Economic efficiency of application of artificial air cooling for normalization of thermal conditions in oil mines

Vadim R. Alabyev[a,*], Marina N. Kruk[b], Tatiana P. Bazhina[a], Aleksandr S. Semenov[c], Vladimir I. Demin[a]

a. *Department of Life Safety, Kuban State Technological University 350072, 2 Moskovskaya Str., Krasnodar, Russian Federation*
b. *Department of Organization and Management, Saint-Petersburg Mining University 199106, 21 Line Vassilievsky Isl., bld. 2, Saint-Petersburg, Russian Federation*
c. *Department of Mining Engineering, Mining Faculty, Saint-Petersburg Mining University 199106, 21 Line Vassilievsky Isl., bld. 2, Saint-Petersburg, Russian Federation*

Abstract. The work substantiates a technical solution for improving the working conditions for the thermal factor in the extraction of oil by the thermoshaft method using the mine refrigeration technology. The review of manufacturers and technical characteristics of refrigeration technology in Russia, CIS countries and Western Europe was conducted. For the selected set, the economic efficiency of the project was assessed and a conclusion was made about the feasibility of implementing this project solution. It was shown that the use of a water cooling machine in the mine air conditioning system will reduce the air temperature in the oil production gallery to the required values and will allow to abandon the long-term construction of a surface stationary refrigeration station. Normalization of the thermal regime reduces the costs of benefits and compensation for work in harmful labor conditions and improves the quality of service of production wells by operators. The project for the introduction of air conditioning has a high level of profitability, and its payoff will occur in the second year of operation.

Keywords: Oil mine; Thermal regime; Refrigeration technology; Technical solutions; Temperature; Air conditioning; Working conditions; Economic efficiency.

1. Introduction

Yaregskoye field of heavy high-viscosity oil is unique in Russia. This is the only place where hydrocarbon production is carried out by an underground thermoshaft method. The basis of the thermoshaft method is a decrease in viscosity and an increase in oil mobility due to the formation heating up to a temperature of 70-90 °C with the aid of a heat transfer fluid pumped into the oil-bearing horizon. A saturated water vapor with a temperature of 170-200 °C is used as a heat transfer fluid. The main development system (70%) is the underground-surface system. In other cases, a one-dimensional development system is used [1].

With this oil production technology, even at shallow depths with the natural temperature of the enclosing rocks 10-12 °C, there are problems associated with maintaining the permissible air temperature, which can reach 50-55 °C in the drilling galleries and ventilation openings [2, 3], which significantly exceeds the permissible standards [4]. According to the requirements of the safety rules for the Russian oil mines, the air temperature in the existing workings should not exceed 26 °C at relative humidity up to 90%. In those workings, where there is no permanent presence of people during the shift, air temperature up to 36 °C is allowed [5].

In the process of oil production, the thermal regime of the drilling galleries is mainly formed due to the thermal divisions of the enclosing rocks stipulated by the action of the heating coolant, the breakthroughs of the heating coolant from the side of the roof and the bottomhole area, as well as

[*] *Tel: (861) 255-84-01. E-mail address: avr.09@mail.ru (V.R. Alabyev)*

the heat released by the oily liquid during direct contact with air in the process of its collection and transportation by gravity method [6]. The increased temperature and air humidity lead to rapid fatigue, reduced attention and labor productivity, overheating of the working organism and may be the cause of accidents [7, 8].

2. Materials and methods

The authors analyzed enough scientific research. It was established that the ventilation measures associated with the sectional ventilation of sloping blocks, the choice of rational ventilation schemes for operating panels and the increase in the speed of air movement in the drilling galleries are used in order to regulate the thermal regime in oil mines. Mining measures are used to reduce the negative impact of heat emissions from various sources on the increase in air temperature in drilling galleries and workings of ventilation horizons. These include the definition of the permissible extent of mine workings depending on the magnitude of heat inflows [9, 10], the use of a closed oil collection system, as well as the thermal insulation of steam steampipes and pipelines for pumping oily liquid. The issue of reducing heat emissions from the mountain massif by concreting and thermal insulation of the walls of drilling galleries, as well as their irrigation with cold water, is being studied [11].

However, as shown by field observations, these measures are clearly not enough to meet the required temperature standards. An increase, for example, of supplying air to the mine by 1.5 leads to a decrease in air temperature in the drilling galleries by only 1-2 °C [2]. Therefore, more effective measures are required. In this issue, one cannot use the experience of foreign countries, since the extraction of high-viscosity oil, for example in Canada, is conducted using technologies that do not require the constant presence of people under the ground [12].

The experience of developing reservoir deposits in Germany, Poland, the Czech Republic, and Ukraine shows that artificial air cooling is used at the depths with the 45 °C and higher temperature of the host rocks to normalize the thermal working conditions in the productive workings. For cooling, underground stationary and mobile air-conditioning systems for mine air (ACSMA) are used, as well as central cooling systems with superficial arrangement of refrigeration stations [13]. Proceeding from the analogy with reservoir deposits, we believe it possible to apply artificial air cooling to improve the thermal regime of the operating sloping blocks of oil mines, which belongs to the thermal engineering group of control methods [14]. However, up to now, ACSMAs have never been used in Russian oil mines, there is no experience of their exploitation, and the economic feasibility of their use is questionable.

Consequently, the authors justified design solutions for the use of refrigeration technology to improve and normalize thermal conditions in drilling galleries in the extraction of oil underground. The authors analyzed the economic efficiency of the introduction of refrigeration technology on an example of a typical oil-extracting gallery of the Yaregskoye field.

3. Results and discussion

Improvement of thermal conditions by means of refrigerating machines will be considered on an example of a typical oil-extracting gallery of the Yaregskoye field. Hygrothermal air parameters along the way of its movement from the air supplying shaft trunk to the drilling gallery (Figure 1) are presented in Table. 1.

Figure 1

Table 1

As shown by the results of thermal surveys, the air temperature on the airborne horizon does not exceed the norms permitted by the safety rules. However, it reached its critical value and amounted to 26.0 °C already at the entrance of the drilling gallery. The main increase in air temperature is observed in the drilling gallery itself and on the outgoing air jet in the slope, which is caused by the above factors. According to the results of thermal surveys, it is determined that the cooling demand of the drilling gallery, provided that the air temperature at the end of the slope does not exceed 35.0 °C, is about 1000 kW (Figure 2).

Figure 2

Usually in an underground oil producing enterprise, 5-6 drilling galleries are in operation at the same time. Based on the assumption that the remaining drilling galleries have the same cold demand, we can conclude that normalizing the thermal conditions within the enterprise will require a cooling capacity of about 5-6 MW. The realization of such cooling capacity by underground cooling means in oil mines' conditions is impossible, since the issues of placing refrigerator machines and removing the heat of refrigerant condensation in mine workings seem to be an intractable task. In such cases, it is necessary to construct an ACSMA with a surface location of the refrigeration station. However, the construction period for such facilities takes at least 4-5 years (the development of an air conditioning project, its expertise, certification of foreign refrigeration equipment, construction of a surface refrigeration plant complex, equipment installation, pipelines, etc.), and the problem of normalizing thermal conditions must be solved today already.

At the initial stage, it is proposed to introduce an underground cooling machine of a water-cooling type with a power of 500 kW to normalize the thermal conditions in one drilling gallery. For this purpose, the compressor-and-condenser unit of the refrigeration machine is located in the broadening of the air-producing horizon, and the air coolers (2 pieces of 250 kW) are located directly in the drilling gallery itself at points where the air temperature exceeds the norms allowed by the safety rules (Figure 3). In this case, the air temperature at the outlet of the drilling gallery does not exceed 26.0 °C (Figure 2).

Figure 3

The water cooler for removing the condensing heat of the refrigerating machine is located in one of the workings located in the immediate vicinity of the air-supplying shaft trunk (Figure 3). The term of commissioning such an ACSMA into operation taking into account design and survey and certification works will not exceed 1 year.

When implementing this approach, the following tasks will be accomplished:

1. Complete normalization of thermal working conditions in the drilling gallery and a significant improvement in thermal conditions in a sloping production in a relatively short time;

2. Training of the personnel of the oil-producing underground enterprise to work with the mine refrigeration equipment, the acquisition of the necessary skills for servicing the ACSMA;

3. Installation of the possibility of operation of refrigeration equipment for specific conditions typical for oil mines;

4. Making a final decision on further ways to normalize thermal conditions (surface or underground machines, their power, location, etc.).

The review of the producers of mine refrigeration equipment in the mine explosion-proof execution showed that only the air conditioning mine KShR-350N, manufactured by NPO Aerosphere (Perm), is produced at present [15]. This air conditioner, designed on the wheelbase for mine conditions, has a rated output of 350 kW. This fact, as well as the overall dimensions and operation principle of KShR-350N, does not allow to recommend it for use in the conditions under consideration.

Of the CIS countries, currently only the OJSC "Kholod-mash" (Odessa, Ukraine) produces refrigeration equipment. The KPSh300 air conditioner, which is produced by this company, is designed to cool air in coal mines, although it has suitable overall dimensions for the conditions under consideration, also cannot be recommended for use due to insufficient cooling capacity and the principle of producing artificial cold [16].

Among European manufacturers, there are such recognized leaders as WAT (Germany), Eurotech and Termospec (Poland) [17-19]. The produced refrigeration equipment of these companies is characterized by a wide range of nomenclature that allows satisfying any demand in the required refrigeration capacity. Composition and technical characteristics of the equipment of these companies are approximately the same. It can only be noted that WAT heat exchangers have a cylindrical shape instead of a rectangular due to the double screw cooling elements (Figure 4), so that the heat transfer coefficient of these devices is much higher, and the overall dimensions are smaller, which is an advantage when using them in cramped conditions of underground workings.

Figure 4

The cost of a set of basic refrigeration equipment, for example, WAT, which includes: a mechanical unit (Figure 4a), two air coolers of 250 kW of cold each (4b) and a 600 kW water cooler (Figure 4c) are approximately 600 thousand euros. Taking into account design and installation works, acquisition of auxiliary equipment and materials (pipelines, pumps, water tanks, shut-off valves, etc.), investments in the implementation of the ACSMA will amount to no less than 1 million euros.

To determine the feasibility of investing in the introduction of refrigeration technology in oil mines, we will determine the economic efficiency of the project, provided that the project implementation period is equated to the useful life of the equipment and is assumed equal to 10 years. We will define the changes in the parameters included in the formula of net present value (NPV) as the resultant indicator of the effectiveness of the investment project for 1 year of the project. In constructing the model for determining economic efficiency, we use the assumption of the invariance of the parameters during the project implementation.

1. Changes in revenues due to increased production volumes because of the ability of operators to serve production wells per year more often:

$$\Delta_B = Q \cdot C \cdot \%_{in}/100 = 150 \cdot 23{,}41 \cdot 0{,}03 \cdot 365 = 38450{,}92 \text{ thousand rubles/year} \quad (1)$$

where: Q – daily oil production in the drilling gallery, t. (determined based on the annual oil production at the Yaregskoye field [20]);

C – cost of 1 ton of Urals oil, thousand rubles. (determined based on the data of the Ministry of Finance for September-October 2017 [21]);

$\%_{in}$ - percentage of increase in oil production as a result of working conditions normalization (provisionally accepted 3%).

2. Change in operating costs:

2.1. As a result of the reduction in the costs of benefits and compensation for work in unfavorable working conditions for the year:

$$P_l = W_p \cdot ZP \cdot \%_d/100 = 25 \cdot 57{,}5 \cdot 0{,}4 \cdot 12 = 6900 \text{ thousand rubles,} \quad (2)$$

where: W_p – is the average number of people employed in work performed in mine workings with an air temperature of +30 °C or higher (oil production operators);

ZP – average salary of the operator of oil production, thousand rubles. (adopted equal to the average wage for workers employed in the work on the extraction of crude oil and natural gas in 2015 [22, 23]);

$\%_d$ – percentage of surcharges for benefits and compensation for work in unfavorable conditions (provisionally accepted 40%).

2.2. As a result of the reduction in the class of working conditions from 3.2 to 2 in a year:

$$P_{lc} = W_p \cdot ZP \cdot \%_{3.2\text{-}2}/100 = 25 \cdot 57{,}5 \cdot 0{,}04 \cdot 12 = 690 \text{ thousand rubles/year}, \quad (3)$$

where: $\%_{3.2\text{-}2}$ – percentage of surcharge for work in hazardous working conditions (4%) [24].

2.3. As a result of changes in payments for insurance contributions due to a change in the wage fund:

$$P_{ins} = (P_l + P_{lc}) \cdot \%_{ins}/100 = 7590 \cdot 0{,}3 = 2277 \text{ thousand rubles/year}, \quad (4)$$

where: $\%_{ins}$ – insurance premiums (30%).

2.4. As a result of changes in payments for insurance contributions in case of accidents due to changes in the wage fund:

$$P_{ins.n} = (P_l + P_{lc}) \cdot \%_{ins.n}/100 = 7590 \cdot 0{,}085 = 645{,}15 \text{ thousand rubles/year}, \quad (5)$$

where: $\%_{ins.n}$ – insurance contributions in case of accidents (8.5%).

2.5. As a result of changes in the costs of equipment maintenance, fuel and lubricants, ordinary repairs:

$$P_{maint} = 0{,}1 \cdot \text{Amortization} = 0{,}1 \cdot 6870000 = 687 \text{ thousand rubles/year}. \quad (6)$$

Expenses for equipment maintenance, fuel and lubricants, ordinary repairs are taken equal to 10% of depreciation charges for equipment.

2.6. As a result of a change in the cost for electricity required for the operation of the 500 kW ($P_{el.c}$) mine refrigeration equipment per year (Table 2). The electricity cost is accepted according to [25].

Table 2

2.7. As a result of changes in production costs due to the increase in oil production:

$$P_{o.p} = P_{ud} \cdot Q \cdot \%_{in} = 1766{,}86 \cdot 150 \cdot 365 \cdot 0{,}03 = 2902 \text{ thousand rubles/year} \quad (7)$$

where P_{ud} – the value of unit costs for oil production, is equal to 241 rubles per barrel of oil [26]. In terms of ton, this value will amount to 1.766.86 rubles/ton.

Thus, the total value of the change in operating costs:

$$\Delta Э = - P_l - P_{lc} - P_{ins} - P_{ins.n} + P_{maint} + P_{el.c} + P_{o.p} =$$
$$= -6900 - 690 - 2277 - 645{,}15 + 687 + 2270{,}59 + 2902 = -4652{,}6 \text{ thousand rubles/year}. \quad (8)$$

Calculations for the definition of net present value (NPV) are presented in Table 3. The efficiency calculation was based on the 15% discount rate accepted by PJSC "LUKOIL" [26]. The conducted calculations also took into account changes in the property tax and income tax. The calculated performance indicators of the investment project are presented in Table 3. The effectiveness period was determined graphically, based on the analysis of the net present value as a cumulative result of time (Figure 5).

Tables 3, 4

Figure 5

On the basis of the obtained indicators (Table 4), we can conclude that it is economically feasible to implement and attract such an investment project, since the value of net discounted income significantly exceeds the zero mark. In addition, estimating the obtained value of the internal rate of return in 59%, we can speak of stability and a sufficiently low risk of the project. The event has a high level of profitability, as evidenced by the high value of the investment return index of 3.48. The pay-off period of the project already happens in the second year of the project realization. Also, the results of the sensitivity analysis performed indicate the sustainability of the project (Table 5 and Figure 6) [27].

Table 5

Figure 6

Analyzing the data obtained in the course of the risk analysis by the sensitivity analysis method, we can confidently speak of the stability of such an investment project and its non-adherence to the influence of external factors on the resulting indicator, which was chosen as the net present value (Figure 5) [28, 29]. Based on the results of the performed analysis, it can be said that the project for the implementation of the ACSMA in the oil mine is most sensitive to changes in the revenue parameter. This is also evident both from the graph of the dependence of the net present value on the change in parameters (the line describing the change in the NPV from the change in revenue is steeper than the rest with respect to the horizontal axis), and by a relative change -88.63% (Figure 6). However, the significance of the relative change in the revenue parameter tells us that it is very unlikely that such a situation, in which the project is not going to be profitable, will occur. Given the current situation on the world oil market, the level of oil prices will have a minor impact, since the revenue should decrease by almost 100% in order to make the project unprofitable.

4. Conclusions

1. In the oil well drilling galleries, the values of the heat and humidity parameters of air significantly exceed the norms permitted by the safety rules. The introduction of an underground water-cooling refrigeration machine with a capacity of 500 kW will ensure the air temperature in the drilling gallery in accordance with the requirements of safety rules for oil mines.

2. Normalization of thermal working conditions in the drilling gallery will reduce the class of working conditions and lead to a reduction in the costs of benefits and compensation for work in adverse climatic conditions, an increase in production due to the ability of operators to more often serve production wells.

3. On the basis of the obtained indicators, the authors can conclude that the value of net discounted income significantly exceeds the zero mark. In addition, estimating the obtained value of the internal rate of return in 59%, we can speak of stability and a sufficiently low risk of the project. The project has a high level of profitability, as evidenced by the high value of the investment return index of 3.48 and payback will occur in the second year after the introduction of the air-conditioning system.

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Vadim R. Alabyev graduated from the Leningrad Mining Institute in 1989. He had been working at the Makeevka Research Institute for Mining Safety since 1989 to 2010. He is an expert in the field of normalization of the thermal, ventilation and dust regimes of deep mines. He is an author of more than 60 scientific papers on these topics. He had been working at the mine named after Zasyadko (Donetsk) in 2010-2016. His responsibilities were to normalize the thermal regime of the mine, including through the introduction of mining refrigeration equipment. Vadim R. Alabiev is a Doctor of Technical Sciences since 2016. He is a professor of the Department of Life Safety of the Kuban State Technological University since 2016.

Marina N. Kruk graduated from the Saint-Petersburg Mining Institute (Technical University) named after G.V. Plekhanov in 2009. She successfully defended her PhD thesis "Economic evaluation of project risks during the development of offshore gas fields of the Ob Bay" (specialty 08.00.05) in 2012. She is an associate professor of the Department of Organization and Management of the Saint-Petersburg Mining University since 2012. Her research interests include the assessment of the economic efficiency of investment projects in the mining and oil and gas complexes, the assessment of the risks of such projects by qualitative and quantitative methods, the assessment of environmental and economic damage, and the issues of corporate social responsibility of companies in the matter of labor protection. Marina N. Kruk is an author of 40 scientific and methodological works.

Tatiana P. Bazhina graduated from the Krasnodar Polytechnic Institute in 1990. She defended her PhD thesis in 1995. She has been working as an associate professor at the Department of Life Safety of the Kuban State Technological University since 1996. She deals with the issues of labor protection, environmental, industrial and economic safety of mining enterprises. Tatiana P. Bazhina carries out the certification of workplaces at enterprises and organizations in various industries. She underwent professional retraining in the specialty "Technosphere safety at work" and refresher courses for persons conducting fire safety measures.

Aleksandr S. Semenov graduated from the Saint-Petersburg Mining Institute (Technical University) named after G.V. Plekhanov, where he currently works as an Associate Professor of the Department of Mining Engineering. He is a Candidate of Technical Sciences. He was the winner of the contest "Professional Engineer" in the field of "Mining" in 2016. He has been the secretary of the Council of the Mining Faculty of the Saint-Petersburg Mining University since 2017. He is the author of 45 scientific papers, including: 3 patents for invention, 2 certificates for a utility model, 5 scientific and methodological works.

Vladimir I. Demin graduated from Kharkov Higher Military Command and Engineering School with a degree in Power Supply of Military Facilities in 1978. He is the Candidate of Technical Sciences, Associate Professor. He has been working as an associate professor of the Department of Life Safety of the Kuban State Technological University since 1999. He deals with industrial safety and power supply issues in various industries, including the oil and gas industry. He has over 60 publications in this field. Vladimir I. Demin trains workers of enterprises and organizations of the Krasnodar Territory in industrial safety, labor protection and electrical safety in the framework of additional professional education programs.

Table 1. Heat and humidity parameters of the air along the route of the oil gallery.

The number of the measurement point (fig.1)	**The air temperature, t, °C**	**Relative humidity, %**	**The moisture content of the air, g/kg**	**The enthalpy of the air, kJ/kg**
1	6	46	2,6	12,6
2	18	48	6,0	33,3
3	21	43	6,5	37,6
4	26	39	8,0	46,5
5	37	65	25,5	102,8
6	39	60	26,3	106,9
7	49	78	60,5	205,9

Table 2. Electricity costs.

Name of the equipment	**Engine power, kW**	**The number**	**The electricity tariff, RUB/kW.h**	**Energy costs, RUB**
Refrigerating machine IDV600	160	1	0,96	1 345 536
The air cooler RWK250	25	2		420 480
The water cooler RK600	60	1		504 576
TOTAL:				2 270 592

Table 3. The main indicators of economic efficiency of the project.

Parameter	**The value**
Net Present Value, rub	136821954,5
IRR, %	59%
DPI, unit	2,99
Pay-off period, years	2

Table 4. Economic efficiency of the project.

No.	**Indicator**	**Designa-tion**	**Periods, years**						
			0	**1**	**2**	**3**	**…**	**9**	**10**
1	Change in revenue (ex-cluding VAT), rub	Δ_B		38450925	38450925	38450925		38450925	38450925
1.1	The cost of 1 ton of Urals oil, ru-bles/ton.			23410	23410	23410		23410	23410
1.2	Increase in production, t	$365*Q*\%_{increase}$		1642,5	1642,5	1642,5		1642,5	1642,5
2	Change in operating costs, rub	$\Delta_Э$		-3281340,45	-3281340,45	-3281340,45		-3281340,45	-3281340,45
2.1	Change in the wage fund due to reduc-tion of costs for benefits and compen-sation for work in unfa-vorable work-ing condi-	P_l		-6000000	-6000000	-6000000		-6000000	-6000000

	tions, rub								
2.2	Change in the wage fund due to the reduction of the class of working conditions from 3.2 to 2 per year, rub	P_{lc}		-600000	-600000	-600000		-600000	-600000
2.3	Change in payments for insurance contributions due to a change in the wage fund, rub	P_{ins}		-1980000	-1980000	-1980000		-1980000	-1980000
2.4	Change in payments for insurance contributions in case of accidents due to changes in the wage fund, rub	$P_{ins.n}$		-561000	-561000	-561000		-561000	-561000
2.5	Change in maintenance costs for equipment, fuel and lubricants, ordinary repairs, rub	$P_{maintenance}$		687000	687000	687000		687000	687000
2.6	Change in electricity costs, rub	$P_{el.c.}$		2270592	2270592	2270592		2270592	2270592
2.7	Change in oil production costs, rubles	P_{ud}		2902067,55	2902067,55	2902067,55		2902067,55	2902067,55
3	Investments, rub		68700000						
4	Change in taxes, rub			1360260	1209120	1057980		151140	0
4.1	Increase in property tax due to commissioning of cooling equipment, rub			1360260	1209120	1057980		151140	0
5	Change in depreciation, rub			6870000	6870000	6870000		6870000	6870000
6	Change in profit before taxation, rub			33502005,45	33653145,45	33804285,45		34711125,5	34862265,5
7	Change in			6700401,09	6730629,09	6760857,09		6942225,0	6972453,0

	income tax, rub							9	9
8	Change in net profit, rub			26801604,36	26922516,36	27043428,36		27768900,4	27889812,4
9	Cash flow, rub		-68700000	40541604,36	40662516,36	40783428,36		41508900,4	41629812,4
10	Discount coefficient		1	0,869565217	0,756143667	0,657516232		0,28426241	0,24718471
11	Net present value, rub		-68700000	35253569,01	30746704,24	26815766,16		11799420,1	10290252,9
12	Net present value of ac-cumulated total, rub		-68700000	-33446430,99	-2699726,749	24116039,41		126531702	136821955

Table 5. Method of control points.

Parameter	The base value	The critical value	Relative change, %
Change in revenue, rub	38450925	4373320,12	-88,63
Change in operating costs, rub	-3281340,45	30796264,11	-1038,53
Investments, rub	68700000	497398495	624,02
Rate of discount,%	15	59	293,33

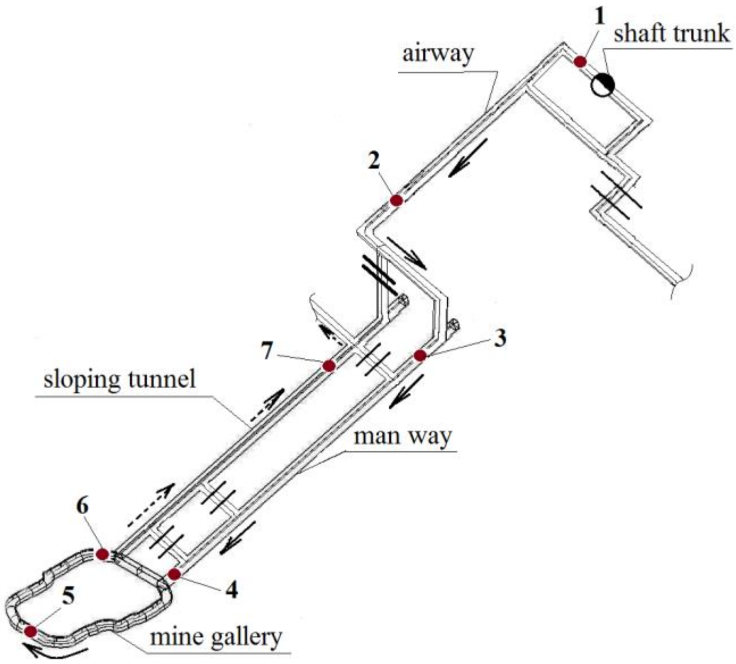

Figure1. The scheme of location of points of measurements along the route of the oil gallery: 1-7 – point of measurement hydrothermal characteristics, → - fresh air, - - → - return air.

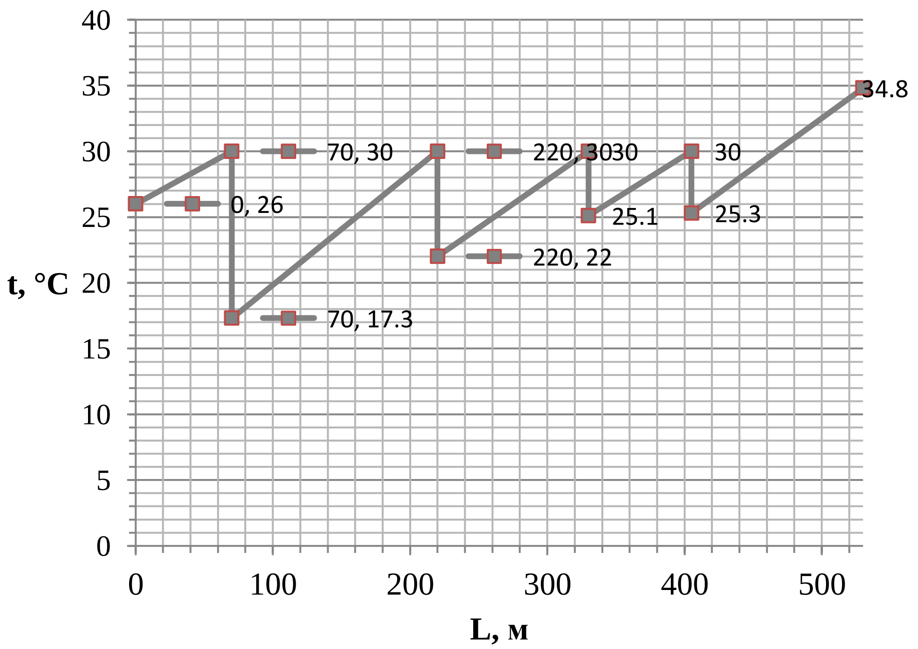

Figure 2. The change in temperature oil gallery: ■ - air cooler; - air temperature at artificial cooling of 500 kW; - air temperature at natural mode; - air temperature at artificial cooling of 1000 kW.

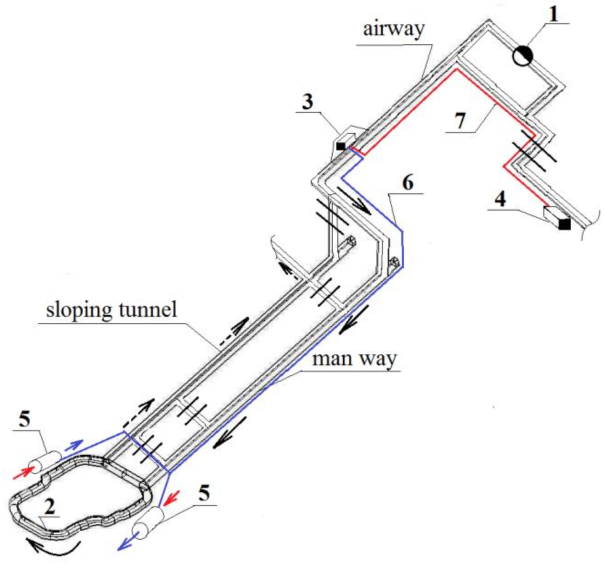

Figure 3. The scheme of arrangement of underground water-cooling refrigerating machines with a capacity of 500 kW into the mine: 1 – shaft trunk; 2 – mine gallery; 3 – refrigerating machine; 4 – water cooler; 5 – air cooler; 6 – supply pipeline; 7 – return pipeline; → - fresh air; - - → - return air.

a) b) c)

Figure 4. Refrigeration equipment company WAT: a) refrigerating machine IDV600; b) the air cooler RWK250; c) the water cooler RK600.

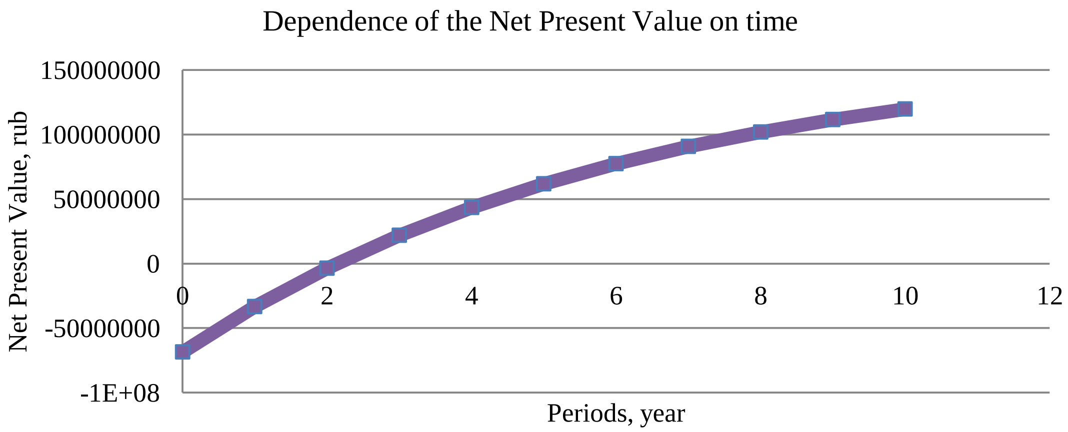

Figure 5. Dependence of the net present value on time.

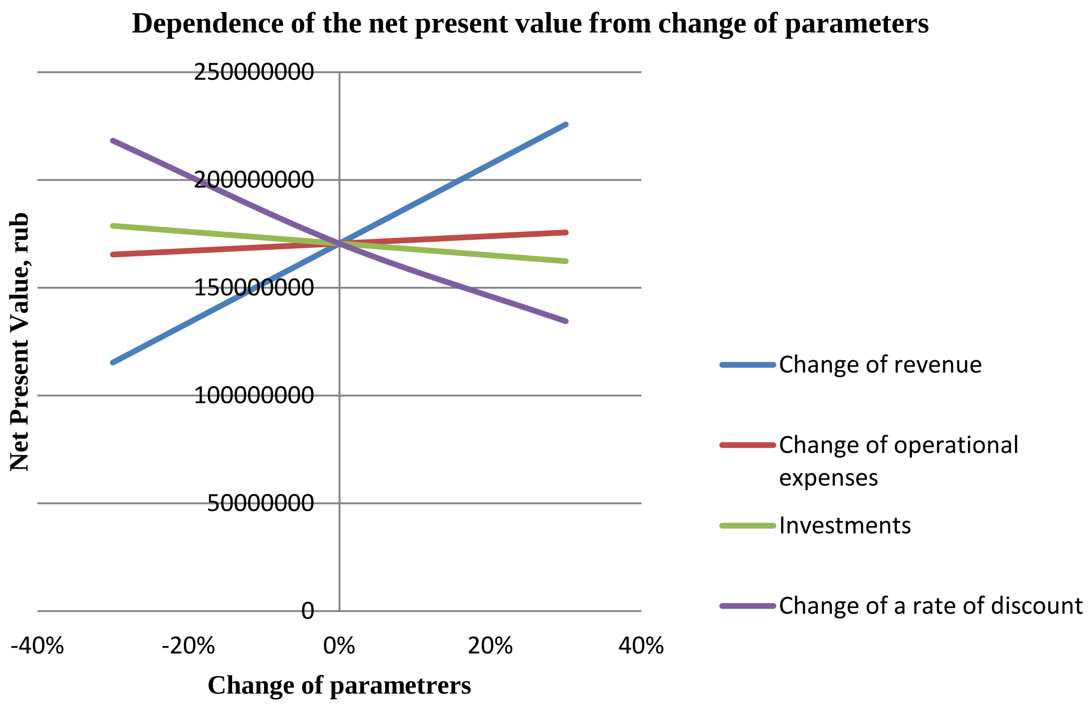

Figure 6. The method of rational ranges.