumer(s)

The main feature of this geotechnical design is that the storage and heat resources of disturbed rocks in mines to be flooded are utilised by coupling the UHPP in the shaft with the equipment using mine water heat. Water is pumped from flooded excavations in a daily cycle with alteration of intake and discharge. The module is positioned depending on the volumes of discharge into surface water bodies and pipeline characteristics. The hydropower plant generates electricity during the periods with maximum daily loads in electrical networks.

The UHPP as the tool for smoothing peak loads in electrical networks doubles the effectiveness of heat generating equipment recovering mine water heat. The economical effect increases by the difference in prices for electricity in day and night. Environmental effect is reached by keeping the safe elevation of the ground water level, which prevents from flooding the land surface without additional efforts.

Combining heat recovery and water supply

Ground water reserves in southern regions of Ukraine are poor and do not meet the local needs for supplying potable water without shortages. This is due to commonly brackish ground water in the shallow aquifer that does not meet drinking quality standards. Regarding to population density in these regions the centralized water intake and water treatment f. e. desalinization of this water will be not profitable.

The major feature of this design consists in coupling of water intake and re-circulating facilities in one module that provides utilisation of low-potential heat and partial extraction of water for desalinization that should meet drinking quality standards after treatment. This design implies modular arrangement of heat and water supply facilities for building as well as the option to use ground water of low quality for producing potable water, which makes such a technology economically more attractive. The design implies separated subsurface storage of the water heated in summer through a “warm” well and the water cooled in winter through a “cold” well. The notations in Fig. 2.4 are following.

$Q_{1,s}$ is the pumping rate of ground water withdrawn for cooling the building in summer from the “cold” well,

$T_{1,s}$ is the temperature of ground water withdrawn from the “cold” well,

$Q_{1,w}$ is the pumping rate of ground water withdrawn for heating the building in winter from the “warm” well,

$T_{1,w}$ is the temperature of ground water withdrawn from the “warm” well,

$Q_{2,s}$ is the discharge of water after conditioning the building in summer to the “warm” well,

$T_{2,s}$ is the temperature of water after conditioning the building in summer,

$Q_{2,w}$ is the discharge of water cooled after heating the building in winter to the “cold” well,

$T_{2,w}$ is the temperature of water cooled after heating the building in winter.

In summer ground water is withdrawn from the “cold” well in the aquifer at the initial temperature $T_{1,s}$ of 10 to 12 ºC. After conditioning the building the water temperature raises to $T_{2,s}$ = 30–32 ºC. Then, some portion of this water is stored in the aquifer through the “warm” well; the rest can be additionally heated, e. g. by available heat pumps or solar panels and then used for producing potable water. Water desalinization and treatment is recommended to carry out in membrane distillation units especially effective in the presence of cheap low-grade waste heat.

In winter ground water is withdrawn from the “warm” well at the initial temperature $T_{1,w}$ of 20 to 25 ºC and then heated by heat pumps to the operational temperature $T_{2,h}$ of 45 to 55 ºC and used for heating and hot water supply. A portion of heated water can also be used for water treatment in membrane units. Cooled water at a temperature $T_{2,w}$ is stored in the aquifer through the “cold" well.

Estimated specific heat flux gained as a result of applying this scheme amounts in summer 82 MJ/day and in winter 54.3 MJ/day.

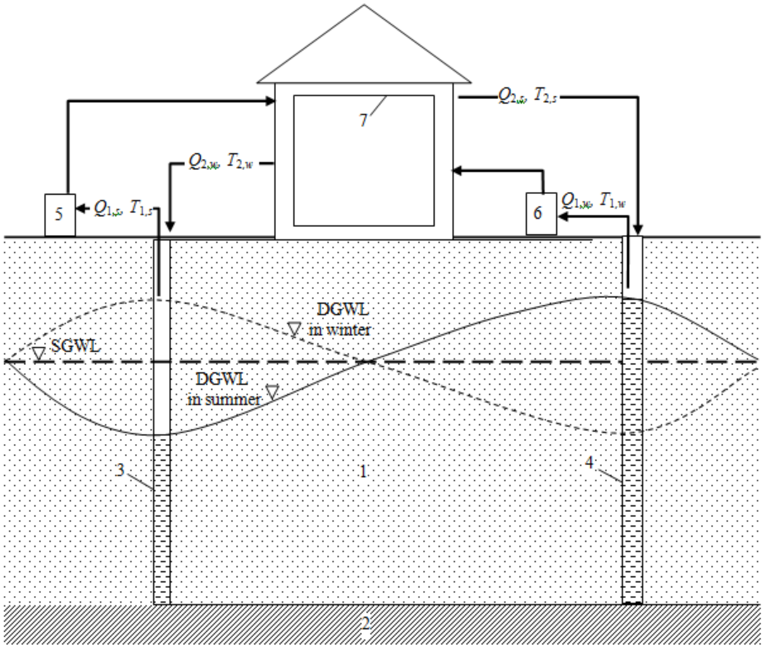

Figure 2.4 – Design of combined low-grade heat recovery and water treatment and supply: SGWL and DGWL – static and dynamic ground water levels, respectively, 1 – shallow aquifer, 2 – aquitard; 3 – “cold” well, 4 – “warm” well, 5 – unit for preparing cold ground water to condition building, 6 – heat pump, 7 – heat transfer loop in the building

Conclusions. Analysis of power generation and energy consumption as well as actual environmental conditions in coal-mining lands of Ukraine demonstrates the growing need for larger exploitation of alternative energy sources, particularly, geothermal energy and available resources of residual coal and man-made heat and water storages in abandoned mines. Besides, the problems linked with ground water management in post-mining lands, particularly, controlling the ground water level in abandoned and adjacent active mines, have to be solved simultaneously. In addition, shrinking amounts of fossil fuel that can be profitably extracted as a result of mine closure necessitate using alternative sources of thermal energy. This demand can be met by leveraging the vast amounts of natural and man-made energy resources in Donetsk coal basin formed as a result of long-term underground mining, primarily, warm mine waters and residual low-grade and thin coal seams.

Three developed engineering designs aim to use mine water waste heat of residual coal reserves in flooded mines in combination with environmental geotechnologies. These design include (1) coupled regulation of water flows and low-grade heat recovery at an abandoned mine, (2) using residual coal reserves of a flooded mine, and (3) combining an underground hydropower plant and heat pumps. The fourth geotechnical design combines heat recovery and water treatment for domestic supply by leveraging heat resource accumulated in summer for heating and cold resource accumulated in winter for conditioning the building in summer. This geotechnology is recommended to application in southern areas of Ukraine characterized by poor availability of drinking water and some excess of on-ground heat or cold that can be temporarily stored underground.

The main feature of all proposed designs is combination of power generation or heat extraction with addressing environmental challenges in the man-made environment, mostly in coal-mining lands. Economical feasibility of all developed designs is enhanced due to their multi-purpose nature.

3. Estimation of effectiveness of development of heat potential of flooded mine field

One of the cardinal directions of restructuring the coal industry of Ukraine and restoring the natural regime in coal mining regions is closure of non-operational and unprofitable mines. Due to this, many small mining towns began to have an acute shortage of thermal energy in conditions of constantly growing prices for gasoline and diesel fuel. An example of the present situation is “Novohrodivska 2” mine in Krasnoarmiysky coal-mining region that underwent liquidation by the order of the Ministry of Coal Industry of Ukraine No. 237 of May 24, 2001, with maintaining the level of flooding by drainage regime. The town of Novohrodivka with a population of 15 thousand people is located in immediate vicinity of it (10 km), some industrial and civilian facilities of which remained without heating and hot water supply during the cold season. At the same time, the world scientific and practical experience (Germany, France, England) shows examples of profitable usage of low-potential heat from flooded mines to heat single- and two-storey buildings of various purposes, in comparison with other types of energy carriers. In this regard, the issue of quantitative estimation of thermal and capacitive resources of “Novohrodivska 2” mine, as well as determination of a possibility and effectiveness of its usage for heating buildings, becomes urgent.

Mining-geological and hydrogeological conditions of “Novohrodivska 2” mine in Donbass during liquidation. The examined mine, located in a southern part of Krasnoarmiysky coal-mining region of Donbass, started operation in 1951 and has since been developing seams k_8 and l_1. The upper limit of coal seam development has a mark of +120 m, above which rocks are mostly filled with water [29] to the mark of the local drainage base of groundwater in the valley of

r. Solona (+155 m). Closed Korotchenko mine is from the south of "Novohrodivska 2" mine, and operating mines "Novohrodivska 1" and "Rossiya" are from the north and east.

The mine field is geologically and structurally located within the southwestern wing of the Kalmius-Toretska depression and is confined to the footwall of a large regional tectonic disturbance – Selidovsky thrust fault. Mid-Carboniferous sediments (C_2^6 and C_2^5), overlapped by Paleogene-Neogene sands and Quaternary loamy soils are present in a structure of the area. Series C_2^5 contains a large amount of sandstones and a small amount of coal [29] in the lower 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 m^3/hr and frequent water influxes from overlying sandstones and limestones.

Balance reserves of coal in k_8 seam in the territory of "Novohrodivska 2" mine in 1995 were estimated to be 988 thousand tons, and industrial – 841 thousand tons. Thus, as a result of losses caused by mining conditions of deposit development, more than 140 thousand tons of coal were left in the ground. In addition, according to the data of PJSC "Donbassgeology", about 120 thousand tons of off-balance reserves of coal are contained within the mine field in the series C_2^5, concentrated in substandard and thin seams k_7^5 and $k_8^н$.

Balance reserves of coal l_1 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 "Novohrodivska 2" mine during liquidation, the properties and composition of which are given in Table 3.1.

Table 3.1 – Properties and grade composition of coal in the territory of "Novohrodivska 2" mine

Seam index	W^a, %	$V^г$, %	$Q_б^г$, MJ/kg	Coal rank
k_8	1,3 – 3,2	34 – 40	32,81 – 35,01	G
l_1	5,0 – 10,2	40 – 44	31,12 – 32,51	D
k_7^5	1,5 – 2,5	38 – 46	33,10 – 33,53	G
l_4	1,1 – 2,4	33 – 39	33,70 – 33,86	G

Data analysis of Table 1 shows that the moisture content of coal of mine area by seam samples varies in a wide range – from 1.1 to 10.2%, averaging 3–5%. The devolatilazation is also quite diverse, with an average value of 39 %, it varies from 33 to 46% [61]. The specific heat of combustion of coal varies slightly and on average is 32 MJ/kg. The sulfur content ranges from 2.5 to 3.5 % (Group 3 of sulfur content). It should be noted that according to their physico-chemical characteristics, all the coals of series C_2^6 and C_2^5 are suitable for development by the method of underground burning.

The hydrogeological conditions of "Novohrodivska 2" mine field are closely connected to its geological structure [41]. Mine water of "Novohrodivska 2", as well as water of adjacent mines, was characterized by sulphatic magnesium-calcium-sodium composition and mineralization of 3.1 – 3.4 g/dm^3 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 m^3) practically did not affect their chemical composition. At the present time, the mine water has mineralization of 3.3 – 3.7 g/dm^3 and contain the following basic microcomponents (mg/dm^3): 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. 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 enter the stream, water salinity and hardness in it decrease to 2.2 – 2.7 g/dm^3 and 15.0 –21.7 mmol/dm^3 respectively.

Development of a numerical model and solution of geofiltration problems in a coal massif disturbed by mining. Creation a conceptual model and schematization of hydrodynamic processes in a mine field. The model is based on the data of geological and hydrogeological structure of "Novohrodivska 2" mine field. Model created in the licensed software «MODLOW v. 4.5» (Schlumberger Water Services, Canada), displays two industrial layers, a separating layer between them, as well as the roof of l_1 seam and the bottom of k_8 seam. As a result, it contains five layers with angles of inclination corresponding to their mining and geological conditions, and has an area of 20 km^2 (4000 x 5000 m) (Fig. 3.1).

Thicknesses of productive strata in the model were assumed in accordance with the dependency of permeability of the underworked rock massif on a multiplicity of its underworking (on average equal to 10 – 40 thicknesses of a coal seam).

To specify the outer boundaries of the simulated area, the recommendations given in the papers [43] were used, according to which the tectonic disturbance (Novohrodivsky fault in the north of the mine field) is a screen in a path of groundwater movement. This determines the necessity of setting the hydrodynamically impermeable boundary in the fault area. In the southwest and southeast, where coal seams have a direct hydraulic connection with watered Paleogene-Neogene deposits, it is necessary to set the boundary condition of the third kind, reflecting the interconnection of groundwater flow rate of the Paleogene-Neogene horizon into the productive stratum with the difference of hydrodynamic pressure in them.

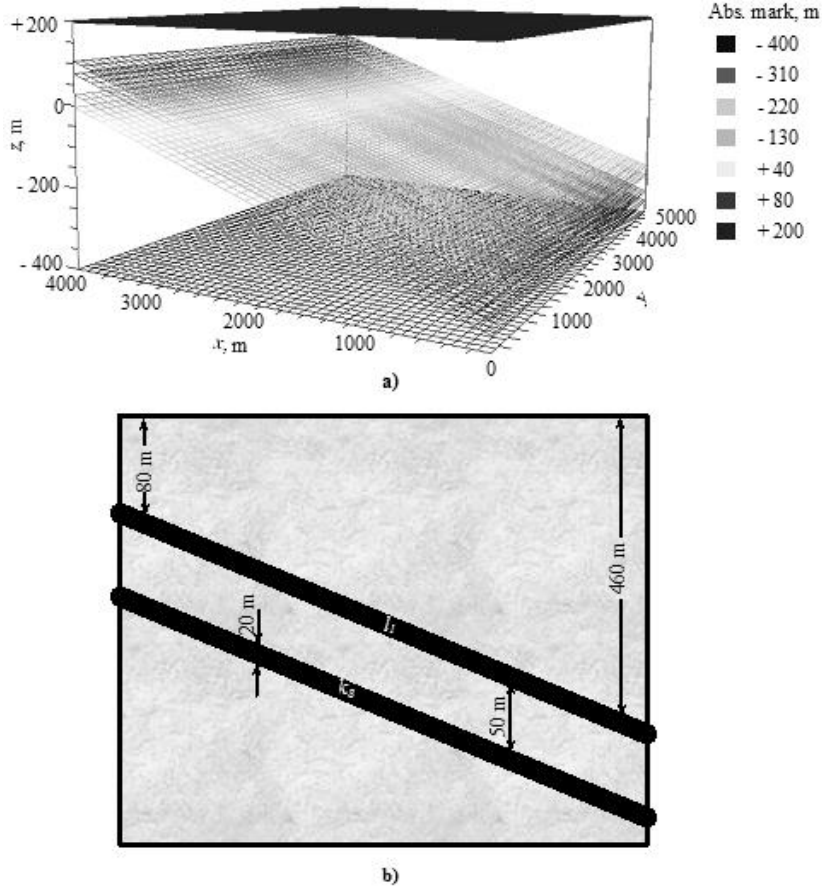

Figure 3.1 – Three-dimensional representation of geometry of simulated area (a) and a schematic section of “Novohrodivska 2” mine (b)

At the same time, the resistance determining the interconnection between the flow rates and the difference in pressure at the bassets of coal seams is determined by the total value of permeability of seams and Paleogene-Neogene deposits, recalculated in accordance with the dimensions of calculated blocks. In places of groundwater cross-flows between ”Korotchenko” – “Novohrodivska 2” mines and “Novohrodivska 2” – “Novohrodivska 1” mines set boundary conditions of the second kind with flow rates corresponding to their specific values (Table 3.2).

Table 3.2 – Distribution of values of specific cross-flows in zones of barrier pillars between mines

Abs. mark of interval of depth, m	**Specific cross-flow (parameter** $km\frac{B}{L}$**)***	
	”Korotchenko” – “Novohrodivska 2”	**“Novohrodivska 2”– “Novohrodivska 1”**
–300…–250	0,36	0,16
–250…–200	4,20	0,12
–200…–150	0,40	0,21
–150…–100	0,36	0,02
–100…–50	0,36	0,10
–50… ± 0	0,26	0,15
± 0…+50	0,58	0,24

*Km – water transmissibility, m^2/day; B and L – the width of a front and the length of a filtration path respectively, m

The internal boundaries of “Novohrodivska 2” mine model are stoping and development workings, displayed by the boundary conditions of the first kind with a hydrodynamic pressure equal to the absolute mark of bottom of coal seams. The position of these boundaries was determined by constructing a plan of mine workings in AutoCAD software environment and transferring the contours of excavation areas to simulated layers (Fig. 3.2). When simulating the mine operation after shutting down water drainage, internal boundary conditions were not set.

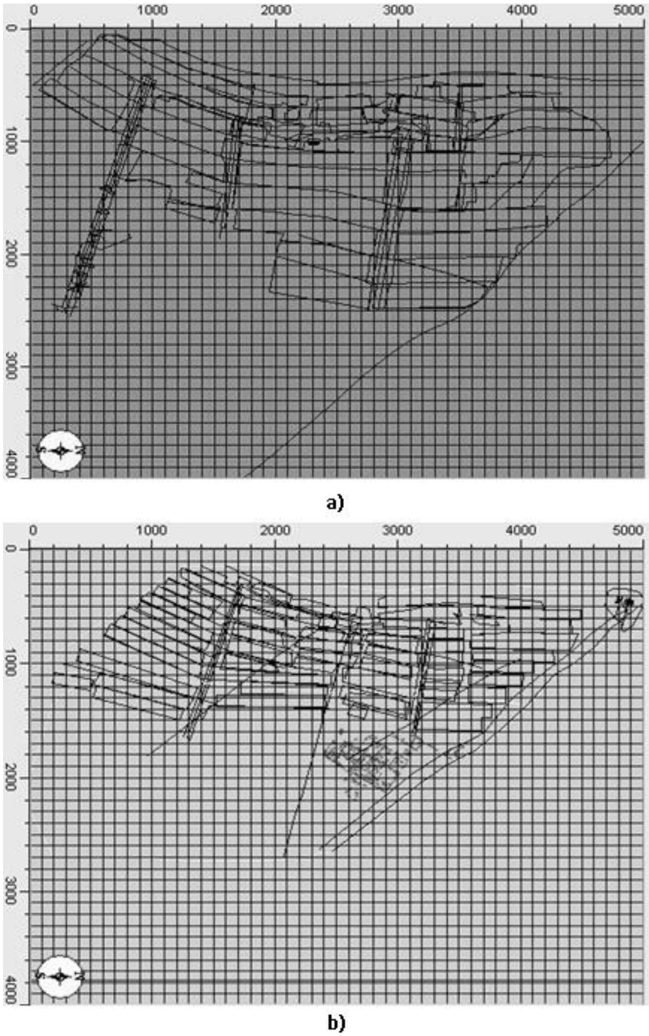

Figure 3.2 – Model contours of stoping areas based on the mine workings plan for the seam k_8 (a) and l_1 (b)

The volume of cavities within the mine field was represented as a sum of crack-porous and mined space. Its change in the model was set layer-by-layer on the basis of mining plans in each developed horizon with a thickness Δz [43]. According to the accepted design scheme, the mine shaft was a perfect borehole into which a time-dependent water inflow moves from aquifers. When schematizing the filtration properties of a massif of rocks, according to generalizations carried out in [60], the value of filtration coefficient of Mid-Carboniferous sandstones forthe interval of 0 – 200 m was assumed to be equal to 0.2 m/day, and for the interval of 200 – 500 m – 0.08 m/day.

Based on the existing theoretical concepts [60, 70] on the permeability of mined rock massif, the value of porosity and filtration coefficient in a range of simulated mine workings was set to an average increase of 7 – 10 times compared with zones outside of mining operations. The model discretization step in space was 100 x 100 m (2000 blocks in total), which made it possible to consider the configuration of workings within the mined seams at the mine scale with sufficient accuracy, while the time step did not exceed 20 days. Infiltration of precipitation in the upper layer of the model was set at 25 % of their average annual amount in the region. Zones of increased infiltration (settling ponds of mine waters, erosional relief dissections) were simulated by setting the intensity of infiltration feeding that is uneven over the area.

Capacitive properties of the strata of rocks lying above the upper boundary of mining operations (+120 m), were determined by the elastic capacity of the aquifer of weathering crust of Carboniferous (10^{-3}) and gravitational water loss of Paleogene-Neogene sands (0.1). The average value of effective porosity in a range of marks

+120…+155 m (basis of groundwater discharge in the valley of the r. Solona) was assumed equal to 0.2.

Solution of an inverse problem to prove adequacy of a developed model. Completed and planned stages of usage of resources of “Novohrodivska 2” mine are shown in Fig. 2 in the time section. The first stage corresponds to the period of mine operation and coal mining, and the second stage – to its liquidation with the operating drainage and maintaining the groundwater level at –157 m in the north wing. The next stage corresponds to the completion of drainage regime and flooding of mine workings to the mark +113.3 m (as of April 15, 2012). During this period, employees of JSC “Dniprogiproshakht” conducted observations of the mine’s flooding rate, which provided data for solving the reverse geofiltration problem within the mine field. The start of operation of a hydrogeothermal module, with the aim of developing the thermal and capacitive resources of the mine for heat supply of Novohrodivka, is expected at the fourth stage.

The developed methodology is applicable to calculation of groundwater level changes within the mine boundaries throughout all four stages of its operation. However, for an adequate prediction of water inflows in the model, it is necessary to perform an epignostic modeling, the purpose of which is to correct a hydrodynamic role of external boundaries of aquifers and their filtration properties [64]. At the same time, the values of hydrodynamic parameters of aquifers should be characteristic of hydrogeological conditions of “Novohrodivska 2” mine. The basis for their variation was the results of pilot filtration works and measurements obtained by the Production Geological Enterprise “Artemivsk hydrogeological party” during the mine operation [27].

The inverse (epignostic) problem was solved under the conditions of non-stationary filtration mode, the main criterion of correctness of the solution of which was the similarity of actual and simulated values of the mine shaft flooding. The results of solution show that the model was able to almost completely reflect the dynamics of water level raising in the system of mine workings during the third stage of mine operation. Fig. 3.2 shows the model distribution of groundwater level in the mine field before and after the drainage shutdown (as of April 15, 2012, at least 2000 days), as well as its intermediate positions throughout the flooding period [19]. In this case, the absolute error between the actual and model level data is within 3 – 11 m, and the relative error does not exceed 10 % (Table 3.3).

Table 3.3 – The error of determining the dynamics of raising water level during flooding of "Novohrodivska 2" mine according to the results of simulation

Time since the beginning of flooding, days	**Abs. mark of flooding water table, m**		**Absolute error, m**	**Relative error, %**
	actual	**model**		
300	–120,50	–110,45	10,05	8,34
900	–1,15	–1,05	0,10	8,69
1200	25,40	22,90	2,50	9,84
1500	95,10	92,12	2,98	3,13
1800	110,80	99,85	10,95	9,88
2000	109,72	113,3	3,58	3,16

Analysis of distribution of groundwater level shows that before the drainage is turned off, the cone of depression follows the contours of mining zones. The largest subsidence is confined to zones where the volumes of developed space are the largest. As flooding occurs, the noted patterns smoothen, while the rise of the groundwater level occurs unevenly, with a slowdown in intervals of the greatest concentration of mine workings and falling behind the water level in the shaft.

Thus, the created geofiltration model of “Novohrodivska 2” mine adequately reflects the dynamics of flooding of workings considering the specifics of mining-geological and hydrogeological conditions of the mine field. By using the suggested approach, it is possible to calculate the change of the level regime, the velocity and direction of filtration of groundwater in various mine horizons when using it to create a hydrothermal module. On the basis of the created and calibrated numerical model of geofiltration, the prediction of position of mine water level at the present time (June 15, 2015) and the beginning of the fourth stage of mine operation (launch of the hydrothermal module) was carried out. The results of solving the problem on April 15, 2012 (see. Fig. 3.3, b) were assumed as basic conditions. The boundary conditions remained the same as in the inverse problem.

Fig. 3.4 shows the predicted position of groundwater level (plan view of hydroisogipsos) within the “Novohrodivska 2” mine field, obtained from the simulation results and characterized by the following features of dynamics of changes of the level surface. When the drainage is shut down, the tendencies to a gradual increase in groundwater level over time and a decrease in the hydraulic slope towards the center of the mine field remain that were established in the epignostic problem. The overall level difference is 30 m. The influence of it raising to the marks of +120...+130 m does not affect the flooding of day surface, since the closing of the upper aquifer of

Paleogene-Neogene sands and the level of flooding of the developed space occurs above these marks.

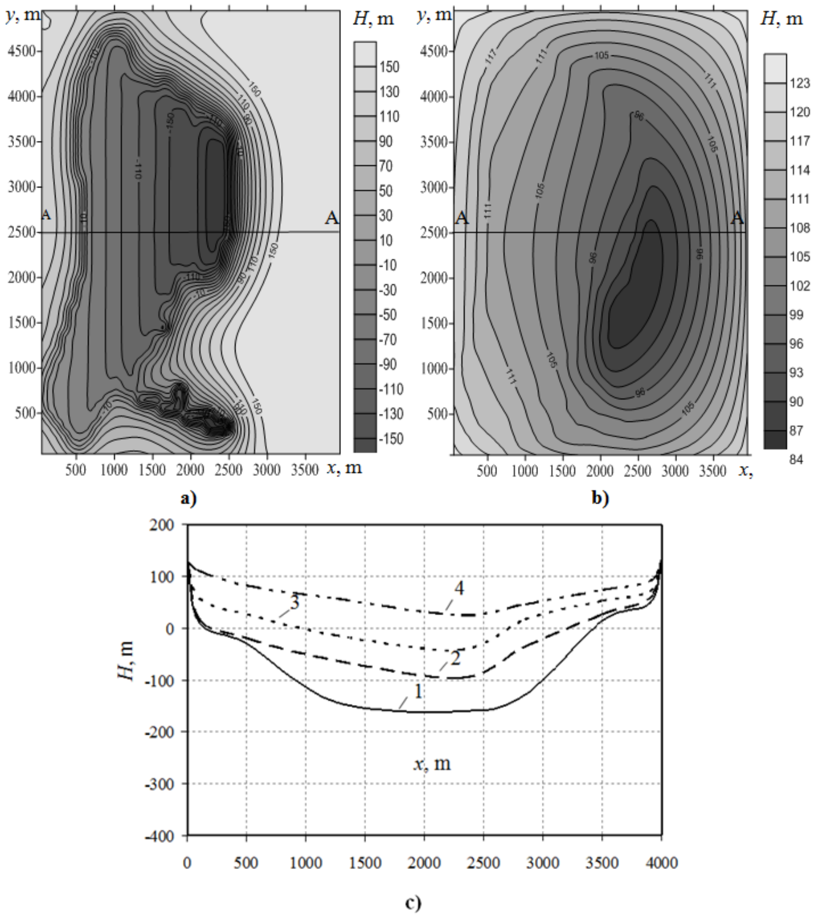

Figure 3.3 – Groundwater level (H, m) in the mine field before drainage shutdown (a), after 2000 days after shutdown (b) and at intermediate times along the profile A – A (c): 1 – 4 – after 100; 700; 1000 and 1500 days after drainage shutdown respectively

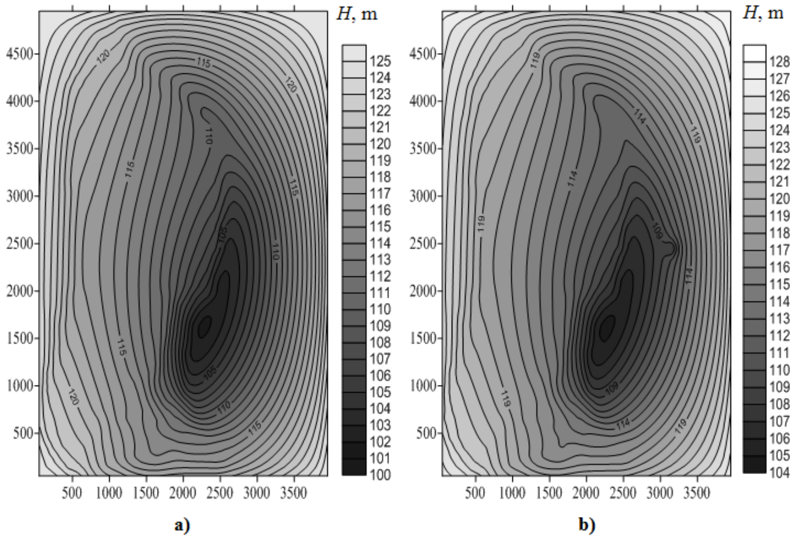

Figure 3.4 – Predicted position of groundwater level within a mine field as of June 15, 2015 (a) and a start of operation of hydro-geothermal module (b)

In general, the model adequately reflects the hydrodynamic situation and makes it possible to establish the main features of filtration within the mine field in existing conditions and with various design decisions aimed at the pumping out and injecting groundwater. The obtained model distributions of levels can serve as a basis for developing geotechnological schemes for a complex usage of thermal energy contained within flooded mine workings for heat and cold supply of buildings of various purposes through a system of operation wells, which is discussed in the next chapter.

Quantitative estimation of a geothermal resource of a flooded mine and profitability of its development with a help of heat pumps. To develop geotechnological solutions aimed at using the heat contained in flooded workings and disturbed rock massif, it is necessary to determine the existing thermal potential of “Novohrodivska 2” mine.

In this case, in the first approximation, it can be assumed that hydrodynamic parameters of seams do not depend on heat transfer processes [19], and the water temperature and temperature of a rock skeleton coincide at every point. Assume that mine water movement within the mine field occurs along the collapsed massif and flooded workings, heat exchange in the computed plane is absent [23], the *H* axis is directed down (Fig. 3.5). The heat flow *q* caused by heat of earth interior enters the flooded mined space from the bottom (from the depths). A neutral stratum of rocks, the temperature of which is constant and equal to the average annual temperature in the region (about +10 °C), lies above, 6 – 7 m below the day surface. Under these conditions, a differential equation of heat conduction about *H* axis considering convection is

$$\frac{\partial^2 T}{\partial H^2} - \frac{V}{a} \cdot \frac{\partial T}{\partial H} = 0, \qquad (3.1)$$

under the following boundary conditions:

$$T = T_1 \text{ when } H = H_1;$$
$$q = -\lambda \partial T / \partial H \text{ when } H = H_2.$$

The general solution of equation (3.1) with given boundary conditions is [19]

$$T = T_1 + \frac{q}{\lambda B}\left[\exp B(H - H_2) - \exp B(H_1 - H_2)\right]; \; B = \frac{V}{a}. \qquad (3.2)$$

In this case, the thermal potential of mine water contained in the flooded workings is determined from the expression:

$$Q = C \cdot \rho \cdot t \cdot V_v. \tag{3.3}$$

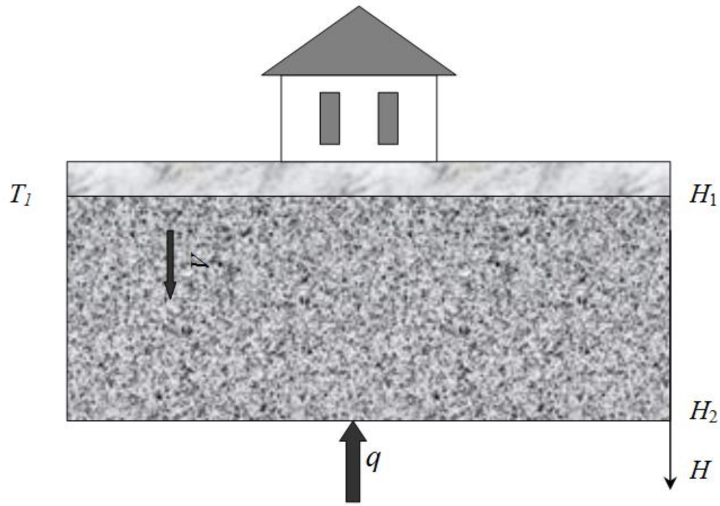

Figure 3.5 – Scheme for calculating temperature of groundwater within mine field

In formulas (3.1) – (3.3): T_1, H_1 – temperature and distance to the neutral stratum; H – depth of location; a, λ – thermal diffusivity and thermal conductivity of water-saturated rocks; V – vertical filtration velocity; Q – quantity of heat; C, ρ, t, V_v – specific heat capacity, density, temperature and volume of mine water, respectively.

Fig. 3.6 shows the temperature and existing thermal potential of mine water contained in flooded workings [23] calculated by formulas (3.2) – (3.3). It should be noted that the results of calculations are in good agreement with the actual data obtained by the Production

Geological Enterprise “Artemivsk Hydrogeological Party” during temperature measurements at various horizons, and the total amount of thermal energy accumulated by mine water averages 1300 TJ [23].

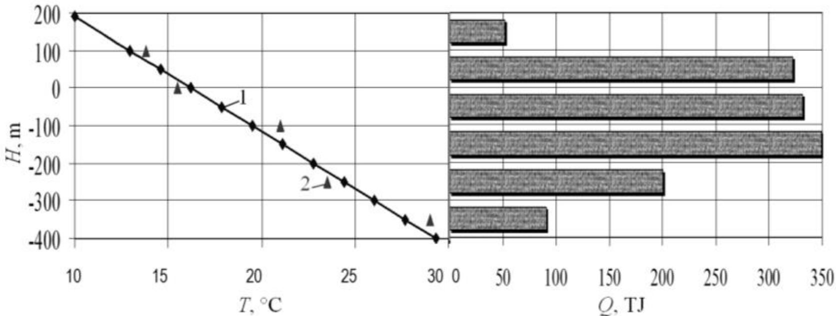

Figure 3.6 – Changes in temperature and amount of heat of water concealed in a flooded massif of “Novohrodivska 2” mine: 1 – 2, calculated and actual data respectively

Usage of heat energy from “Novohrodivska 2” mine during liquidation is associated with the periodic injection and pumping out of mine water from flooded mine workings. At the same time, water cooled as a result of heating the building to 7 °C will flow to the horizon of ±0... +100 m with an average temperature of 12 °C, and water heated as a result of conditioning the buildings to 30 °C will be directed to the horizon with marks of –300… –400 m and temperature 26 °C. There is a two-month period of inactivity between the periods of injection and subsequent pumping out of mine water: April-May – for cooling buildings and September-October – for heating. Due to the temperature difference between flooded horizons and the injected water, they will change their temperature both during the period of operation and during the period of inactivity of the geothermal module. In addition, loss of temperature during the water movement is inevitable in the process of injection of mine water due to lack of thermal insulation of wells. The given thermo-physical characteristics of usage of mine water for heat and cold supply of buildings indicate the need to fulfill predictions for changes of their temperature.

Reducing the temperature of hot water in the well when it is pumped into flooded mine workings can be calculated according to the following calculation scheme [23]

$$T(z,t) = T_n + \frac{G}{\beta}(\beta z - 1) + (T_0 - T_n + \frac{G}{\beta})\exp(-\beta z); \qquad (3.4)$$

$$\beta = \frac{2\pi}{\frac{QCw}{\lambda_a} \cdot \ln\frac{2Z(t)}{d}}, \quad Z(t) = 2\sqrt{a_a t},$$

where $T(z,t)$ – the corresponding temperature at a given depth z after t days since the start of water injection; T_n, T_0 is the temperature of the earth neutral stratum reduced to the well mouth and the water pumped; G – geothermal gradient; β – an indicator characterizing heat exchange with the environment; Q, C_w – flow rate and volumetric heat capacity of the injected water; λ_a, a_a – average coefficient of heat conductivity and thermal diffusivity of rocks surrounding the pipe; d – the outer diameter of the pipe.

The results of calculations by the formula (3.4) are shown in Fig. 3.7 [23]. From the graphs obtained, it is concluded that the temperature of injected water at the well bottom rises first and after some time (approximately by the middle of the injection period) stabilizes.

The average loss of water temperature during the flow along the well are approximately 1.5 °C (no more than 5%). In addition, an insignificant (no more than 0.5 °C) influence of the pumping rate on water temperature was found. Thermophysical properties of rocks characteristic for “Novohrodivska 2” mine were assumed in the calculations: G = 0.026 °C/m; C_w =4187 kJ/m^3; λ_a=245 kJ/m·day·°C; a_a=0.05 m^2/day. Technological parameters of injection: T_0 = 30 °C; d = 0.2 m.

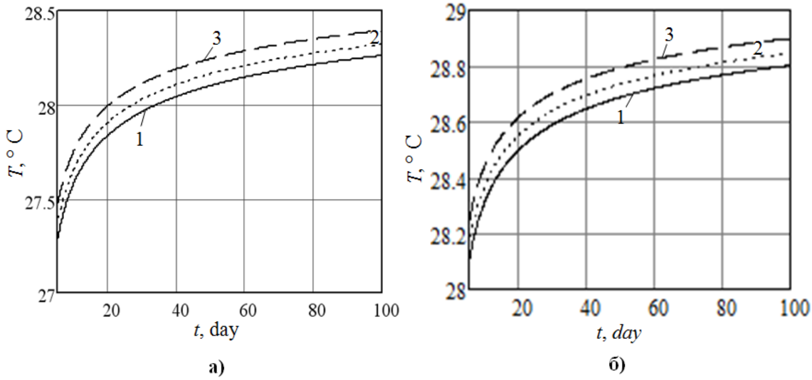

Figure 3.7 – Water temperature change at the well bottom on duration of injection with a flow rate of 450 (a) and 650 (b) m^3/day: 1, 2, 3 – at injection depth of 600, 550 and 500 m respectively

The change of temperature of injected water after entering the flooded mine workings and the rock massif can be approximately determined using the analytical solution of Lapshin N.N. on the basis of Lauwerier solution and formula [19]. These solutions do not consider conductive transfer in the aquifer, which is acceptable at high flow rates and injection rates; however, when developing a real geotechnological scheme that assumes simultaneous injection and pumping out of water of different temperatures through a system of several wells, it is necessary to use a numerical heat transfer model.

$$T(r,t) = T_0 + (T_w - T_0)\operatorname{erfc}\frac{\left(\sqrt{\lambda_1 C_1} + \sqrt{\lambda_2 C_2}\right)\pi\left(r^2 - r_s^2\right)}{Q\, C_в \sqrt{t-\eta}}; \qquad (3.5)$$

$$\eta = \frac{\pi\left(r^2 - r_s^2\right)m}{Q\,\overline{C}}; \quad \overline{C} = \frac{C_w}{C_{sk}},$$

where *T (r,t)* is the temperature of mine water at a distance *r* from the well *t* days after the start of injection; T_w is the initial temperature of groundwater; $\lambda_1 C_1$ and $\lambda_1 C_1$ – thermal conductivity and volumetric heat capacity of the rocks of roof and bottom, respectively; r_s - well radius; r_s is the volumetric heat capacity of rocks containing the injected water.

Using the expression (3.5), it is possible to make a prediction of changes of temperature of water entering the flooded mine horizon. Fig. 3.6, a shows the change of this temperature at different distances from the bottom of injection well. Thermo-physical properties of rocks and technological parameters of injection are assumed as follows: λ_1=221 kJ/m·day·°C; λ_2=150 kJ/m·day·°C; z = 550 m; C_1 =1840 kJ/m^3; C_2 =1656 kJ/m^3; Q = 650 m^3/day.

To estimate the change of water temperature during the inter-heating period, the flow rate of the injection well was conventionally assumed to be 0.1 m^3/day in the formula (3.5), what made it possible to consider only heat loss into the surrounding massif. The results of calculations showed that during this period of 60 days, the temperature of mine water does not fall below 28 °C. The following calculation was made for the period of heating season (November-March) during the pumping out of mine water from a depth of 550 m. It was established that at this time the water temperature decrease was insignificant at first, and then it quite sharply reduced from 28 to 25.5°C.

Similarly, calculations were performed for the case of injection, inactivity and subsequent pumping out of cooled mine water, as a result of heating up the buildings to 7 °C, pumped into the flooded mine horizon at a depth of 100 – 200 m (Fig. 3.8, b). The results of calculations show that during the period of pumping out the temperature of water used for cooling buildings varies slightly (from 8 to 9.5 °C).

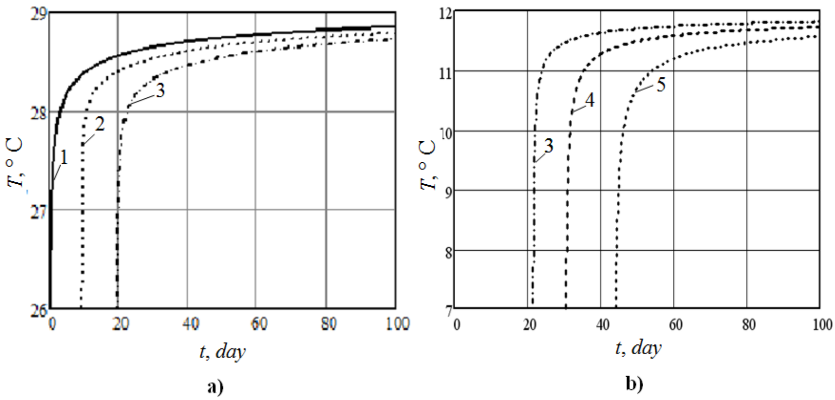

Figure 3.8 – Temperature change of warm (a) and cold (b) water, injected into ”Novohrodivska 2” mine: 1 – 5 – at a distance from the well bottom of 1; 15; 20; 25 and 30 m respectively

At the same time, the conversion coefficients of heat K_h and cold K_c, representing the ratio of the heat output of the pumps to the electricity consumed by them and determined from the following expressions, are taken as the main indicator of pump efficiency

$$K_h = h \cdot \frac{T_1}{T_1 - T_2}; \; K_c = h \cdot \frac{T_2}{T_1 - T_2}, \tag{3.6}$$

where h is the coefficient of thermodynamic perfection; T_1, T_2 – temperature of condensation (of heat consumer) and evaporation of the refrigerant (low-potential energy source), K.

To determine K_h of a heat pump using the formula (3.6), which uses mine water pumped out of the –300...–400 m horizon as a low-potential source of thermal energy, it is necessary to set its temperature change (from 28 to 25.5 °C) determined from the expression (3.5). Also, the coefficient of thermodynamic perfection (assumed to be 0.6) and the temperature of heat consumer (the temperature of hot water entering the heating system, from 50 to 70 °C, depending on the outside air). Analysis of the obtained results shows a slight decrease in K_h (not more than 0.1), caused by a small fluctuation (1–3°C) of the temperature of mine water pumped out during the heating period. Similarly, K_c was determined, the value of which slightly increases (not more than 0.2) by the end of the summer period due to decrease in temperature difference between the heat consumer and the low-potential energy source.

Scientific and practical interest is the performance of a comparative analysis of usage of mine water in heat pumps with other types of low-potential sources of thermal energy (heat of outside air, groundwater and natural water flows). To do this, graphs (Fig. 3.9) were constructed in Mathcad software to change the K_h and K_c depending on the source and temperature of the heat consumer.

Graphs (Fig. 3.10) were also constructed to show heat energy savings during the heating and summer periods when using mine water in heat pumps. The following parameters were assumed in the calculations: during the heating period – the temperature of the soil base and water bodies is 10 and 5 °C respectively, the heat flow for heating buildings in Novohrodivka (15 thousand people) is 600 GJ/day;

in the summer period – heat flow for air conditioning of buildings is 168 GJ/day.

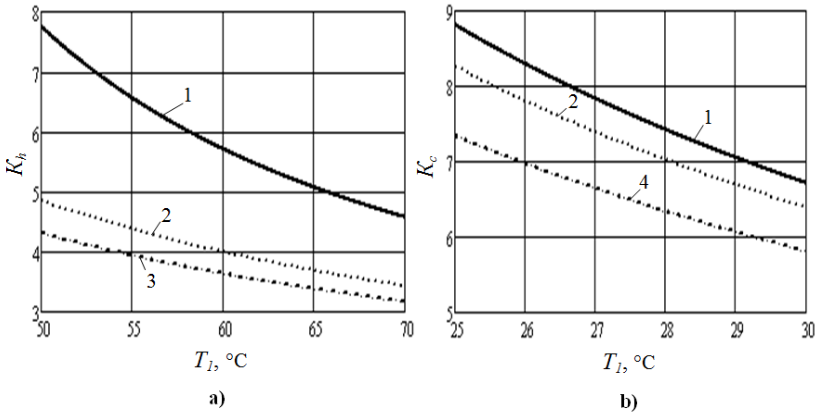

Figure 3.9 – Comparison of conversion coefficient of heat (a) and cold (b) of a heat pump when using: mine water (1), soil base (2), reservoirs (3) and groundwater (4) as a low-potential energy source

Analysis of graphs in Fig. 3.9 – 3.10 shows that with the usage of mine water in a heat pump, the highest heat and cold conversion coefficients are achieved. Their usage is especially efficient in the heating period, causing K_h to be 1.5 and 2 times more than when using heat of the soil base and open water bodies as a source of low-potential energy. When air-conditioning the buildings, pump K_c operating on mine water also exceeds other variants – the heat of the soil base and the groundwater by 10 and 25% respectively.

The amount of energy saved by a heat pump during the heating period when using mine water, in comparison with alternative low-potential energy, is on average 5,000 GJ. During the conditioning of buildings, this value is equal to 300 GJ. The results obtained indicate high efficiency and profitability of using mine water as an energy source in heat pumps.

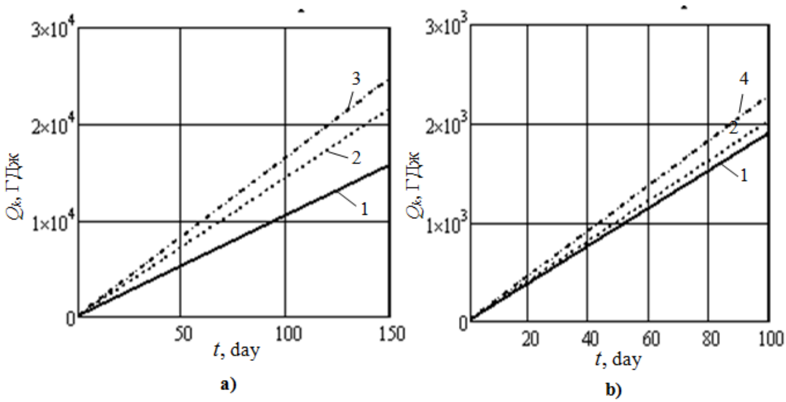

Figure 3.10 – Change of power Q_k used by a heat pump in heat equivalent for heating (a) and air conditioning (b) of buildings in Novohrodivka

Conclusions. Created geofiltration model of the mine field, based on the finite-difference solution of non-stationary planned filtration equations in “Modflow” software, displays the uneven character of permeability and water inflow in a mined massif depending on its crack-porous structure and volumes of the developed space. Performed on a basis of epigenostic modeling, the approbation of the model allowed specifying the hydrodynamic influence of external boundaries of a calculated area and filtration properties of rocks, as well as establishing the dynamics of lowering the pressure of groundwater in zones of coal mining and restoration of their level after mine drainage shutdown. At the same time, the absolute error between the actual and model data of distribution of mine water levels is within 3 – 11 m, and the relative error does not exceed 10 %.

With the help of the model, the predicted position of groundwater level within the mine field at the present moment of time and the planned launch date of the geothermal module was established. The results obtained made it possible to estimate the horizon-by-horizon variation of temperature of mine water and their natural thermal potential of 1300 TJ, within the boundaries of the flooded massif.

The performed thermodynamic calculations for the non-operational massif, based on the results of numerical simulation of geofiltration and analytical solutions, showed that the total heat loss in a process of pumping out, injection and storage of mine water does not exceed 15 %. The usage of mine water with a temperature of 26 – 28 °C as a low-potential energy source in heat pumps, in comparison with other alternatives (soil bases, surface water, groundwater), gives the greatest heat conversion coefficients (4.5 – 7.5), which allows saving a significant amount of heat pump power.

4. Geotechnological Foundations Of Natural-Tecnogenic Deposits Mining In Donbas

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 as for the use of natural and technogenic resources concentrated within the worked-out areas [12, 17, 14]. In coordination of different stages of prospecting, 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 collector which hydrothermal resource is considered as negative one 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 as well as a potential of technogenic hydrothermal deposits, engineering foundation for integrated development of energy intensive resources of coalfields, and mining enterprises under liquidation which can satisfy current thermal requirements of the country. Thus, coordination of development stages of coal deposits on the unified theoretical basis with characterization of geotechnological moduli concerning the use of natural and technogenic energy resource as well as capacity properties of the worked-out rock mass and contiguous areas is both topical and strategic theoretical and practical problem.

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

Substantiation of module of accumulation of heat carriers within water-bearing levels. A system of underground heat accumulation is profitable if only its mining conditions and operating schedules avoid mutual effect of heat envelopes of wells; in this context, thermal losses should not be more than 25%. Taking into consideration complex nature of physical processes and recommendations of the world theory and practice [2, 21], the geotechnology application should be supported by numerical modeling of filtration and heat transfer within a water-bearing level used as a collector of warm and cold water.

When injection and pumpout take place in water forced mode, filtration equation is

$$\frac{\partial}{\partial x}\left(Km\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(Km\frac{\partial H}{\partial y}\right)+Q_{\Sigma}-\frac{K_1}{m_1}\left(H_1-H\right)-\frac{K_2}{m_2}\left(H-H_2\right)=S_s\frac{\partial H}{\partial t}, \quad (4.1)$$

where K and m are filtration coefficient and water-bearing 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 water-bearing level, in overlying water-bearing formation, and underlying water-bearing formation respectively; and Q_{Σ} is time-variant total intensity of water intake and injection by means of wells

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

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

Two-dimensional heat migration within underground water is described by means of the equation

$$\frac{\partial}{\partial x}\left(\lambda m \frac{\partial T}{\partial x} - \rho_w C_w v_x m T\right) - \frac{\partial}{\partial y}\left(\lambda m \frac{\partial T}{\partial y} - \rho_w C_w v_y m T\right) +$$
$$+ m q_\Sigma - q_b - q_t = m\left[n \rho_w C_w + (1-n)\rho_{sk} C_{sk}\right]\frac{\partial T}{\partial t}, \tag{4.2}$$

where λ is heat-transfer coefficient of a water-bearing level 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 a water-bearing level to its roof and bottom; C_w, C_{sk} are specific densities of underground water rock matrix; q_Σ is source intensity as well as heat water flow distributed within a formation

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

where q_i is intensity of i^{th} heat source (water runoff) corresponding to a location of i^{th} well for water injection (abstraction).

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

Thermophysical properties of water are determined for the area of water-bearing level in the neighbourhood of the well.

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

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

Both parts of equation (4.2) division into $n C_w \rho_w$ product helps proceed to the equation

$$\frac{\partial}{\partial x}\left(\frac{\lambda m}{C_w \rho_w n} \frac{\partial T}{\partial x} - \frac{v_x m}{n} T \right) - \frac{\partial}{\partial y}\left(\frac{\lambda m}{C_w \rho_w n} \frac{\partial T}{\partial y} - \frac{v_y m}{n} T \right)$$
$$+ \frac{m q_\Sigma - q_b - q_t}{C_w \rho_w \, n} = m \, R_T \, \frac{\partial T}{\partial t} , \tag{4.3}$$

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

Numerical model, relying upon equations (4.1) and (4.3) with nonstationary sources and water runoffs and heat sinks, makes it possible to describe transient processes of heat transfer with random arrangement of several wells, various temperatures of water being injected and abstracted, nonhomogeneous structure, and variable thickness of the water-bearing level. It is impossible to solve analytically such a boundary heat-transfer problem.

Evaluating thermal balance within water-bearing rocks over underground gas generator. Substantiation of rational parameters to extract heat energy should involve modeling of propagation of geothermal fields being formed within a water-beating seam in the process of coal burning.

Reasonable formulation of a boundary condition in terms of temperature within the water-bearing level bottom over reaction channel is of crucial importance. To determine underground water temperature, three-dimensional shallow-thickness module in the form of a brick is separated within the share of the water-bearing level. The module is located directly over a heat separating seam (i.e. aquifuge) where thermal exchange is taking place (Fig. 4.1). 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 right in 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 [50]

$$U_\Sigma = (q_0 + q_1 - q_2 - q_3)\tau = U_{heat.} T_1 - T_0) \cdot B; \qquad (4.4)$$

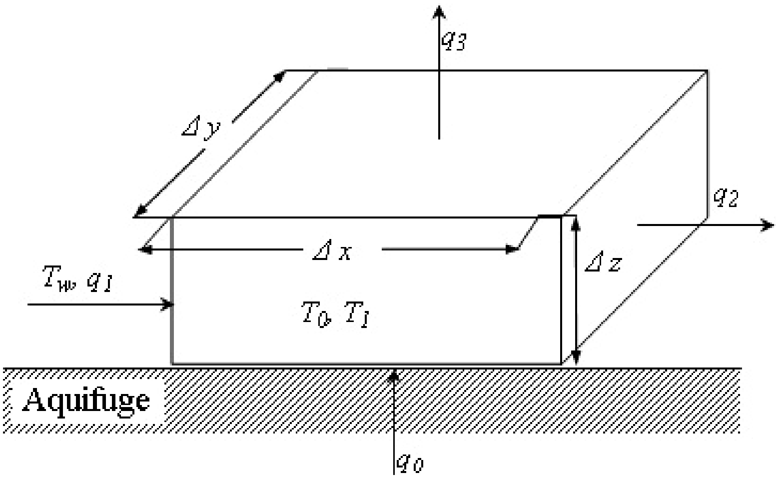

Figure 4.1 – Heat balance scheme within water-bearing seam block over a reaction channel roof

and $$q_1 = AT_w;\ \ q_2 = A \cdot \frac{T_1 + T_0}{2};\qquad (4.5,\ 4.6)$$

$$q_3 = D \cdot (\frac{T_1 + T_0}{2} - T_w);\quad D = \frac{\lambda \Delta x \Delta y}{\Delta z},\qquad (4.7,\ 4.8)$$

$$A = \Delta y \cdot \Delta z \cdot v \cdot C_w \rho_w;\qquad (4.9)$$

$$B = \rho_w C_w V_w + \rho_{sk} C_{sk} V_{sk};\qquad (4.10)$$

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 the block to over block; λ is thermal conductivity of the water-bearing seam; ρ_w, C_w, and V_w are density, thermal capacity, and amount of water within the block; ρ_n, C_n, and V_n are density, thermal capacity, and amount of rocks within the block.

Substituting (4.5) – (4.10) expressions in (4.4), we obtain an equation for time temperature series

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

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

Evaluating the model accuracy while epignosic problem solving. The developed parametrically modeled technique, aimed at the activation of water-saturated rock mass 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) [7]. In the context of the experiment, the effect, used by us, was considered as a side problem.

According to recommendations, proposed in [42, 46], layout of the studied area Hanna – 1 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. 4.2).

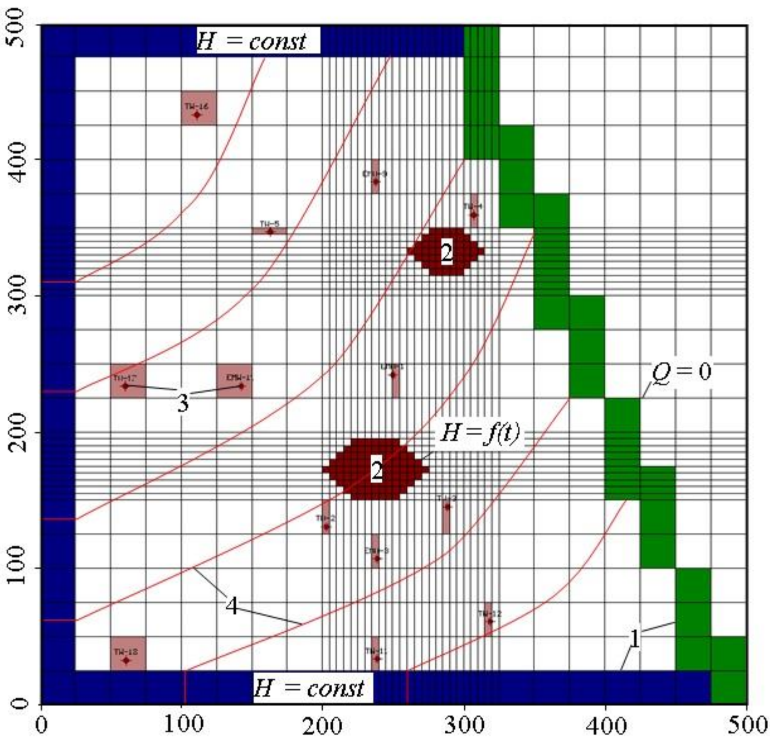

Figure 4.2 – Schematization of Hanna – 1 area model in terms of ModFlow software solution: 1 – hydrodynamic borders; 2 – IAF modules; 3 – wells; 4 – piezo-isohyps

According to the data of geological structure, filtration is considered as a multilayer formation where average thickness of coal seam is 10 m, average thickness of aquifer is 7 m, and average thickness of water seam is 15 m. Rocky Mountain, located within the area and stretching south-easterly north-westwardly, is a barrier for water movement; it is specified as impenetrable hydrodynamic border. Since detailed information, concerning the remain line of Hanna – 1 area as for the water-bearing level injecting and abstracting is not available, conditions of the first type are defined with such aquifer values simulating accrual hydraulic gradient of underground water (i.e. 0.006).

Burning cavities are internal boundaries of the model. The cavities are also measured with the help of boundary conditions of the first type with a value of hydrodynamic height being equal to absolute elevation of a coal seam floor. The boundaries were determined while the worked-out sites tracing on the calculated layers. While modeling operation of IAF modules, internal boundary conditions were escaped after blow stopped to be supplied.

Fig. 4.3 explains comparison of full-scale data and simulated data concerning changes in underground water temperature in wells located near moduli for coal burning. Analysis of the graphs shows that maximum relative calculation error is not more than 5% confirming 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 water-bearing levels in the process of underground coal seam burning.

Parameterizing the development, activation, and use of thermal potential in terms of Novogrodovskaia 2 mine being under liquidation. Preliminary calculations have helped determine that total amount of thermal energy, accumulated by water from the flooded workings of *Novogrodovskaia* 2 mine, is 1300 TJ [49, 58]. Its use with the help of geomodule can be considered in terms of two technological variants (Fig. 4.4). 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).

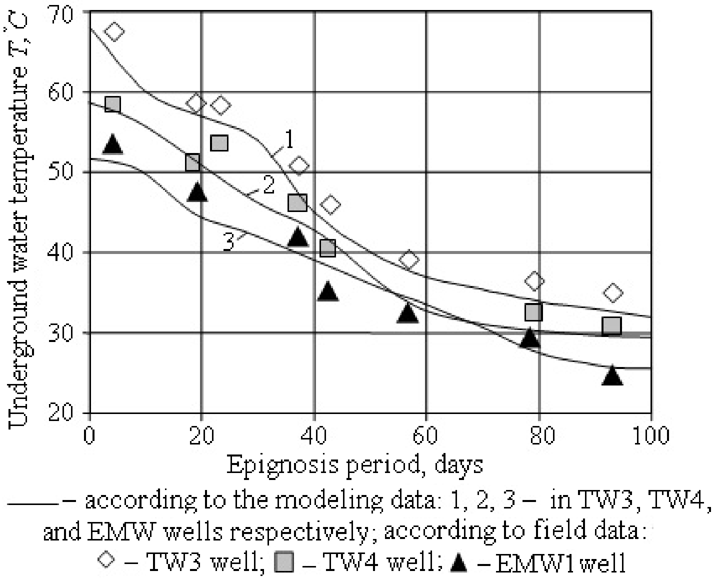

Figure 4.3 – Dynamics of changes in underground water temperatures within Hanna – 1 area

Analysis of diagrams in Fig. 4.5 explains that thermal resource, generated by the geomodule in terms of variant two, is quite sufficient to meet thermal requirements of Novogrodovka town during its heating season. That gives ground to consider the operation schedule as the most advanced one while using resources of *Novogrodovskaia* 2 mine being under 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, will be 150 GJ/day to be four time less than that of the required thermal flow. Efficiency of operation schedule one may be improved while expensive thermal pumps replacing by such heating facilities as heat-insulated floor system.

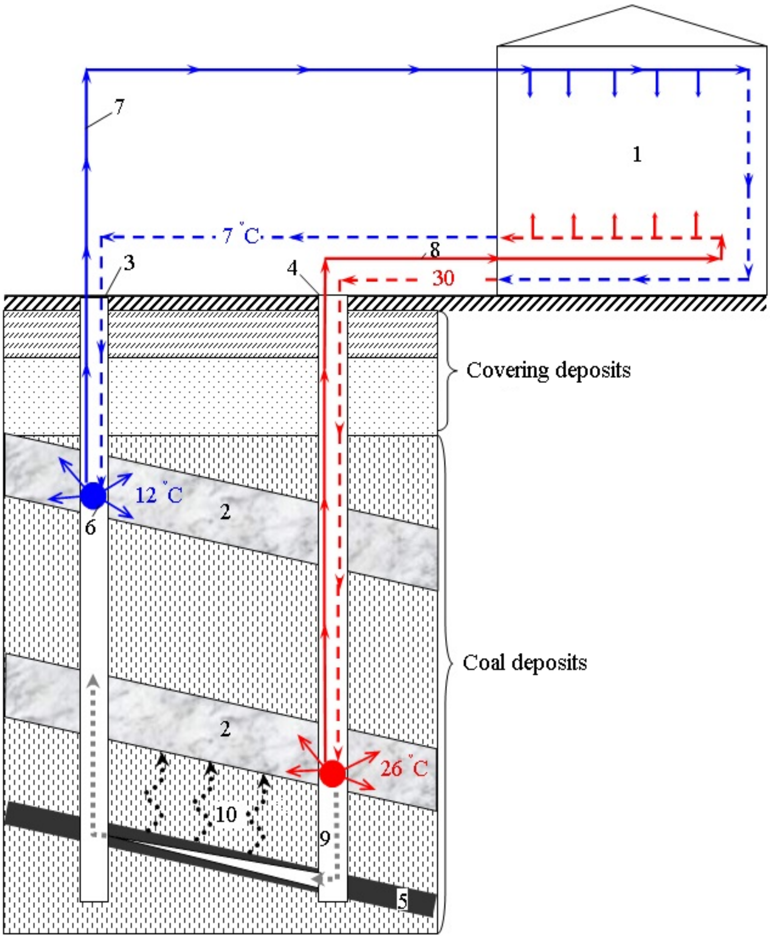

Figure 4.4 – Operation schedule of geomodule within a territory of Novogrodovskaia 2 mine field: 1 - a building; 2 - productive stratum with the flooded mine workings; 3, and 4 - cold well as warm well; 5 - off-grade coal seam; 6 - packer; 7, and 8 - a path of mine water motion from cold well and warm one; 9, and 10 - the directions of blow (gas) flow and thermal flow while coal burning

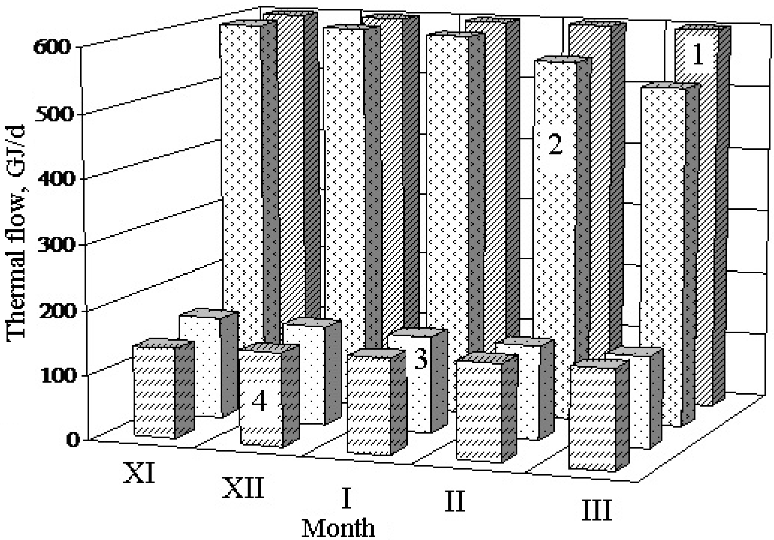

Figure 4.5 – Geomodule efficiency at the territory of Novogrod-ovskaia 2 mine: 1 – 3 - a thermal flow, required to heat up Novo-grodovka town, generated by the geomodule according to operation schedules one and two respectively; 4 - thermal capacity equivalent required by a pump to heat up buildings with the help of mine water (variant one) as a source of low-potential energy

Conclusions. Long-term coal mining as well as mine liquidation in Ukraine has resulted in the formation of natural and techno-genic environment at the territories of coal-mining regions; the environment contains substantial reserves of power resources in the form of residual coal and off-grade coal, and warm mine water as well as underground water. The disturbed rock mass 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 waterflooded 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 warmth and winter coldness within the disturbed water-bearing rocks.

Numerical modeling has been applied to simulate formation dynamics and a pattern of heat resource within water-bearing level occurring over the coal seam being burnt depending upon its inclination angle, coal mining stage, and aquifuge thickness. The model has been identified relying upon epignosis simulation of industrial experiment concerning underground coal burning in the context of Rocky Mountain deposit (the USA). Relative calculation error is not more than 5 %.

Geomodule, providing efficient development of a thermal resource of the flooded mine has been substantiated. It operates owing to abstraction and injection of water from different levels for warm- and cold supply of buildings depending upon ambient temperature with its periodical activation by means of underground burning of residual coal. It has been proved in terms of Donbas *Novogrodovskaia* 2 mine being under liquidation that thermal flow formed while coal burning and heat water pumping out is quite sufficient to meet thermal requirements of a settlement where is quite sufficient to meet calorific requirements of a town with 15 thousand inhabitants since its calorific capacity is 500-580 GJ/day.

5. Hydrogeomechanical assessment for parameters of underground gas storage in the aquifer

Nowadays underground storage of gas is recognized worldwide as a generally accepted technology [1]. The UGS facilities are currently exploited in the USA (80 reservoirs of working volume 90 billions m^3), Canada (30 reservoirs storing 25 billions m^3), Russia (10 reservoirs storing 25 billions m^3), France (3 reservoirs storing 1,5 billions m^3), and other countries. One of the UGS great advantages is cost efficiency in comparison to steel reservoirs [3]. The average specific cost spent for increasing the working volume underground by 1,000 m^3 makes 50 USD, which is 7-10 times cheaper than creation of equivalent capacities on the ground. Besides, depositories in aquifers are sufficiently tight against gas leakage to be used also for storing greenhouse gases (f. e. CO_2).

Prospecting for the geological structures suitable for UGS became the topical problem in Ukraine. Concentrating the "Naftogas" available underground facilities in Western Ukraine makes unreasonable their using to supply big consumers located on East and Center of the country. Steel reservoirs up to 500,000 m^3 volume are able to smooth only day load fluctuations; however, the seasonal peak difference reaches hundreds of millions of cubic meters. The other natural reservoirs such as salt caverns and depleted gas deposits are unlikely to be used as alternative storages in Central Ukraine because of their small number and limited volumes. Therefore, prospecting for deep aquifers as potential gas storages and their hydrogeomechanical estimation is getting of increasing interest for big gas consumers in Ukraine.

As an alternative capacity to accumulate gas volumes needed for smoothing consumption peaks in Central Ukraine a Permian-Triassic aquifer occupying 1930 km^2 can be used. It is located within the Leventsovska area in Western Donbas. The aquifer thickness ranges from 113 to 127 m, with the top elevation deepening from 350 to 580 m below the ground surface (Fig. 5.1). Extremely salt ground waters (33-65 g/l) are useless for water supply.

The aquifer is quantified by the average values of conductivity 3 m/day, transmissivity 290 m^2/day, elastic storage coefficient $7 \cdot 10^6$ m^2/day, and active porosity 0,15. The overlying Jurassic clays of 110-200 m thickness and conductivity 10^{-4} m/day make projected gas storage almost tight. These characteristics allow recommending this site for underground gas storage from the viewpoint of geotechnical feasibility.

The study aim is to estimate geotechnological parameters for UGS under conditions of the Leventsovska area. This requires complex evaluation of gas and water flows as well as geomechanical changes induced by UGS from the viewpoint of stable operation of facilities and their environmental safety.

Regarding to seasonal changes of gas consumption the following UGS stages can be distinguished: 1) pumping gas during the warm season, 2) storing pumped and cushion gas, 3) gas extraction during winter, 4) storing cushion gas. After pumping or extraction gas pressure is stabilizing and re-distributing in porous space during several days or weeks depending on the reservoir size.

Spatial and temporal fluctuations of gas and water pressure can be simulated in details by using simultaneous equations of two-phase flow in porous media [10, 4, 38, 9]. The 2D model proposed in [20] describes gas-water movement in a vertical cross-section during one of the exploitation stages. The developed model outlined below aimed at preliminary estimation of the ranges limiting the size of the aquifer zone filled with gas, pressure and volume of stored gas, and its losses.

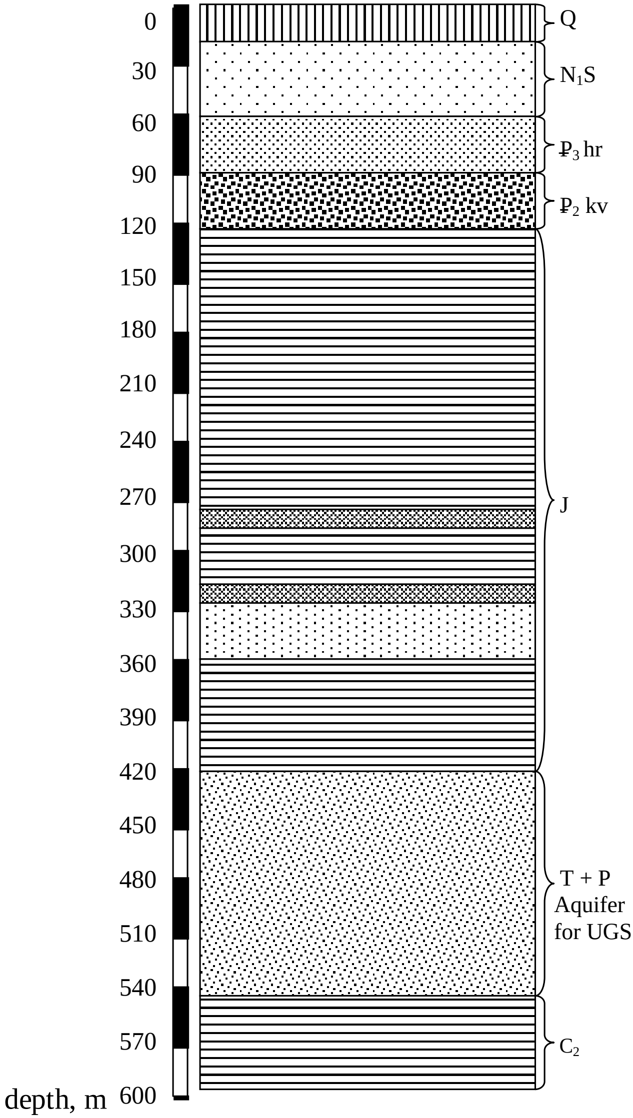

Figure 5.1 – A stratigraphic column from a borehole on the Leventsovska area

The necessary computations are carried out by using the fluid and gas seepage equations and relevant hydrogeological data.

The scheme of the aquifer limited by the top plane (Fig. 5.2) can be applied to the hydrogeological conditions of the Leventsovska area. The aquifer zone filled with gas is assumed to have the shape of cylinder of the radius ranging from R_{min} to R_{max} depending on pumping or extraction. The aquifer is underlain and overlain by the low-pervious beds, with gas leakage directing upwards.

Strictly speaking, the shape of this domain is similar to a cut cone due to the difference in densities of water and gas. The deviation from the cylindrical shape can be estimated by comparison of hydrostatic pressure applied to elementary gas cylinders of unit height on the aquifer bottom and top. The relation of their radiuses can be expressed as $\sqrt{H_e/(H_e+m)}$, which equals to 0,79 under conditions of the Leventsovska area (H_e=200 m, m=120 m). For the connected volumes at the approximately equal pressure this relation will tend to 1,0. More exactly the shape of gas-water contact can be determined by numerical modeling with using Kelvin's condition on the phase boundary [8].

The pressure in pores filled with gas during the storage stage has to be balanced with the pressure of water averaged along the aquifer thickness

$$P_g = P_c = \frac{1}{m}\int_0^m \rho_w gz\,dz + \rho_w gH_e = \rho_w g\left(H_e + \frac{m}{2}\right), \tag{5.1}$$

where ρ_w = water density, g = gravitational acceleration.

The compressed gas volume in the aquifer is determined in accordance with Boil-Marriott's law

$$V_g = V_0 P_g / P_a\ , \tag{5.2}$$

where V_0 = the working volume of gas under standard conditions, P_a = atmospheric pressure.

The radius of the gas reservoir R_g in the aquifer around the borehole is determined as

$$R_g = \sqrt{V_0 / (\pi m n_a)}, \tag{5.3}$$

where n_a = active porosity of rocks.

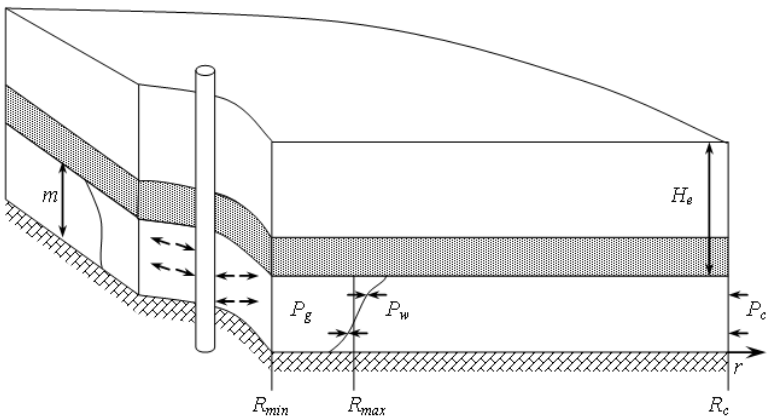

Figure 5.2 – The scheme of USG facilities in the aquifer: H_e = saturated rock thickness over the aquifer top, m = aquifer thickness.

In case of placing UGS facilities in the Leventsovska area their horizontal area will expand from 500 to 1100 m for the gas volume ranging from 150 to 300 millions m^3 (Table 5.1). So the relation of the working volume (150 millions m^3) to the cushion gas volume (150 millions m^3) makes 1,0, which is achievable for currently exploited aquifers [32]. The volume needed for 300 millions m^3 of gas under standard conditions is estimated at 12 millions m^3, which does not exceed the useful elastic capacity of this aquifer established previously by field studies at 17,5 millions m^3.

The gas pressure in the reservoir changes from P_w on the well to $P_{g,c}$ on its boundary during pumping. Prevailing pressure of gas on that of water on the phase contact leads to reservoir enlargement. The pressure maintained in the well has to exceed the water pressure 2-3 times to provide pumping, which gives P_w=5-7 MPa for the aquifer considered. The gas pressure before and after pumping estimated by the equation (1) makes about 2,6 MPa. During extraction it has to be $P_w<P_g$, with the relatively small difference $P_g–P_w$ to regulate stable discharge.

Gas losses are caused by its seepage and gravitational rising through the overlying saturated clays and sealed voids around the pipes, and by dissolution in groundwater. The leakage rate depends on the operation stage. The leakage estimations were carried out for the following typical schedule of UGS facilities (Table 5.2):

1) pumping gas during June till the end of September (122 days),

2) keeping pressurized gas during October and November (61 days),

3) extracting gas in winter (90 days),

4) storing cushion gas in spring (92 days).

Leakage through sealed voids around the pipes can be calculated by the formula [9]

$$Q_p = \frac{\kappa_p S_p}{\mu_g H_e} \frac{P_{g,w}^2 - P_a^2}{2P_a}, \tag{5.4}$$

where μ_g = gas viscosity, $P_{g,w}$ = gas pressure in the reservoir at the well, S_p = cross section flow area. It can be determined as a ring horizontal section of the width ω_p outside the pipe. This space is usually filled with a sealing material of permeability κ_p that is to calculate as $\kappa_p = 8{,}4 \cdot 10^{-6} \omega_p^2$.

During pumping $P_{g,w}=P_w$, the rest of time $P_{g,w}=P_g$, where P_g is calculated according to the equation (5.1). The computations showed that intensity of leakage during pumping reaches 580 m^3/day, the rest of time it does 150 m^3/day, which gives the discharge Q_p = 108,000 m^3 per year or losing 0,07% of the working volume.

The discharge of gas losses through the overlying bed during pumping is calculated with regard to changing pressure and enlargement of the area filled with gas

$$Q_1(t) = 2\pi \int_0^{Rg(t)} v_g(r,t) r\, dr\,, \tag{5.5}$$

where gas flow velocity v_g through the saturated clayey layer of thickness L_c is determined as

$$v_g = \frac{\kappa_c}{\mu_g L_c}\left(P_g - P_a\right). \tag{5.6}$$

Here κ_c = clay permeability, t = time.

The following pressure distribution

$$P_g(r) = \sqrt{P_w^2 + \left(P_{g,b}^2 - P_w^2\right)\frac{\ln(r/r_w)}{\ln(R_g/r_w)}} \tag{5.7}$$

is acceptable for the quasi-steady enlargement of the pervious gas reservoir during pumping. Here $P_{g,b}$ is the gas pressure on the reservoir boundary. The reservoir radius R_g can be approximately evaluated by the gas volume and corresponding horizontal size. Neglecting elastic properties may give a slightly heightened value for Q_1 due to substituting the larger radius R_g than it is in reality.

The stage of storing pumped gas can be conditionally subdivided into the periods of (5.1) stabilizing pressure and the reservoir volume, and (5.2) quasi-stable dynamic equilibrium. The first period duration can be estimated in accordance with Fourier's criterion for the linearized equation governing gas flow in porous media [3, 4, 38]

$$Fo = \frac{at}{l^2}, \quad a = \frac{\overline{P}_g \kappa_{aq}}{\mu_g n_a}, \tag{5.8}$$

where κ_{aq} = permeability of the aquifer, $\overline{P}_g$ = average pressure in the gas reservoir, l = typical horizontal size, f. e. the radius R_g. The process is considered almost stable for Fo>1,0; before this moment the average pressure in the reservoir can be determined as harmonic or geometrical means between the values at the well P_w and on the contour $P_{g,c}$. These amount 3,42 and 3,6 MPa respectively, so that $\overline{P}_g$ =3,5 MPa was used for calculation. Therefore a=0,7 m^2/s for $n_{a,min}$=0,25 and a=1,75 m^2/s for $n_{a,min}$=0,1; which gives the duration of pressure stabilization roughly 2,1 days.

The leakage intensity during this stage is calculated by the formula

$$Q_{2,1}(t) = \pi R_{\max}^2 v_g(t), \tag{5.9}$$

where the upward gas flow velocity v_g takes into account decreasing pressure in the reservoir from $\overline{P}_g$ to P_c. The leakage intensity for the rest of time before extraction is determined according to the formulae (5.6) and (5.9) at the velocity v_g calculated assuming constant pressure in the reservoir. Such approach is acceptable because the squeezed out gas is simultaneously replaced with the equivalent volume of water, which provides gas and water equilibrium on the reservoir boundaries.

Stable extraction requires maintaining the almost constant gas discharge close to the day average rate $Q_3 \approx V_0/t_3$. Corresponding pressure P_w in the well can be estimated by using the formula for steady gas inflow to a sink in radial flow [4, 38]

$$Q_{st} = \frac{\pi \kappa m}{\mu_g} \frac{\overline{P}_g^2 - P_w^2}{P_a \ln\left(R_g / r_w\right)}. \tag{5.10}$$

The condition $Q_3 \approx Q_{st}$ for $R_{min} < R_g < R_{max}$ yields the required difference in pressure $\Delta P = \overline{P}_g - P_w$ ranging from 9 to 10 kPa. Actually it means minor fluctuations in pressure during extraction and followed storing cushion gas.

Reduction of the reservoir horizontal size lasts much slowly comparing to its enlargement due to lower pressure gradient. Moreover, the main depression zone is located near the well; hence, pressure is falling on the moving water-gas contact with delay. For the stage of storing cushion gas its seepage velocity through the overlying clays is calculated by the formula (5.6); and the flow area is decreasing to $\pi R_{\min}^2 / n_a$.

Actually gas penetrates saturated clays at the flow resistance increased due to the phase boundary impact. Therefore, the relative phase permeability [3, 4, 38] should be taken into account in the equation (5.6), which corresponds to decrease of κ_c approximately by 10-12 times ($\kappa_c \approx 10^{-17}$ m^2). The calculations were carried out under the assumption that leakage does not lower gas pressure in the reservoir. The computation results for hydrogeological conditions on the Leventsovska area are listed in Table 5.2. It can be seen that the highest estimation for gas losses due to leakage makes maximally 3% of the UGS working volume.

Table 5.1 – Estimated radius and volume of the hypothetical UGS facilities in the Leventsovska area

	R_{min}, m	R_{min}, m
$n_{a,\,min}$=0,1	400	565
$n_{a,\,max}$=0,25	253	375
V_g, millions m^3	5,77	11,54

Table 5.2 – Estimated gas leakage through the overlying bed above the UGS facilities in the Leventsovska area during one operation year

Stage(s)	Duration,		Q_1, millions m^3		Q_2, millions m^3	
	months	days	totally	per month	totally	per month
1) pumping	4	122	1,31	0,328	0,52	0,13
2) storing pumped gas	2	61	0,81	0,405	0,32	0,16
3) extraction	3	90	1,19	0,396	0,48	0.16
4) storing cushion gas	3	92	0,91	0,303	0,37	0,123
1 – 4 (total)	12	365	4,22	0,352	1,69	0,141

Q_1 is calculated at $n_{a,min}$, Q_2 is calculated at $n_{a,max}$.

Exploitation of UGS facilities can lead to displacement of some water from the aquifer. The volume of active pores in the aquifer within the geological boundaries of the Leventsovska area makes at least $2{,}36 \cdot 10^{10}$ m^3. The maximal volume taken by gas in the reservoir does not exceed 12 millions m^3 or 0,05% of the active pore volume. Injecting such volume may cause shift of the steady boundary between salt and fresh waters by 5-10 m on the flow width from 10 to 20 km. This movement is considered as minor to be neglected from the viewpoint of ground water deterioration in the closest aquifer used for water supply.

Estimation of porous pressure impact on rock properties. Evidently rock properties change due to porous pressure variations induced by pumping and extraction of gas. Because of significant pressure fluctuation in UGS facilities it is important to predict possible changes of rock properties and their feedback on the storage capacity.

Before pumping saturated rocks are under normal stress σ and water is under pressure P; the whole system can be considered in the equilibrium state (Fig. 5.3). Porous pressure increases due to pumping gas and displacement of water; this reduces water and solid volumes and enlarges pores. Eventual volume deformation dV can be determined by calculating the difference between actual stress and pressure, which allows estimating additional space for gas to be stored in the aquifer.

The following assumptions were made to assess the changes of rock properties of pervious layers used as UGS facilities: 1) the aquifer is exploited under isothermal conditions at equal temperatures of gas and displaced water, 2) aquifer deformations are elastic and less than the failure limit of the rock skeleton, 3) compressibility of solid phase is constant because pressure does nor exceed 60 MPa [71] for the spherical stress tensor.

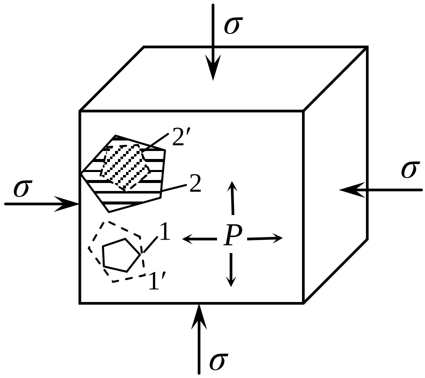

Figure 5.3 – Scheme of elementary volume deformation in the aquifer: 1 and 1′ are pore volumes, 2 and 2′ are solid phase contours in a section; prime denotes the state before and during pumping respectively.

Under these assumptions the deformations of pores and the solid skeleton are governed by the equations [11]

$$\frac{dV_p}{V_p} = \beta_p d(\sigma - \text{Đ}) + \beta_s dP\,, \tag{5.11}$$

$$\frac{dV_s}{V_s} = \frac{1}{(1-n)}\beta_s d(\sigma - \text{Đ}) + \beta_s dP\,, \tag{5.12}$$

where V_p, V_s = volumes of pores and skeleton in the aquifer, β_p, β_s = coefficients of compressibility of porous space and solid phase respectively, n = porosity coefficient.

The normal stress can be determined from the following equation

$$\sigma = k\rho_b gh, \tag{5.13}$$

where

$$k = \frac{\nu}{1-\nu}, \tag{5.14}$$

ν = Poisson’s ratio, ρ_b = average density of rocks in the overlying bed, h = aquifer depth.

Young’s modulus is calculated according to Ter-Mikaelian’s formula [11] at known Poisson’s ratio

$$E = 10^4 f'(1-\nu)\cdot(26 - f')^{-1}, \tag{5.15}$$

where f' = Protodiakonov's strength coefficient.

Different relationships have been proposed for the compressibility of porous space, particularly, by V.N. Shchelkachov

$$\beta_p = \frac{2}{3}\frac{1}{n}\left[\frac{3(1-\nu^2)}{E}\right]^{\frac{2}{3}}(\sigma - P)^{-\frac{1}{3}}, \tag{5.16}$$

H. Brandt

$$\beta_p = 6{,}53\left(\frac{1-\nu^2}{\text{Å}}\right)^{\frac{2}{3}}(\sigma - \text{Ð})^{-\frac{1}{3}}, \tag{5.17}$$

I. Fett

$$\beta_p = \frac{2}{n}\left[f_1^2\left(\frac{1-\nu_1^2}{E_1}\right) + f_2^2\left(\frac{1-\nu_2^2}{E_2}\right) + f_1 f_2\left(\frac{1+\nu_1^2}{E_1} + \frac{1+\nu_2^2}{E_2}\right)\right]^{\frac{2}{3}}\cdot(\sigma - P)^{-\frac{1}{3}} \tag{5.18}$$

where E_1 and E_2 = Young's modules for aquifer grains at minimal and maximal elasticity, ν_1 and ν_2 = Poisson's ratios for them respectively; f_1 and f_2 = percent contents of these grains in the solid skeleton.

The change of porosity coefficient due to stress change can be determined by integration [11]

$$n^{(\sigma-P)} = n \cdot \exp\left(- \int_0^{(\sigma-P)} \beta_p(\sigma, P)\, d(\sigma - P) \right), \tag{5.19}$$

Porosity coefficient n and permeability κ are related by the equation

$$\frac{n^{(\sigma-P)}}{n} = \left[\frac{\kappa^{(\sigma-\text{Đ})}}{\kappa} \right]^{2\frac{(3+\alpha)}{(2+\alpha)}}, \tag{5.20}$$

where α = the structural index of rocks.

Solid phase density under all-side compression of water is governed by the equation

$$\left(\frac{\Delta\rho}{\rho} \right)^{\sigma,\text{Đ}} = -\grave{A}\left(\frac{\Delta n}{n} \right)^{\sigma,P} + \left(\hat{A}\beta_f + \tilde{N}\beta_s \right)\Delta\text{Đ}, \tag{5.21}$$

where

$$\grave{A} = \frac{\rho_s - \rho_f}{\dfrac{\rho_s}{n} - (\rho_s - \rho_f)}, \quad \hat{A} = \frac{n}{\dfrac{\rho_s}{\rho_f} - \left(\dfrac{\rho_s}{\rho_f} - 1 \right) n}, \quad C = \frac{1-n}{1 - \left(1 - \dfrac{\rho_f}{\rho_s} \right) n},$$

ρ_s and ρ_f = densities of solid and liquid phases, β_f = fluid compressibility coefficient.

Diffusive and adsorptive capacity q of the aquifer depends on specific storage of adsorption and stress under atmospheric pressure and differences between effective stress during pumping or extraction [66]. It can be written as

$$\frac{q^{(\sigma-P)}}{q} = \frac{\frac{\Delta n}{n} + \frac{1}{n} - 1}{\left(1 - \frac{\Delta n}{n}\right)\left(\frac{1}{n} - 1\right)}, \tag{5.22}$$

where Δn = increase of porosity coefficient.

Computations were carried out using the MathCad software. Normal stress was determined according to the equations (5.13) – (5.15). Then, the coefficients of fluid and skeleton compressibility were calculated by the expressions (5.16) – (5.18) at the varying porous pressure. The volume deformations of the aquifer dV at given pressure were determined by summing deformations of solid phase and pores. Aquifer properties were calculated according to the equations (5.19) – (5.22).

Computations were made for the following parameters close to conditions of UGS operation: P_1 = 0,3 MPa, P_2 = 2 MPa; n = 0,35; h = 100 m; ρ_s=1900 kg/m^3; β_s = 0,03 GPa^{-1}; ν = 0,2; f' = 0,5; β_f = 0,4 GPa^{-1}; ρ_f = 1010 kg/m^3; α = –1; f_1 = 40%; f_2 = 60%; E_1 = 2 GPa; E_2 = 0,5 GPa.

Also volume deformation was studied experimentally by triaxial testing sandy samples of known grain distributions and physical properties on the equipment TriSCAN (VJTech, Great Britain). Acquisition of porous pressure, load, and deformations were carried out automatically, which allowed simultaneous calculating pore volume changes.

The experimental results are fitted better in Shchelkachov's formula (Fig. 5.4), with the correlation coefficient reaching 0,9. Brandt's formula gives the highest values for aquifer deformations, up to 4%. The increase in porous pressure from 0,3 to 2 MPa results in growth of porosity by approximately 1% and permeability by 4%, which allows pumping more gas to big UGS facilities. According to the equation (5.22), greater porosity in aquifer leads to lower specific adsorption capacity (Fig. 5.5). Rock density increases by 2%, specific adsorption capacity does by 1,5%, and adsorption of rock related to gas does the same by 1% for the pressure range from 0,3 to 2 MPa. These estimations show slightly more storage capacity of UGS facilities in comparison to constant parameters, which has to be accounted for storing millions of cubic meters of gas.

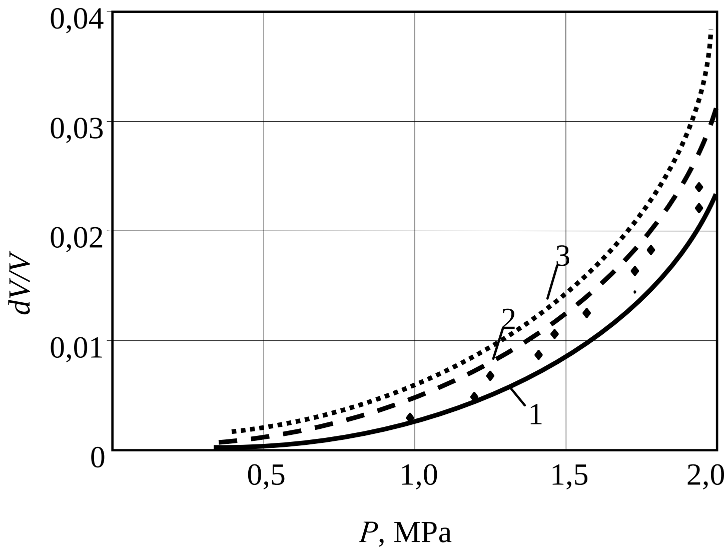

Figure 5.4 – Volume deformation of the aquifer caused by increase of porous pressure *P*. Curves 1, 2, 3 were calculated by using the approximations of Shchelkachov (5.16), Fett (5.17), and Brandt (5.18); the points show the experimental values.

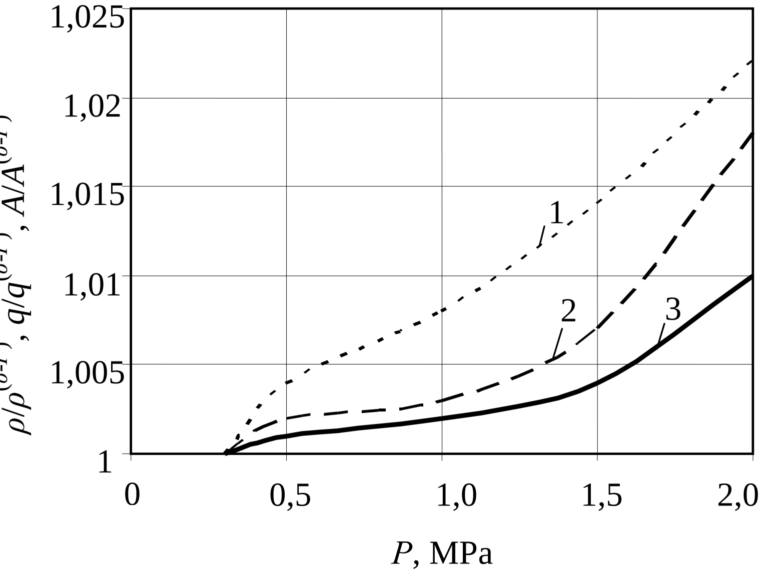

Figure 5.5 – Change of density ρ (1), specific adsorption capacity *q* (2), and adsorption capacity of rocks *A* (3) due to increase of porous pressure *P*.

Conclusions. The gained highly cautious estimations for gas leakage through the overlying clayey bed do not exceed 3% of the working volume of the hypothetical UGS facilities in the Leventsovska area. This is comparable to the losses from currently operated capacities in the world and can be regarded as an argument in favor to the feasibility of the project to create UGS facilities on the site considered. Further studies have to make more precise the obtained estimations depending on heterogeneities of crucial rock and gas properties such as permeability, adsorption capacity, and gas solubility in water using results of previous field and experimental works.

6. Method for Stimulating Underground Coal Gasification

A characteristic feature of the fuel and energy industry of Ukraine is localization of hydrocarbons and incomplete extraction of known coal reserves. Proven coal reserves of the country are estimated as 53.6 Bt [17] out of which more than two thirds occurs in low-quality and thin seams unsuitable for mining with conventional methods. Around 70% of different grade coal remains underground, which dictates application of underground gasification. However, despite the century-long scientific and industrial development [20, 28, 30] as well as some considerable advantages (ecologically clean energy generation, minor natural landscape impact and hazardous underground work release), the technology enjoyed no wide application due to low chemical efficiency. This index is determined s a ratio of chemical heat of gasification product to chemical heat of gasified coal [19], is actually not more than 65% and needs improvement.

This chapter aims to determine dynamics of thermal field formation around underground gasifier and its applicability to stimulating underground coal gasification (UCG). Pursuing this objective requires solution of such problems as: formulation of mathematical model of heat transfer in burning coal seam roof rocks; implementation of the model; estimation of influence exerted by waterproof stratum on quantity of thermal energy accumulated in aquifer and by heated water production on UCG efficiency.

Model formulation. Let us consider the process of underground coal gasification in terms of a system composed of three layers having direct thermal contact with each other (Fig. 6.1). During lower coal seam burning, some heat transfer to fuel components of produced gas (chemical heat) and some heat wars gasification product and enters adjacent rocks (physical heat). Warm combustion products have much smaller weight as against blast components fed into reaction channel; therefore, they will occupy the upper degasified space and create higher temperature there. Thus, the coal seam roof rocks are exposed to the higher thermal influence. This layer is heated above the recreation channel during coal burning and cools after blasting is stopped. The overlying aquifer warms up in the thermal flowfrom this separation layer.

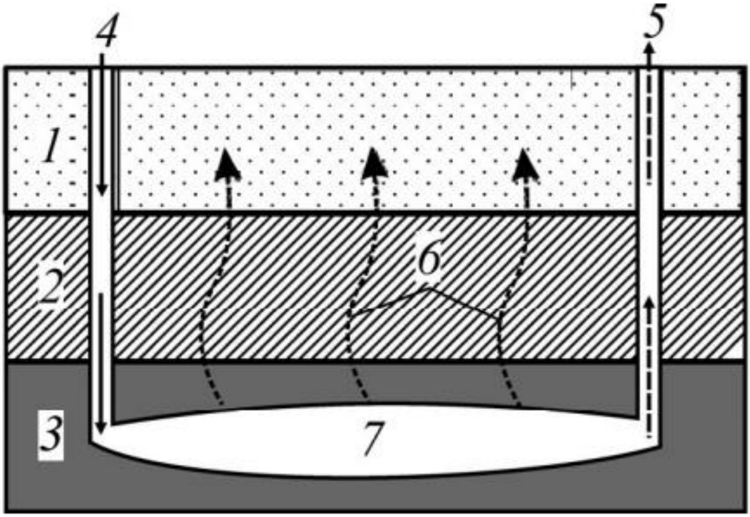

Figure 6.1 – Mechanism of underground water heating during UCG: 1–3—aquifer, separation layer and coal seam, respectively; 4–6—direction of blasting, produced gas flow and heat flow; 7—recreation channel.

Geotechnologically, it is important to find the thermal energy inflowing through recreation channel rocks to aquifer as it can be taken by means of heated water pumping. The intensity of groundwater warm-up heat flow capacity directly depends on the burn coal volume and on air-blast fed to the gasifier. Air required to burn 1 kg of coal is determined in cubic meters from the empirical relation [26]:

$$q_v = \frac{\alpha(0.001Q_y + 25.1W_y)}{418}, \tag{6.1}$$

where α = 1.08–1.11 is an experimental coefficient; Q_y is the low heat value, MJ/kg; W_y is the moisture content of coal, %; 418 is an empirical coefficient.

Underground gasifier capacity is defined by the volume of coal burning for a certain time period and can be written in the form of [26]:

$$P = \frac{D_v}{q_v}, \tag{6.2}$$

where P is the gasifier capacity, kg/day; D_v is the air flow rate, m^3/day; q_v is the quantity of air per 1 kg coal burning, m^3/kg.

Gas yield per 1 kg coal is:

$$q_g = \frac{1}{q_y},\ q_y = 12\sum\frac{C_{yg}}{22.4}C'_{yg}, \tag{6.3}$$

where q_y is the coal consumption per 1 m^3 gas, kg/m^3; $\sum C_{yg} = aCO_2 + bCO + cCH_4$ is the sum of coal-bearing components in gas in percent by volume; *a*, *b*, *c* are, respectively, percentage of CO_2, CO and CH_4 in gas; $C^{/}_{yg}$ is the content of carbon in fuel, %.

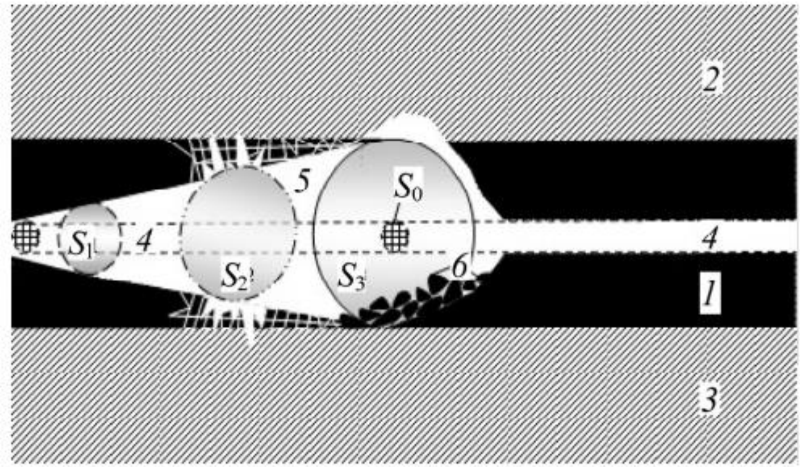

Figure 6.2 – Mechanism of gasified area formation: 1–3—coal seam, its roof and floor, respectively; 4—initial (cut-through) channel; 5—gasified area; 6—collapsed rocks; S_0, S_1, S_2, S_3 —initial and subsequent cross-sections of the channel.

The enforced air blast in the gasifier creates a vertical pressure gradient which is the source of convection in overlying rocks. The total heat flow from the recreation channel to the separation layer is:

$$q(t) = q_{cv}(t) + q_{cd}(t), \tag{6.4}$$

where $q_{cv}(t)$ *and* $q_{cd}(t)$ are the convective and conductive components, W. It is assumed that the heat-transfer properties of rocks are independent of water exchange in the upper-lying aquifer.

The convective and conductive heat exchange areas S_{cv} and S_{cd} change with time as the recreation channel expands and coal burning proceeds. According to the data of explosure of underground gasifiers in Shakhty and Lisichansk stations of Podzemgaz, the thermophysical and geometrical parameters of the channel are unsteady, and the bonding between voids in the channel is local and limited [56, 72]. This is connected with the factthat initial channel with the cross-section S_0 continuously expands to S_1 during gasification and approaches the roof and floor of the coal seam (S_2, Fig. 6.2). As a result, both coal and rock wall appearin the gasified area. Later on, the section of channel continues growing up to the limit S_3 and diminishes afterwards as a consequence of roof rock collapse. Then, the channel cross-section pattern recurs.

Considering that gasification involves coal seams not thicker than 1 m, as a rule, the recreation channel rapidly approaches the coal seam roof and floor. Then the gasified area widens across the whole thickness of the seam. The seam area can be averaged with respect to time with regard to unit efficiency of the gasification channel: $E = F/l$, where F is the burn coal seam area, m^2, per its unit length l, m, along the fire face [19].

The heat exchange between the gas outflow from the recreation channel and the aquifer overlying the separation layer [44] is given by:

$$q_{cv} = Q_g c_g \rho_g (T_g - T_w), \ Q_g = \frac{k}{\mu_g} \frac{P_g^2 - P_{atm}^2}{2P_{atm} L_g} S_{cv}, \qquad (6.5)$$

where Q_g is volume gas flow in fractures and pores in roof rocks, m^3/s; c_g is the specific heat, J/(kg·°C); ρ_g is the density of gas, kg/m^3; μ_g is the dynamic viscosity, Pa·s; T_g is the temperature of gas in the recreation channel, °C; T_w is the temperature of water in the aquifer, °C; k is the permeability of rocks, m^2; S_{cv} is the area of convective heat exchange, m^2; P_g is the pressure of gas in the recreation channel, Pa; P_{atm} is the atmospheric pressure, Pa; L_g is the length of gas filtration path to the level of the atmospheric pressure action, m.

It is assumed that the gas pressure is the same across the void volume. At high gas flow rate up to a few millimeters per second, the convective heat floor reaches the aquifer within a day. As this happens, as small volume of rocks is warmed around fractures, and major portion of roof rocks of the recreation channel is heated as a result of the conductive heat transfer.

Let $\chi = q_{cv} lq$ be the portion of the convective flow in the total heat flow through the separation layer. The rest heat $(1-\chi)q$ goes to overlying rocks in the conductive flow. By estimates, χ is never higher than a few percent even in highly permeable roof rocks.

The conductive heat flow enters the overlying rocks in different places as the fire face advances. In accord with the assumed time-slotting, in all sections of the coal seam floor above the underground gasifier, the heat flow is set in the numerical calculations such that to fit the average daily value of q_{cd}, and at all time moments, $q_{cd} = (1-\chi)q$.

The conductive heat flow diffuses in the separation layer bottom. For each j-th section, where heat enters since the moment t_i, q_{cd} can be given constraints:

$$q_{cdj} = \begin{cases} q_j, t_i < t < t_{i+1}, \\ 0, \ t < t_i, t > t_{i+1}, \end{cases} \tag{6.6}$$

where q_j is the conductive heat flow (W/m^2) from below in each j-th section of the separation layer floor in the time t (days).

For the approximate calculations, the temperature in rocks above each section of heat inflow can be calculated from the formulas:

$$T_j(z,t) = T_0 + q_j(T(z,t) - T(z,t-t_s)), \tag{6.7}$$

$$T(z,t) = \frac{2}{\lambda_\rho}\sqrt{a_\rho t}\, ierfc \frac{z}{2\sqrt{a_\rho t}}, \tag{6.8}$$

where $t_s = t-1$, T_0 is the initial temperature of rocks, °C; z is the vertical coordinate counted upward from the separation layer bottom, m; t is the time, s; λ_p is the heat conductivity factor, W/(m·°C); a_p is the thermal diffusivity of rocks, m^2/s; $ierfc(x) = e^{-x^2} / \left|\sqrt{\pi} - xerfc(x)\right.$ is the error function complement.

Formula (6.8) is an analytical solution of the heat conduction equation in a uniform semirestricted domain with the constant unit heat flow set at the boundary. Thermal inertia of rocks is taken into account by the heat conductivity factor.

Heat flow in the separation layer roof can be calculated as follows:

$$q_{cd,w}(t) = S_{cd}\lambda_\rho \frac{\partial T(t)}{\partial z}\Big|_{z=m_\rho}, \tag{6.9}$$

where S_{cd} is the conductive heat exchange area, m^2; m_p is the roof rock thickness above the recreation channel, m; z is the vertical coordinate, m.

Summation of (6.9) calculated for all sections of spatial discretization defines total conductive inflow in the seam.

The calculation of the heat flow using (6.8) somewhat underestimates actual heat inflow in the permeable seam. In fact, heat abstraction by the flow will lower the temperature in the seam bottom and increase heat outflow from the separation layer. However, the effect will be short due to small difference between the warm water temperature and the natural temperature of seam water.

Extraction of heat from the aquifer is possible using the pumping hole arranged nearby the recreation channel. Assume that the flow is totally spent to warm water flowing in the hole and the water is immediately discharged from the seam. In this case, water temperature in the hole can be given by:

$$T_{sk}(t) = T_w + \frac{q_{cd}(t) + q_{cv}(t)}{c_w \rho_w Q_{sk}(t)}, \tag{6.10}$$

where T_w is the natural groundwater temperature,°C; $q_{cd}(t)$, $q_{cv}(t)$ are the conductive and convective heat flows, W; c_w— is the water heat capacity, J/kg·°C; ρ_w is the water density kg/m^3; Q_{sk} is the well flow rate, m^3/s.

A more accurate estimation of T_{sk} is possible using numerical modeling of heat transfer in a permeable seam with regard to vertical arrangement of the hole and dynamics of heat inflow.

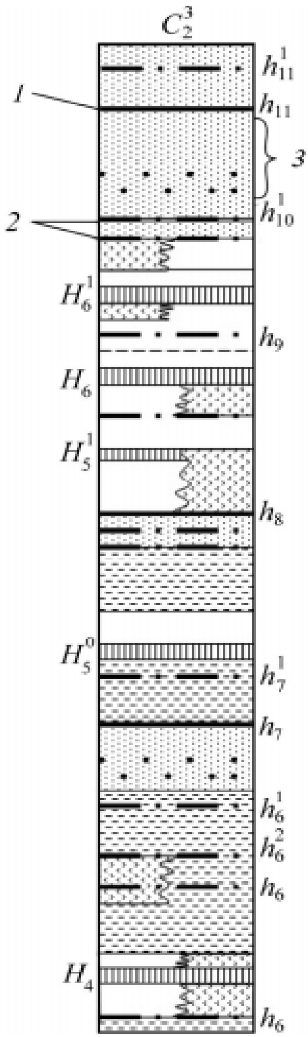

Figure 6.3– Lithological and stratigraphic section of coal measures C_2^3: 1–2—operating and nonoperating coal seams; 3—babakovskie sandstone aquifer $h_{10}Sh_{11}$.

It is worthy of mentioning that the proposed mathematical model of heat transfer in burning coal seam roof: neglects radiation heat exchange between gases and enclosing rocks, assumes that temperature of gases along the gasification channel is equal to the maximum gas temperature in the section of exothermal and endothermal reactions, disregards convection heat transfer from gases to roof rocks of underground gasifier.

The comparative calculations using formulas (6.1) – (6.10) are implemented in Mathcad for geological conditions of the Olkhovio-Nizhnee sitewithin the Chistyakovo–Snezhnoe industrial region of Donbass, with total cola reserves over 3 Bt out of which around 400 Mt of coal occur in off-standard thickness seam suitable for gasification.

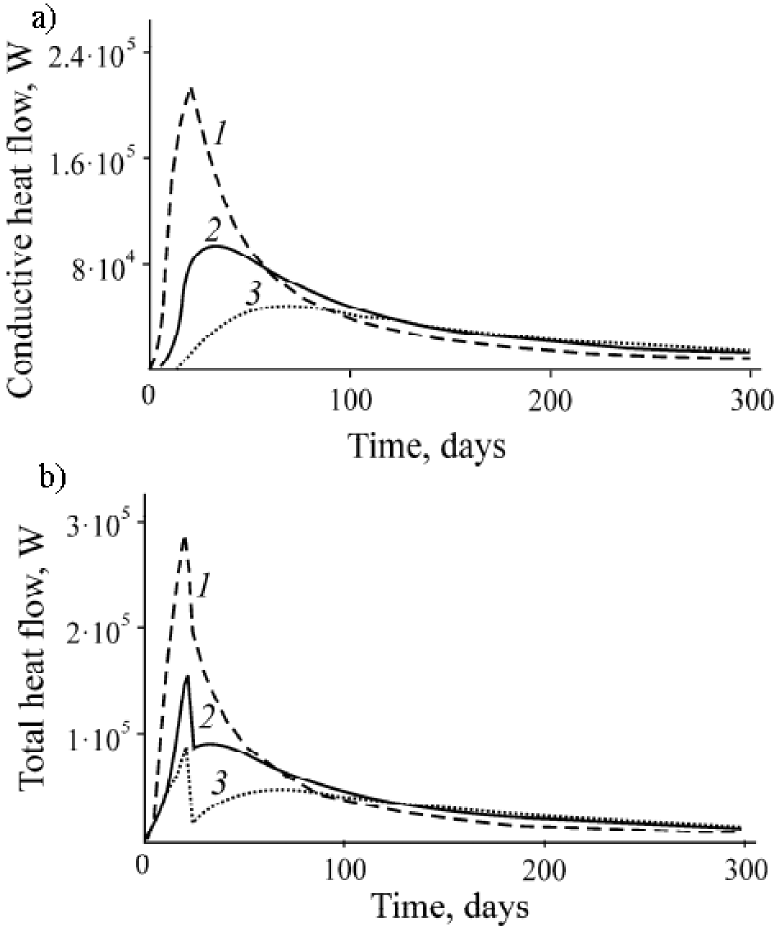

Figure 6.4 – Variation in (a) conductive and (b) total heat inflows in aquifer during UCG: *1–3*—separation layer thickness of 2, 4 and 6 m, respectively.

This site in the east of the Donets Region has the dimension 55 × 15 km. The relief is greatly intersected with a dense network of gulches with dividing upheavals. The maximum height marks are observed in the east (+ 325 m) the minimum—in the west

(Olkhovaya river valley, + 125 m). The highest water content due to rock fracturing is traced near the zones of faulting and weathering. Water mineralization in coal formations increases from 1.5–2.0 g/dm^3 in the east to 3.0–3.6 g/dm^3 in the west in connecting with the growing thickness of overburden in this direction. Rock permeability makes 3.4–9.6 m/day. At the depth of 100–300 m, across almost the whole area of the region, there is a 200-m zone of chloride–sodium alkaline water unsuitable for supply. The region accommodates towns of Snezhnoe, Torez, Shakhtersk and Zugres that are the large consumers of thermal energy.

According to geological survey [44], for the full-scale UCG experiment, because of weaker faulting, it is most convenient to use Smolyaninov coal measure $C^3{}_2$ 740–900 m thick in the east of the Olkhovo-Nizhnee site (Fig. 6.3). The section of the measure is dominated by siltstone (48%), argillite (18%) and thick (50–60m) sandstone strata (tolstovinskie underlying coal seam h_1, podremovskie— $h_2^1Sh_3$, usovskie— h_4Sh_5 and babakovskie—$h_{10}Sh_{11}$). Limestone strata (H_5^0, H_5^1, H_6^1) are thin, occur within the dense argillite strata and are not always traced in the geological section. The main limestone strata are H_3 (micro-grain, detrital) and H_4 (fine-grain, algal). The measures C_2^3 contains 20 coal seams, out of which 11 seams are operating. Between the operating seams h_8 and h_{11}, there lie a few off-standardcoal beds and interbeds (h_0, h_{10}^n, h_{10}^1). For instance, lithologically, the operating seam h11is overlaid at a distance of 30 m and underlaid at a distance of 60 m by the off-standard beds h_{11}^1 *and* h_{10}^1. Within the stratigraphy section, these spacings are filled with watered babakovskie sandstone filled with water unsuitable for supply due to higher mineralization.

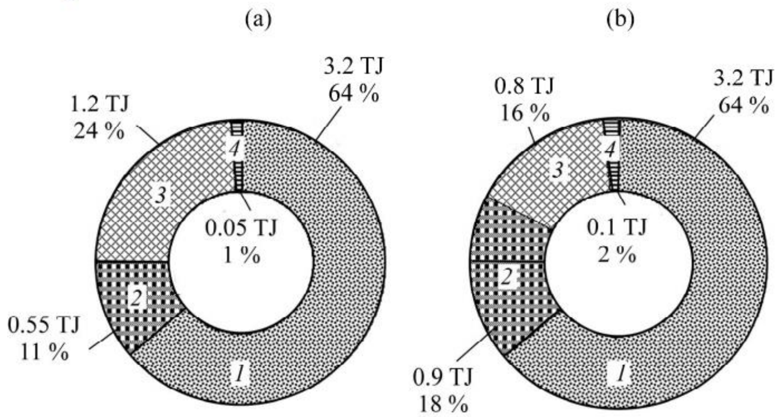

Figure 6.5 – Heat energy balance in underground coal gasification with separation layer (a) 2 m and (b) 6 m thick: 1—heat in produced gas; 2—heat spent to warm recreation channel-adjacent rocks; 3, 4—conductive and convective heat inflows in aquifer. Numerical symbols give amount of heat (TJ) and its percentage (%) of burning coal heat energy.

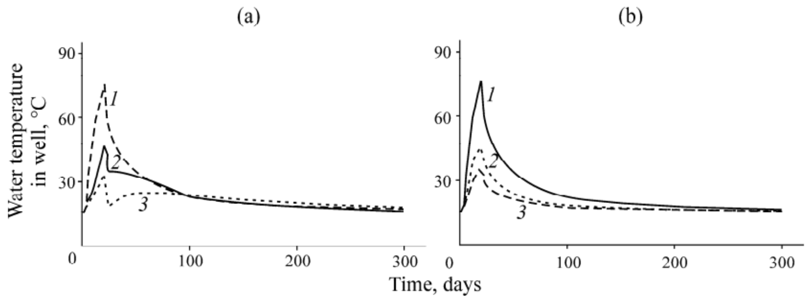

Figure 6.6 – Change in temperature of groundwater pumped from aquifer overlying underground gasifier: (a) Q_{sk}= 100 m^3/day; (b) m_p= 2 m; 1–3—well flow rate of 100, 200 and 300 m^3/day, respectively.

Thus, in the test site area, it is an optimal scenario to carry out UCG in the seam h_{10}^{1} with the sandstone stratum $h_{10}Sh_{11}$ water used as a heat source. The thermophysical properties of rocks and the technological parameters of UCG are: α = 1.1; Q_y = 15 MJ/kg; W_y = 35%; ρ_g = 1.1 kg/m^3; T_g = 1000°C (temperature in the section of exothermal and endothermal reactions in the gasification channel); t = 20 days; k = 10^{-15} m^2; $\sum C_{yg}$ = 39%; C_{yg} = 65%; c_g = 1000 J/(kg·°C); μ_g = $1.79 \cdot 10^{-5}$ Pa·s; P_{atm} = 0.102 MPa; λ_p = 2.5 W/(m·°C); ρ_w = 1000 kg/m^3; P_g = 4 MPa; T_w = 15°C; c_w = 4100 J/(kg·°C); L_g = 400 m; D_v = 1800 m^3/h; Q_{sk} = 100–300 m^3/day. The heat exchange area was set as a volume of gasified space at the coal seam thickness of 1 m. The heat inflow in the roof rocks of the underground gasifier was found as the difference between the heat value of coal and heat in produced gas (3.33 MJ/m^3). The calculations were performed with a time step of 1 day.

Figure 6.4 shows calculated results for the conductive and total heat inflows in the overlying watered stratum $h_{10}Sh_{11}$ during burning of coal seam h_{10}^{1}. Curves 1–3 are obtained for different thickness of the separation layer. The analysis shows that with the thicker separation layer, the heat inflow in the aquifer lowers but percentage of the convective component in the total heat flow grows from 6.5 to 9.3% as the thickness of the roof rocks increases from 2 to 6 m, respectively.

Figure 6.5 depicts thermal balance of UCG process. From the analysis of the diagrams, the most heat (64%) burning coal is contained in produced gas. Percent of physical heat is 36%. The aquifer, depending on the separation layer thickness, receives from 18 to 25% of thermal energy released during burning. The rest physical heat is absorbed by enclosing rock mass.

To evaluate extraction of heat permeating roof rocks, the plot of change in temperature of groundwater pumped from the aquifer above the underground gasifier is drawn (Fig. 6.6). The warm water temperature decrease with increasing thickness of separation layer and flow rate of the water intake well (from 75 to 30°C), and even drops as UCG is stopped. After 90 after termination of coal burning, the water temperature in the seam reaches initial values (15°C). In view of the fact that the pumped-out water has temperature below standards (70°Cfor hot water supply and 90°C for heating), such water can be used as a low-potential energy source in thermal pumps, "warm floor" heating system and for pre-heating of hot supply water in winter. Thus, recovery and application of warm groundwater will enable partial utilization of rock mass heat energy and, thereby, allow improving efficiency of underground coal gasification by 18–25% depending on the waterproof stratum thickness.

Conclusions. The developed mathematical model of filtration and heat transfer in burning coal seam roof during UCG allows determining the convective and conductive components of heat flow from the reaction channel to the overlying aquifer. The implemented mechanism of the heat exchange area enlargement due to expansions of gasified space gives an adequate description of change in the heat flow and groundwater temperature depending on thickness of waterproof stratum. The geological and thermophysical parameters used in the modeling conform with the real mining conditions (Olkhovo-Nizhnee site, Chistyakovo–Snezhnoe industrial region of Donbass) suitable for underground coal gasification.

From the calculated results, it is found that during coal burning, overlying sandstone accumulates more than 60% of heat from the underground gasifier. Depending on size of the waterproof stratum, the groundwater temperature reaches 30–75°C. Taking and using this water as a low-potential energy source for heat pumps, underfloor heating systems and for pre-heating of water in hot water supply systems in cold seasons will increase efficiency of underground coal gasification by 18–25%.

REFERENCES

1. Aide-memoire de l'industrie du gaz. 4-me edition (1990) Association technique de l'industrie du gaz en France, Paris.

2. Andersen, L.J., Madsen, B., Bull, N., 1985. Hydrogeological investigations as a basis for heat storage in aquifers, New York: IANS Publ, 154.

3. Bachurina N.M. Economic efficiency of creation and operation of underground gas storage facilities: - Abstract of dis. ... Cand. econ. Sciences: - M., 2002 .-- 28 p.

4. Bear J., Zaslavsky D., Irmay S. (1968) Physical principles of water percolation and seepage. UNESCO. Paris.

5. Belmas, I.V., Kolosov, D.L., Kolosov, A.L., & Onyshchenko, S.V. (2018). Stress-strain state of rubber-cable tractive element of tubular shape. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, (2), 60-69.

6. Belousov, V.N., Smorodin, S.N., & Lakomkin, V.Yu. (2014). Energy saving and emission of greenhouse gases (CO_2). Sankt-Peterburg: Sankt-Peterburgskiy gosudarstvennyy tekhnologicheskiy universitet rastitel'nykh polimerov.

7. Berdan, G. A., 1993. Restoration plan for the Hanna. Underground coal gasification site in carbon county, Wyoming, 128.

8. Bottomless supplies. Coal as basis of source of raw materials of Ukraine. Available at: http://www.geonews. com.ua/news/detail scribd.com/doc/1034528/ (accessed 15 February 2013).

9. Charny I.A. Underground fluid dynamics. - M .: Gostoptekhizdat. - 1963.

10. Collins E. (1961) Flow of Fluids through Porous Materials. Reynold, New York.

11. Dobrynin V.M. Deformations and changes in the physical properties of oil and gas reservoirs - M .: Nedra. - 1970.

12. Ermakov, V.N., Semenov, A.P., Ulitskiy, O.A., 2001. Development of processes of flooding of the earth's surface under the influence of the closing mines. Ugol Ukrainy, 6, 12-13.

13. Ermakov, V.N., Ulitsky, O.A, & Spozhakin, A.I. (1998). Changes in the hydrodynamic mode of mines during flooding. Ugol' Ukrainy, (6), 11-13.

14. Falshtynskyi, V.S, Dychkovskyi, R.O, Saik, P.B, Lozynskyi, V.H and Cáceres Cabana, E., 2017. Formation of thermal fields by the energy-chemical complex of coal gasification. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 5, 36-42.

15. Gash, B.W., Hill, V.L., Barone, S.P., & Martin, J.W. 1989. Rocky Mountain 1 Underground Coal Gasification Test: In-Situ Coal Conversion Using Directionally Drilled Wells. Society of Petroleum Engineers, Annual Technical Conference and Exhibition, 8-11 October 1989, San Antonio, Texas.

16. Gavrilenko, Yu.N. and Ermakova, V.N., Man-Made Consequences of Mine Closure inUkraine, Donetsk: Nord-Press, 2004.

17. Gavrilenko, Yu.N., 2003. Technogenic consequences of

the closure of the coal mines of Ukraine. Donetsk: Nord-press, 631.

18. Gholudev, S.V. 2003. Calculation of the thermal mode of gas-generator during underground coal gasification. Announcedr of the Dnepropetrovsk university. Series are geology, geography. 7: 11–20.

19. Goncharov, S.A. (2002). Thermodynamics. Moskva: Izd-vo Moskovskogo gos. gornogo un-ta.

20. Inkin A.V. Hydrodynamic model of a gas storage in the aquifers of Kryvbas // Sb. scientific. tr. NSU. - 2010. - No. 34, T. 2, - S. 216-221.

21. Inkin O., Dereviahina N., 2018. Study of the migration processes in the roof of an underground gas-generator. Dniprop. Univer. bulletin, Geology, geography. 26 (1), 64 – 70.

22. Inkin O., Tishkov, V., Dereviahina, N. & Sotskov, V. (2018). Integrated analysis of geofiltrational parameters in the context of underground coal gasification relying upon calculations and modeling. E3S Web of Conferences, (60), 00035. https://doi.org/10.1051/e3sconf/20186000035

23. Inkin, A.V. (2013). Thermohydrodynamic evaluation of the efficiency of a thermal module within a submerged mine. Vestnik akademii nauk Chechenskoy respubliki, 4 (21), 97 - 104.

24. Ishlinskiy, A.Yu. (1989). Politekhnicheskiy slovar’. Moskva: Sovetskaya entsiklopediya.

25. Kirillin, V.A., Sychev, V.V., & Sheidlin, A.E. (1983). Tekhnicheskaya termodinamika. Moskva: Energoatomizdat.

26. Kolokolov, O.V., Theory and Practice of Thermochemical Technology for CoalExtraction and Preparation, Dnepropetrovsk: NGA Ukrainy, 2000.

27. Krasnopolsky, O.N. (2006). Conclusion “Forecast of changes in the ecological and hydrogeological conditions within the boundaries of the mining allotments of Mine No. 2 “Novogrodovskaya”, which is being liquidated, of the liquidated Selidovskaya Mine and Mine named after D.S. Korochenko, which is subject to liquidation, as well as the adjacent mines with them: a research report. Artyomovsk.

28. Kreinin, E.V., Unconventional Thermal Methods of Difficult-to-Recover Mineral Production: Coal, Hydrocarbons,

29. Kuznetsov, I.A. (1963). Geology of coal deposits and oil shale of the USSR. P.1. Coal basins and deposits of the south of the European part of the USSR. Moskva: Gosgeoltekhizdat.

30. Lindblom, S.R., Smith, V.E. 1993. Rocky Mountain 1Underground Coal Gasification Test Hanna, Wyoming Groundwater Evaluation / Final Report June 10, 1988 - June 30, 1993.

31. Lund, J.W., Freeston, D.H. & Boyd T.L. 2010. Direct Utilization of Geothermal Energy 2010 Worldwide. Review. Proc. of World Geothermal Congress 2010. Bali, Indonesia, 25-29 April 2010.

32. Lurie M.V. Mechanics of underground gas storage in water-bearing formations. - M .: Oil and Gas. - 2001.

33. Malolepszy, Z. 2003. Low temperature, man-made geothermal reservoirs in abandoned workings of underground mines. Proc. 28 Workshop on Geothermal Reservoir Engineer-

ing Stanford University, Stanford, California, January 27-29, 2003. pp. 259–265.

34. Mamaikin, O., Demchenko, Yu., Sotskov, V. & Prykhorchuk, O. (2018). Productive flows control in coal mines under the condition of diversification of production. E3S Web of Conferences, (60), 00008. https://doi.org/10.1051/e3sconf/20186000008

35. National Atlas of Ukraine. 2007. Kyiv: Institute of Geography, Kartographia.

36. Nechitailo, O.N. 2011. Utilization of mine water heat using heat pumps. KiEM, #4. http://ukrrosmetall.com.ua/content/1125

37. Pasechny, V.G. (1994). The conclusion of the predicted values of water inflows into the mine to them. N.I. Stashkova for the period of full development of industrial reserves and recommendations for dumping mine water into the river network. Research Report. Dnepropetrovsk: GGAU.

38. Pykhachev G.B., Isaev R.G. Underground hydraulics. - M .: Nedra. - 1972.

39. Rethinking the Degree of Responsibility to the Future: 2009. National Report about Implementation of the Energy Efficiency State Policy. 2010. Kyiv, National Agency of Ukraine on Ensuring of Efficient Use of Energy Resources Management. 246 p.

40. Robinson, R. (2000). Mine gas hazards in the surface environment. Mining Technology, (109), A228-236.

41. Ruban, S.A., Nikolishina, A.V. (2005). Groundwater of Ukraine, Kyiv: DV UkrDGRI.

42. Rudakov, D.V., 2011. Modeling in hydrogeology. Dnepropetrovsk: Natsionalnyi hirnychyi universytet, 88.

43. Rudakov, D.V., Sadovenko, I.A. (2005). Modeling of hydrodynamic processes in the vicinity of a mine shaft. Naukoviy vísnik NGU, 8, 9 - 13.

44. Sadovenko, I.A. and Inkin, A.V., Geological and Hydrological Survey of Olkhovo-Nizhnee Mining Site with a View to Underground Gasifier Construction, Nauch. Trudy Nats. Gorn. Univer., 2015, no. 48, pp. 8–16.

45. Sadovenko, I.A. and Inkin, A.V., Substantiation of Physicochemical Parameters of Hydrocarbon Pocket Formation and Control in Underground Coal Gasification, GIAB, 2013, no. 8, pp. 275–284.

46. Sadovenko, I.A., 1991. Synthesis of numerical models for solving problems of controlling the geofiltration state of a mountain massif]. Gornyy zhurnal, 12, 19-22.

47. Sadovenko, I.A., Inkin, A.V. 2002. Underground hydroelectric power station as ecological and power regulator. Coal of Ukraine, 5: 32–34.

48. Sadovenko, I.A., Inkin, A.V. 2013. Estimation of efficiency of the thermal module on the basis of resource potential of the flooded mine. Vestnik KNU, Vol. 80, 3: 123–127.

49. Sadovenko, I.A., Inkin, A.V., 2014. Justification of the parameters of heat energy extraction in the conditions of a flooded mine. Gornyy zhurnal, 7, 82-90.

50. Sadovenko, I.A., Rudakov, D.V., Inkin, A.V. 2012. Numerical study of thermal field features around an under-

ground gas generator. Bull. of National Mining University, 39: 11-20.

51. Sadovenko, I.A., Rudakov, D.V., Inkin, A.V., 2012. Numerical study of the features of the thermal field around an underground gas generator. Zbirnik naukovikh prats NGU, 39, 11-20.

52. Sadovenko, I.A., Timoshyk, V.I., Zagritsenko A.N. 2002. Solution of hydrogeological problems in restructuring the coal industry. Bull. of Zhytomyr state technological university, 3 (22): 164-167.

53. Samusia, V. I., Oksen, Yu. I., Komissarov, Yu. O. & Radiuk, M. V. 2012. Utilization of the mine water exhaust heat by means of the heat pump. Hot-water supply plant. Sci. Bull. of National Mining University, 4: 143-147.

54. Samusia, V.I. (2010). Assessment of heat pump technology of air turbocompressor waste heat utilization. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, (6), 78-82.

55. Scherban, A.N., Kremnev, O.A., & Zhuravlenko, V.A. (1977). Rukovodstvo po upravleniyu mineral’nym teplom. Moskva: Nedra.

56. Skafa, P.V., Underground Coal Gasification, Moscow: Gosgortekhizdat, 1960.

57. Snihur, V., Malashkevych, D., & Vvedenska, T. (2016). Tendencies of coal industry development in Ukraine. Mining of Mineral Deposits, 10(2), 1-8. https://doi.org/10.15407/mining10.02.001

58. Sotskov, V. O., Demchenko, Yu. I., Salli, S. V. &

Dereviahina, N.I., (2017). Optimization of parameters of over-worked mining gallery support while carrying out long-wall face workings. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 6, 34-40.

59. Sotskov, V., & Gusev, O. (2014). Features of using numerical experiment to analyze the stability of development workings. Progressive Technologies of Coal, Coalbed Methane, and Ores Mining, 401-404. https://doi.org/10.1201/b17547-68

60. Stepanenko, N.V., Vinogradov, G.V. (1981). Geological report on the revaluation of reserves of coal from a field named after D.S. Korotchenko. Donetsk: PO «Ukrugeol».

61. Trigub, N.G., Kovaleva, L.I. (1978). Catalogs of hydrogeological wells of the Krasnoarmeysky coal-mining region from 1939 to 1978. Artyomovsk: Trudy «Artemgeologiya».

62. Tsyplenkov, D., Krasovskiy, P., & Nesterova, O. (2013). Operating dynamics of parameters and technical losses in the components of power supply systems. Energy Efficiency Improvement of Geotechnical Systems, 113-119.

63. Unlimited resource: Ukrainian potential of renewable energy resources. 2007. Fuel and power complex, No. 8, Pp. 40–46.

64. Vassolo S., Kinzelbach, W., Schäfer, W. (1998). Determination of a well head protection zone by stochastic inverse modelling. J. of Hydrology, 206, 268 – 280.

65. Vinogradov K.V. Thermal studies of wells to evaluate leaks and gas flows during underground storage. - Dissertation ... Ph.D. tech. Sciences: - M., 1983.

66. Wendelstein B.Yu. Investigation of sections of oil and gas wells using the method of their own potentials - M .: Nedra. - 1966.

67. Wieber, G. A. Source of Geothermal Energy – Examples from the Rhenish Massif. 2008. Mine Water: In: Technical University of Ostrava Faculty of Mining and Geology, In: Proceedings of the 10^{th} IMWA Congress –2008 in Karlovy Vary, Check Republic, pp. 113-116.

68. Wieber, G.A. (2008). Source of Geothermal Energy – Examples from the Rhenish Massif. In Proceedings of the 10th IMWA Congress in Karlovy Vary (pp. 113-116). Karlovy Vary, Check Republic: Technical University of Ostrava.

69. Yakovlev, E.A. 2007. Regional man-made changes of geological environment of Donbas under the influence of mining works. – Kyiv, Dumka Publ.

70. Yeh, T., Guzman, A., Srivatsava, R. (2012). Numerical simulation of the wicking effect in liner systems. Ground Water, 32, 2–11.

71. Zheltov Yu.P. Mechanics of oil and gas reservoir - M .: Nedra. - 1975.

72. Zvyagintsev, K.N., Kulakova, M.A., and Volk, A.F., Current Condition and Prospects for Underground Coal Gasification in USSR, Khim. Tverd. Topl., 1980, no. 6, pp. 57–60.

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