https://doi.org/10.33271/nvngu/2022-3/100

N. Spodyniuk[1],
orcid.org/0000-0002-2865-9320,
O. Voznyak[2],
orcid.org/0000-0002-6431-088X,
O. Savchenko[2],
orcid.org/0000-0003-3767-380X,
I. Sukholova[2],
orcid.org/0000-0002-3319-2278,
M. Kasynets[2],
orcid.org/0000-0002-7686-7482

1 – National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine, e-mail: n_spoduniuk@meta.ua
2 – Lviv Polytechnic National University, Lviv, Ukraine

OPTIMIZATION OF HEATING EFFICIENCY OF BUILDINGS ABOVE UNDERGROUND COAL MINES BY INFRARED HEATERS

Purpose. To optimize the energy and economic efficiency of heating system of ground structures of coal mines with infrared heaters due to the rational choice of technical parameters of heating devices and their operating conditions, namely, the irradiation intensity of the floor q, thermal power of the heater Q, blackness degree of the floor surface ε and the height of installation H of infrared heaters. To achieve this goal, the task was to conduct theoretical and experimental studies on infrared heaters NL-12R of heating system of a building above underground coal mines during its thermal modernization.

Methodology. At applying radiant heating systems, infrared heaters provide local heating of the working area of the buildings above underground coal mines. As a result, the necessary temperature conditions are maintained in the buildings above underground coal mines and there is a possibility of creating a local microclimate. A multifactorial experiment was performed taking into account the interaction of factors. The results of the study are presented in graphical and analytical forms. In addition, an analytical method was used to optimize parameters and operating conditions of the radiant heating system with infrared heaters NL-12R, and their number in the system of combined heating of buildings above underground coal mines is optimized.

Findings. According to the experimental results, dependence of the relative floor temperature on the intensity of floor irradiation q, thermal power of the heater Q, blackness degree of the floor surface $\varepsilon_{\text{floor}}$ and the height H of infrared heater's location was determined. The results are presented in the form of graphs and nomograms, as well as approximated by their analytical equations. The annual economic effect of the optimal variant of combined heating system due to use the maximum number of infrared heaters NL-12R is 39.4 Euro/year provided that the installation of infrared heaters NL-12R with a power of $Q = 1200$ W in the number of 5 pcs.

Originality. Optimization of energy and economic efficiency of heating system of buildings above underground coal mines by infrared heaters NL-12R, due to the rational choice of technical parameters of heating devices and conditions of their operation, was carried out by the analytical method.

Practical value. Results of optimization of thermal and economic parameters of operation of the combined heating system of buildings above underground coal mines with installation of infrared heaters NL-12R with power $Q = 1200$ W proved the efficiency of combined heating of above-ground structures and the achievement of the annual economic effect of 39.4 Euro/year.

Keywords: *heating system, buildings above underground coal mines, energy saving, thermal modernization, infrared heaters*

Introduction. Restructuring in the coal industry and the closure of unpromising mines leads to actualization of the issue of constant reduction of costs for coal mining and maintenance of the mine complex in working order. The price of coal in the market and the competitiveness of individual enterprises depends directly on the use of the latest technology and introduction of energy efficiency measures.

The issue of economical use of energy carriers in the current energy crisis and the aggravated environmental situation in Ukraine also arises in the mining industry. Buildings above underground mines and warehouses occupy a large area and require not only structural modernization, but also the use of energy-efficient equipment for heating and ventilation systems.

According to a comprehensive analysis of energy consumption, a large amount of energy is spent on providing the heat supply system of production facilities with a large volume, which include aboveground structures of coal mines [1]. Therefore, the current energy efficiency strategy of this industry covers both the legal framework and technical innovations.

Carrying out of thermal modernization of systems and mechanisms, installation of a set of automation will allow reducing energy consumption of powerful industrial complexes [2, 3]. The use of continuously operating ventilation systems and an additional backup ventilation unit on the surface of the mine leads to the introduction of heat storage devices as a modern solution to increase the energy efficiency of heating systems [4].

The issue of achieving maximum air distribution efficiency also remains relevant. The article [5] gives examples of ventilation systems that increase the efficiency of air distribution in the premises by means of a swirling air flow, compact air jet, flat air jet and rectangular air jet. The expediency of using this type of jets has been proved and the topical issue of eliminating

---

damage in ventilation systems has been solved, which will provide comfortable conditions and increase the energy efficiency of the coal mine.

Mining facilities, which currently consume a lot of energy, contribute to environmental pollution. Therefore, the process of modernization of these facilities is relevant in the context of minimizing harmful emissions, as well as the construction of buildings above coal mines with minimal energy consumption using automatic control systems. This should take into account the air quality both inside the mine and in its aboveground structures, which directly affects human health [6, 7].

The energy consumption associated with the need for quality heat supply in the buildings above underground mines must be reduced as a result of energy efficiency measures [8]. An alternative to traditional heating systems for above-ground buildings is the use of infrared heaters [9]. Infrared heaters, due to their features to provide local heating, allow one to directly heat various areas of buildings above underground mines, warehouses, technical complexes and open areas of coal mines [10].

The use of non-flammable, safe electric infrared heaters in the ground structures of mines and on work areas will minimize the risks associated with increased fire hazard of the coal industry [11, 12].

Literature review. The key criterion for the selection and design of heating systems for buildings above underground coal mines is to provide comfortable conditions for personnel to perform the production task. Labor productivity depends on the quality microclimate in the ground structures of mines.

To maintain the normative temperature of the air environment in the ground structures of mines, the question of quality operation of the combined heating system arises, which is based on a complex combination of traditional heating system of these structures and infrared emitters that provide local heating. In this case great attention is paid to the correct selection and installation of heaters, analysis of the overall economic efficiency of the system as a whole.

Determining the economic feasibility of implementation infrared heaters together with a traditional heating system is an urgent task.

In order to establish the most acceptable options for the operation of the heat supply system based on infrared heaters in the ground structures of mines, it is necessary to optimize all the parameters that affect the overall operation of the system. Qualitative regulation of these factors will lead to energy efficient heat consumption of the heating system of mining facilities [13].

The main feature of infrared emitters is to heat the surface first, and only then give its heat to the environment. It is a key point in the formation of the microclimate in the ground structures of mines, which are mostly open and large volume. In addition, the effect of irradiation intensity and the blackness degree of the irradiation surface takes place. A comprehensive approach to solving the problem of achieving optimal air temperature in the irradiation area will allow choosing correctly the infrared heaters of a certain capacity and saving a lot of energy [14].

In [15], the influence of ceramic and tungsten infrared heating elements on the radiation flux distribution is presented. Experimental results have shown that the change in temperature at the irradiation surface depends on the type of infrared heater, namely its short-wave or long-wave radiation. This proves the fact that the surface temperature of the irradiation is an important variable parameter in providing comfortable conditions in the working area.

Widespread use of infrared heaters in industry has been proven [16]. Their designs are subject to constant improvement, and working conditions provide radiation efficiency by 70–75 %. In [17], a comparison of different types of electric infrared emitters and their ability to generate high radiation power with a corresponding wavelength range is considered. In addition, the surface temperature of the irradiation was investigated.

Along with providing comfortable conditions in buildings above underground mines, the technical and economic assessment of the efficiency of the radiant heating system by infrared heaters plays an important role, namely the analysis of investment and operating costs for re-equipment of the heating system [18, 19].

Unresolved aspects of the problem. Based on the review of literature sources, can be generalized that there is a need to optimize the energy and economic efficiency of the heating system of buildings above underground mines due to the rational choice of technical parameters of heating devices: the intensity of irradiation of the floor surface q, thermal power of the heater Q, blackness degree of the floor surface ε and the height installation of the heater H, to achieve an increase in the relative surface temperature of the irradiation $\overline{t}_s$, and as a result, the air temperature in the building. It is also necessary to determine the optimal number of infrared heaters NL-12R in the infrared heating system and their high-quality combination with the traditional heat supply system of ground structures of coal mines.

The purpose. The aim of the work is to optimize the energy and economic efficiency of the heating system of ground structures of coal mines with infrared heaters due to the rational choice of technical parameters of heating devices and conditions of their operation, namely the intensity of floor irradiation q, thermal power of the heater Q, blackness degree of the floor surface ε and the height of installation H of infrared heaters.

To achieve this goal, the task was to conduct theoretical and experimental studies on infrared heaters NL-12R of heating system of the ground structures of mines during their thermal modernization.

Materials and methods of research of infrared heaters. It should be noted that infrared heaters NL-12R with a maximum thermal power of 1200 W are quite attractive for use in ground structures of mines.

In their application, local heating of the surrounding surfaces in the working area of the premise is provided (Fig. 1). In addition, the air is heated from the heated surfaces in the irradiation area, which has a positive effect on the human body which is in the heating area. As a result, the required temperature conditions are maintained at the location of the emitters.

Results. Experimental studies were performed to determine the radiation temperature of the irradiation area with an infrared heater NL-12R. In addition, the main attention was paid to the study on floor surface temperature as the largest surface area of irradiation. Thermal comfort in the irradiation area and further formation of the temperature regime in the ground structures of mines depends exactly on the temperature of the floor surface.

To ensure the universality of the obtained calculations, the following factors of influence on this temperature were taken

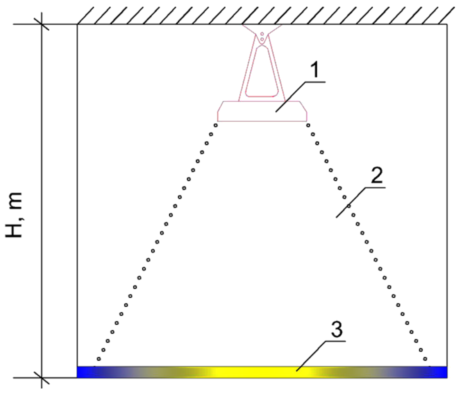


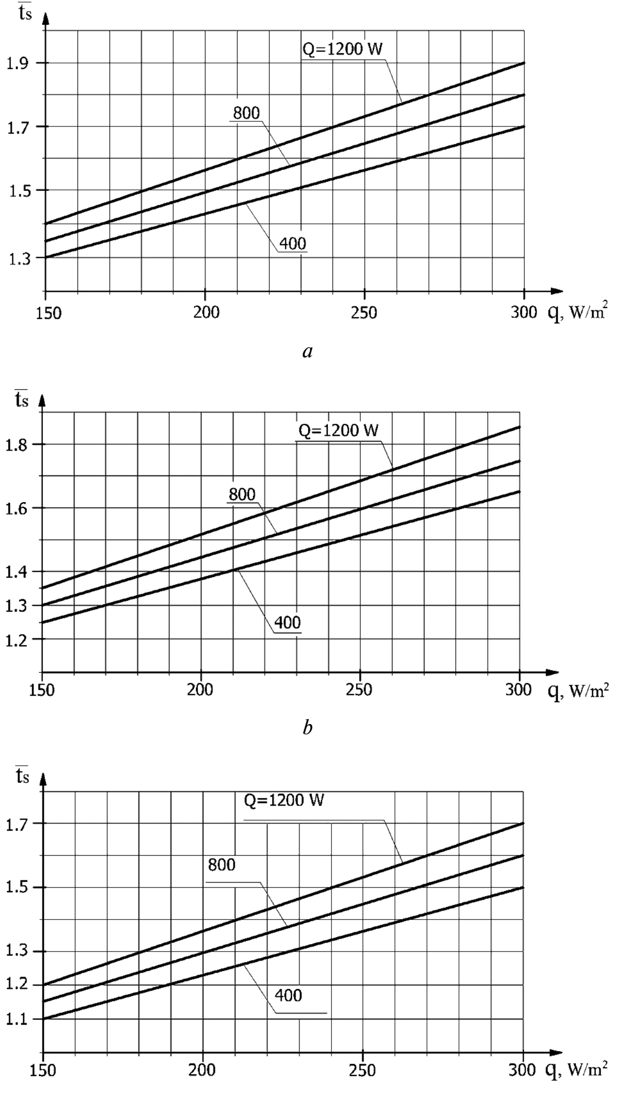
Fig. 1. Infrared heater placement scheme:

1 – infrared heater; *2 – irradiation zone*; *3 – irradiation surface*; *H*, *m – the height of installation of the heater* into account, namely: the intensity of irradiation of the infrared heater q, its thermal capacity Q, the height installation of the device H and the blackness degree of the floor surface ε. According to the obtained results, graphs of the dependence of the temperature of the heated floor surface at different heights of the heater were built. Measurements were performed on the thermal capacity of the device $Q = 400$, $Q = 800$ and $Q = 1{,}200$ W and the height installation of the heater $H = 1$, $H = 1.5$ and $H = 2$ m for the floor surface with the following indicators: $\varepsilon = 0.92$ (black metal sheet), $\varepsilon = 0.75$ (surface covered with sawdust) and $\varepsilon = 0.3$ (peat surface). Fig. 2 shows the results for the blackness degree of its surface ε, which was accepted as permanent, namely $\varepsilon = 0.75$ (surface covered with sawdust).

The study was aimed at determining the relative floor surface temperature, as this value takes into account the ambient temperature, which affects the floor temperature. It is the relative temperature that allows obtaining universal results and is determined by the formul

$$\overline{t}_s = \frac{t_s}{t_{in}},$$

where t_s and t_{in} are respectively the floor surface temperature, °C and air temperature in the ground structure of a mine, °C.



a

b

c

Fig. 2. The dependence of the relative temperature of the irradiation surface on the intensity of irradiation of the floor q, W/m² and thermal capacity of the heater Q, W at the height of its installation:

a – H = 1 *m*; *b – H* = 1.5 *m*; *c – H* = 2 *m* (*the blackness degree of the floor surface is constant* ε = 0.75)

The graphs (Figs. 2, *a, b, c*) are respectively approximated by the following empirical dependences

$$\overline{t}_s = 0.45 + \left(0.0024 + 0.75Q\right)\cdot q; \tag{1}$$

$$\overline{t}_s = 0.425 + \left(0.0024 + 0.75Q\right)\cdot q; \tag{2}$$

$$\overline{t}_s = 0.35 + \left(0.0024 + 0.75Q\right)\cdot q. \tag{3}$$

On the basis of (1–3) the universal dependence (4) is received, which expresses the dependence of the relative floor temperature on three values: intensity of floor irradiation q, W/m², thermal capacity of the heater Q, W, and the height of its installation H, m

$$\overline{t}_s = 0.35 + 0.2H - 0.1H^2 + \left(0.0024 + 0.75Q\right)\cdot q. \tag{4}$$

Equation (4) is obtained for a constant value $\varepsilon = 0.75$. To generalize the results for other values of ε, a universal graphical dependence in the form of a nomogram is constructed, Fig. 3. This nomogram (Fig. 3) is approximated by an empirical (5).

$$\begin{aligned}\overline{t}_s = {} & (0.35 + 0.2H - 0.1H^2 + (0.0024 + 0.75Q)\cdot q)\times \\ & \times (0.98 - 0.35\varepsilon + 0.5\varepsilon^2).\end{aligned} \tag{5}$$

The analysis of Fig. 3 and (5) shows that with increasing intensity of floor irradiation q, thermal power of the heater Q and the blackness degree of the floor surface ε, the relative surface temperature of the irradiation $\overline{t}_s$ increases, and with increasing height of the installation H, it decreases. The relative temperature increases more intensively at large values of the blackness degree of the floor surface ε, and at its small values, the temperature rise is insignificant.

Optimization of parameters of infrared heaters NL-12R of different thermal productivity. The obtained graphical and analytical dependences confirm the fact that the floor surface

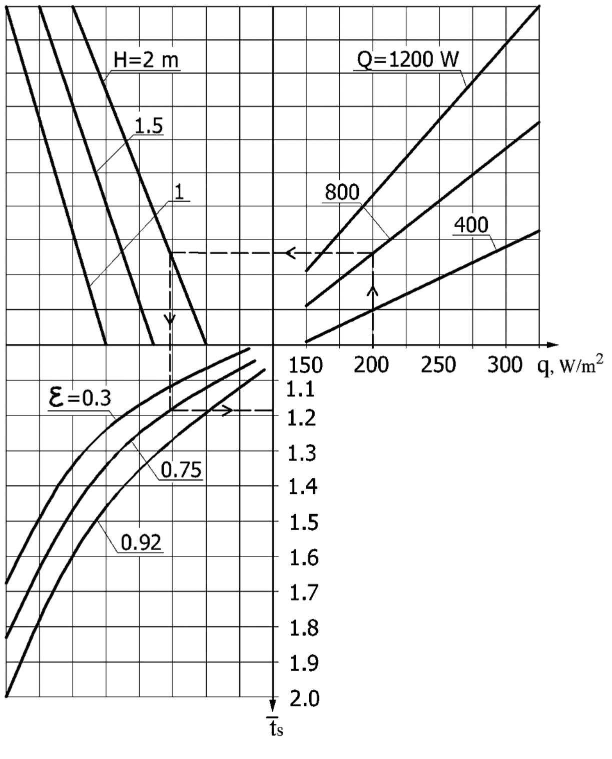


Fig. 3. Universal nomogram of the dependence of the relative temperature of the irradiation surface $\overline{t}_s$ *on the intensity of irradiation of the floor q, W/m², thermal power of the heater Q, W, the height of its installation H, m and the blackness degree of the floor surface* ε

temperature is affected by the thermal power of the heater, the height of its installation and the blackness degree of the floor surface.

Since the intensity of irradiation q corresponded to the values recommended for ground structures of mines, the surface temperature of the heated floor did not exceed the permissible values, i. e., $\overline{t}_s \le 2$. Therefore, for simplification, it is advisable to cite the multifactor experiment to a three-factor one, assuming the irradiation intensity q as a constant value. When processing the results of the three-factor experiment, the calculated dependence (6) was obtained

$$\overline{t}_s = (0.058 + 0.18 \cdot \varepsilon) \cdot (0.002 \cdot Q - 3H + 5.2)^2 + \\ + (0.3 + 0.45 \cdot \varepsilon)(0.002 \cdot Q - 3H + 5.2). \tag{6}$$

Analyzing (6), we come to the conclusion that it must be investigated to the extreme. For this purpose, it is expedient to allocate a simplex $y = -3H + 0.002Q + 5.2$ and constant quantities $C_1 = 0.18\varepsilon + 0.058$ and $C_2 = 0.45\varepsilon + 0.3$.

We convert expression (6) to the form

$$Z = C_1 y^2 + C_2 y.$$

We differentiate this expression

$$Z^1 = 2C_1 y + C_2.$$

Since the values of C_1 and C_2 are positive, the expression Z^1 is also positive, never turns to zero, and the function Z grows monotonically. This means that to maximize it, it is necessary to maximize the simplex

$$y = -3H + 0.002Q + 5.2.$$

This simplex is a two-factor function, i. e. the value of y depends on two quantities $y = f(H; Q)$.

It should be noted that to determine the simplex y, it is necessary to know the value of its maximum. For this purpose, in turn, it is necessary to investigate a simplex y-function on an extremum whose necessary conditions are like this: if the function $y = f(H; Q)$ reaches an extreme at $H = H_0$ and $Q = Q_0$, then each partial derivative of the first order from y becomes zero at these values of the arguments. Let us differentiate by partial derivatives

$$\frac{\partial y}{\partial H} = -3;$$

$$\frac{\partial y}{\partial Q} = 0.002.$$

In general, we obtain a system of two equations with two unknowns (7)

$$\begin{cases} \dfrac{\partial y}{\partial H} = 0 \\ \dfrac{\partial y}{\partial Q} = 0 \end{cases}. \tag{7}$$

Solving the system of equations (7), we find the required values $H = H_0$ and $Q = Q_0$ on a certain segment of these arguments, respectively $[H_1; H_2]$ and $[Q_1; Q_2]$. Therefore, as a result of calculations, we would receive coordinates of a stationary point $M(H_0; Q_0)$.

Since there is no preliminary confirmation of the existence of the maximum of the y-function, additional research is needed, i.e., sufficient conditions for the extremum should be established. If the y-function has continuous partial derivatives of the second order in a certain environment of point $M(H_0; Q_0)$, and if at this time the necessary conditions are met, then in the case where the second differential

$$\partial^2 y = \sum_{i=1}^{2} \sum_{j=1}^{2} \frac{\partial^2 y}{\partial H_i \partial Q_j} \bigg| (H_o, Q_o)^{\Delta H_i \Delta Q_j},$$

is a positive definite quadratic form, then the function $y = f(H; Q)$ has a maximum at this point. Under these conditions, the y-function will have a stationary value at the point $M(H_0; Q_0)$, and point M will be called stationary.

Let us investigate the positive definiteness of the quadratic form

$$\begin{pmatrix} \dfrac{\partial^2 y}{\partial H^2} & \dfrac{\partial^2 y}{\partial H \partial Q} \\ \dfrac{\partial^2 y}{\partial Q \partial H} & \dfrac{\partial^2 y}{\partial Q^2} \end{pmatrix}.$$

It is advisable to enter these notations

$$\frac{\partial^2 y}{\partial H^2} = A; \quad \frac{\partial^2 y}{\partial Q^2} = B; \quad \frac{\partial^2 y}{\partial H \partial Q} = C.$$

Taking into account the property of the order of differentiation in partial derivatives

$$\frac{\partial^2 z}{\partial x \partial y} = \frac{\partial^2 z}{\partial y \partial x},$$

the Jacobian (J) differential determinant will look like this

$$J = \begin{vmatrix} A & C \\ C & B \end{vmatrix},$$

after the disclosure of the determinant, we obtain

$$J = A \cdot B - C^2.$$

Let us find the derivatives of the second order at a stationary point $M(H_0; Q_0)$ and determine its nature

$$A = \frac{\partial^2 y}{\partial H^2} = 0;$$

$$B = \frac{\partial^2 y}{\partial Q^2} = 0;$$

$$C = \frac{\partial^2 y}{\partial HQ} = \frac{\partial^2 y}{\partial QH} = 0.$$

In this case, Jacobian

$$J = AB - C^2 = 0.$$

Considering that $J = 0$, we state that the function $y = f(H; Q)$ has neither a maximum nor a minimum. Therefore, there is no stationary point M. Under this condition, the simplex y at the ends of the argument intervals should be defined $[H_1; H_2]$ and $[Q_1; Q_2]$. This means that it is necessary to determine the largest value of y_i at four points, namely: $y_1 = f(H_1; Q_1)$; $y_2 = f(H_2; Q_1)$; $y_3 = f(H_1; Q_2)$; $y_4 = f(H_2; Q_2)$.

The obtained results showed that the largest value is $y = f(1\text{ m}; 1{,}200\text{ W})$, which is optimal.

This means that the relative floor temperature at this point is optimal, i. e., this value is optimized.

Optimization of the combined system of heating of ground structures of a mine with use of several infrared heaters NL-12R. Of interest is the application of the combined heating system of the ground structure of the coal mine, namely, the combination of a traditional heating system with radiant infrared heaters. In addition, it is advisable to consider alternatives to use infrared heaters NL-12R with the thermal power $Q = 1200$ W, which compensates for the share α of heat load of traditional heating system.

The following optimization technique is proposed:

1. Annual energy consumption for the needs of a traditional heating system Q_0, MJ/year is accepted as the initial data.
2. Energy saving ΔQ_i of each of the alternatives was defined as $\Delta Q_i = Q_o - Q_i$, and hence the annual savings K_i, Euro/year.
3. The cost of heating energy [20] (value P_{HE}), which is in Ukraine 2,000–2,400 UAH per 1 Gcal is accepted $P_{HE} = 17$ Euro/GJ (2,350 UAH/Gcal). Annual operating costs with a traditional heating system make $C_0 = P_{HE} Q_0$, Euro/year.

4. The cost of electricity P_{EE}, which is 194 kop. for 1 kW· year (II voltage class up to 27.5 kV for industrial and similar consumers with a capacity of up to 750 kVA), is accepted $P_e =$ $= 16.3$ Euro/GJ. Annual operating costs for heating with infrared heaters make $C_E = P_E Q_E$, Euro/year.

5. During installation of infrared heaters due to the difference in the cost of thermal and electrical energy, savings are obtained, which is associated with the capital cost of these devices.

6. Carrying out of technical and economic estimation of installation of infrared heaters and substantiation of their economically expedient quantity.

The heat load of a traditional heating system is q_0, W. At this thermal capacity, the annual heating needs will be Q_0, GJ/year

$$Q_0 = 3.6 q_0 24 z 10^{-6},$$

where z is duration of the heating period, days.

Thermal power of the infrared heater NL-12R is q_E, W, and its cost K, Euro. At this thermal capacity, the annual heating needs will be Q_e, GJ/year

$$Q_E = 3.6 q_E n 24 z 10^{-6},$$

where n is the number of devices NL-12R to compensate for the proportion α of the heat load of a traditional heating system.

Annual heat savings make, GJ/year

$$\Delta Q = Q_o - Q_E = (1 - \alpha) Q_0.$$

Annual savings due to the difference between the cost of heat and electricity ΔB_{ec}^{year} make, Euro/year

$$\Delta B_{ec}^{year} = q_E \cdot n \cdot (P_{HE} - P_{EE}),$$

where P_{HE} and P_{EE} are respectively the cost of heat and electricity, Euro/GJ.

Annual operating costs for a traditional heating system EC are, Euro/year

$$EC_{HE} = P_{HE} Q_0.$$

Annual operating costs for the radiant heating system EC are, Euro/year

$$EC_{EE} = P_{HE} Q_0.$$

According to these data, we build a graph (Fig. 4). Fig. 4 shows the dependence on the number of n infrared heaters NL-12R of investment costs IC for their purchase, exploitative costs EC (line 2) and annual combined costs CC for these materials. Fig. 4 shows a geometric interpretation of finding the optimal point for different numbers of n infrared heaters NL-12R. Values n_{opt} and CC_{opt} are determined analytically after differentiating the expression for the combined costs and equating it to zero.

To obtain a solution, it is necessary to reduce the values to the same dimension using the normative coefficient of reduction of different time costs E_N and investigate the function of combined costs CC for the presence of a minimum point.

$$CC = E_N IC + EC, \tag{8}$$

where E_N is the normative coefficient of reduction of different time expenses, 1/year.

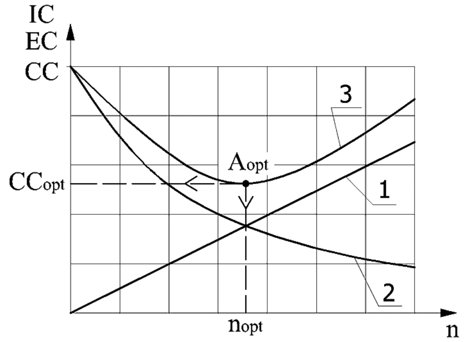


Fig. 4. Dependence of different financial costs on the number of n infrared heaters NL-12R:

1 – investment costs IC, UAH; *2 – annual exploitative costs EC, UAH/year*; *3 – combined costs CC, UAH/year*

This value is inverse to the normative payback period T_N, years.

In this case, the terms of the (8) are investments accordingly (total annual cost of infrared heaters NL-12R) and exploitative costs (specific annual cost of thermal and electric energy to maintain the set temperature in the room t_{in}, °C).

After differentiation of expression (8) and replacement of variables we obtain economically expedient quantity of infrared heaters NL-12R

$$n_{ipt} = \sqrt{\frac{a \cdot T}{b}}, \tag{9}$$

where a and b are respectively, numerical coefficients that express the cost of thermal energy and the cost of electricity.

The analysis of (9) shows a partial case: this expression is not equal to zero, the function is monotonic, the critical point is absent. The largest and smallest values of the function are at the ends of the numerical interval. Therefore, it should be noted that the rise in price of thermal energy leads to an increase in the optimal number of infrared heaters NL-12R. A similar consequence is a decrease in the cost of electricity, but there is usually a tendency to increase its price. Therefore, the ratio of the coefficients a and b is decisive, that is, the cost of thermal energy to the cost of electricity. This factor must be taken into account when designing heating systems for ground structures of coal mines for the future.

The question arises, what are the numerical indicators of the use of a combined heating system? To solve this problem, we represent the fraction α of radiant heating by infrared heaters NL-12R within 10–50 %, that is $\alpha = 0.1–0.5$. Value $\alpha = 0.1$ means the minimum number of infrared heaters NL-12R, i. e., 1 psc., with their maximum thermal output of 1,200 W. Therefore, the total thermal capacity of the heating system is $q_0 =$ $= 12$ kW, and annual thermal capacity is $Q_0 = 192$ GJ/year. So, we consider the following four options:

- traditional heating system (no infrared heaters $q_0 = 12$ kW, $Q_0 = 192$ GJ/year);
- combined heating system with the number of infrared heaters 1 psc. ($q_0 = 10.8$ and $q_R = 1.2$ kW; $Q_0 = 172.8$ and $Q_R =$ $= 19.2$ GJ/year);
- combined heating system with the number of infrared heaters 3 pcs. ($q_0 = 8.4$ and $q_R = 3.6$ kW; $Q_0 = 134.4$ and $Q_R =$ $= 57.6$ GJ/year);
- combined heating system with the number of infrared heaters 5 pcs. ($q_0 = 6.0$ and $q_R = 6.0$ kW; $Q_0 = 96.0$ and $Q_R =$ $= 96.0$ GJ/year).

The results of the calculations are given in Table.

Table

Economic characteristics of combined heating

No	Number of infrared heaters	Capital costs, K thousand UAH	Exploitative costs, EC, thousand UAH/year	Combined costs, CC, thousand UAH/year
1	0	0	107.7	107.7
2	1	1.1–2.2	107.3	107.5–107.6
3	3	3.3–4.4	106.5	107.0–107.2
4	5	5.5–6.6	105.6	106.4–106.6

Taking into account the fact that capital costs are considered as the cost of infrared heaters NL-12R, and the cost of their installation, which depends on various factors, it is advisable to present these data as a gap. Therefore, the values of the reduced costs are similarly given.

As the analysis of the results of the table shows, there is a tendency to reduce the combined costs with an increasing number of infrared heaters NL-12R. This means that it is advisable to increase the share α of radiant heating to $\alpha = 1$, i.e., to the maximum possible 100 %. Therefore, it is advisable to use radiant heating of ground structures of coal mines and the reconstruction of traditional heating systems in the future. The payback period of infrared heaters NL-12R is 1.9 years, that is, when the heating system is reconstructed, these devices will be profitable in less than 2 years.

In summary, we argue about the feasibility of using infrared heaters NL-12R in the maximum possible quantity with the optimized parameters of their operation both in power, and in technical and economic aspects. These measures will provide comfortable conditions in buildings above underground mines and get the maximum economic effect.

The research results can be used in the development of mathematical models and design of energy-saving radiant heating systems of buildings above underground mines with the use of infrared heaters NL-12R.

Conclusions. On the basis of the conducted research, we assert:

- the optimal number of infrared heaters NL-12R with a combined heating system of the building above underground mine is the maximum possible;
- the method for determining the optimal combined costs and the optimal number of infrared heaters NL-12R at constant prices is given;
- the rise in price of thermal energy leads to an increase in the optimal number of infrared heaters NL-12R;
- the maximum economic effect is received at the expense of installation of infrared heaters NL-12R in the maximum possible quantity.

References.

1. Ulewicz, M., Zhelykh, V., Furdas, Y., & Kozak, K. (2021). Assessment of the Economic Feasibility of Using Alternative Energy Sources in Ukraine. *Lecture Notes in Civil Engineering, 100*, 482-489. https://doi.org/10.1007/978-3-030-57340-9_59.

2. Savchenko, O., Voznyak, O., Myroniuk, K., & Dovbush, O. (2020). Thermal Renewal of Industrial Buildings Gas Supply System. *Lecture Notes in Civil Engineering*, *100*, 385-392. https://doi.org/10.1007/978-3-030-57340-9_47.

3. Zhang, H., Li, K., Zhao, L., Jia, L., Kaita, M., & Wan, S. (2021). Modeling of a Wellhead Heating Methodology with Heat Pipes in Coal Mines. *Journal of Energy Resources Technology*, *143*(1). https://doi.org/10.1115/1.4049003.

4. Antypov, I., Gorobets, V., & Trokhaniak, V. (2021). Experimental and Numerical Investigation of Heat and Mass Transfer Processes for Determining the Optimal Design of an Accumulator with Phase Transformations. *Journal of Applied and Computational Mechanics*, *7*(2), 611-620. https://doi.org/10.22055/JACM.2020.34893.2524.

5. Spodyniuk, N., Voznyak, O., Sukholova, I., Dovbush, O., Kasynets, M., & Datsko, O. (2021). Diagnosis of damage to the ventilation system. *Diagnostyka, 22*(3), 91-99. https://doi.org/10.29354/diag/141913.

6. Kapalo, P., & Spodyniuk, N. (2018). Effect of the variable air volume on energy consumption – Case study. *IOP Conference Series: Materials Science and Engineering*, *415*, 1.012027. https://doi.org/10.1088/1757-899X/415/1/012027.

7. Kapalo, P., Vilčeková, S., Mečiarová, L., Domnita, F., & Adamski, M. (2020). Influence of indoor climate on employees in office buildings – A case study. *Sustainability*, *12*(14), 5569. https://doi.org/10.3390/su12145569.

8. Anderson, R., & Souza, De E. (2017). Heat stress management in underground mines. *International Journal of Mining Science and Technology*, *27*(4), 1-5. https://doi.org/10.1016/j.ijmst.2017.05.020.

9. Spodyniuk, N., Zhelykh, V., & Dzeryn, O. (2018). Combined Heating Systems of Premises for Breeding of Young Pigs and Poultry. *FME Transactions*, *46*, 651-657. https://doi.org/10.5937/fmet1804651S.

10. Yadav, G., Gupta, N., Sood, M., Anjum, N., & Chib, A. (2020). Infrared heating and its application in food processing. *The Pharma Innovation Journal*, *9*(2), 142-151. ISSN (E): 2277-7695.

11. Wojtacha-Rychter, K., & Smoli´nski, A. (2018). Study of the Hazard of Endogenous Fires in Coal Mines – A Chemometric Approach. *Energies, 11*(11), 3047. https://doi.org/10.3390/en11113047.

12. Kumar, S., Mishra, P.K., & Mandal, P.K. (2018). Study of detection techniques for heating of coal in underground coal mines. *The Indian Mining & Engineering Journal*, *57*(10), 29-34. ISSN 0019-5944.

13. Gaonwe, T., Kusakana, K., & Hohne, P. (2019). Walk-through Energy Audit and Savings Opportunities: A Case of Water Heaters at CUT Residencial Buildings. *Conference: IEEE open innovations conference 2019,* Cape Town, South Africa. https://doi.org/10.1109/OI.2019.8908172.

14. Cao, Y., Yang, J., & Li, J. (2020). Energy-Saving Research on Residential Gas Heating System in Cold Area Based on System Dynamics. *International Journal of Heat and Technology*, *38*(2), 457-462. https://doi.org/10.18280/ijht.380222.

15. Kebede, T., & Esakki, B. (2019). Effect of Various Infrared Heaters on Sintering Behavior of UHMWPE in Selective Inhibition Sintering Process. *International Journal of Engineering and Advanced* Technology, *8*(6), 725-731. https://doi.org/10.35940/ijeat.F8316.088619.

16. Maznoy, A., Kirdyashkin, A., Pichugin, N., Zambalov, S., & Petrov, D. (2020). Development of a new infrared heater based on an annular cylindrical radiant burner for direct heating applications. *Energy*, *204*, 117965. https://doi.org/10.1016/j.energy.2020.117965.

17. Vidyarthi, S., El-Mashad, H., Khir, R., Zhang, R., Tiwari, R., & Pan, Z. (2019). Evaluation of selected electric infrared emitters for tomato peeling. *Biosystems Engineering, 184*, 90-100. https://doi.org/10.1016/j.biosystemseng.2019.06.006.

18. Haq, H., Valisuo, P., Kumpulainen, L., & Tuomi, V. (2020). An economic study of combined heat and power plants in district heat production. *Cleaner Engineering and Technology, 1*, 100018. https://doi.org/10.1016/j.clet.2020.100018.

19. Paraschiv, S., Barbuta-Misu, N., & Simona Paraschiv, L. (2020). Technical and economic analysis of a solar air heating system integration in a residential building wall to *increase* energy efficiency by solar heat gain and thermal insulation. *Energy Reports, 6*(6), 459-474. https://doi.org/10.1016/j.egyr.2020.09.024.

20. Aedah, M.J. Mahdi (2018). Energy Audit a step to effective Energy Management. *International Journal of Trend in Research and Development*, *5*(2), 521525. ISSN: 23949333.

Оптимізація ефективності опалення наземних споруд вугільних шахт інфрачервоними обігрівачами

Н. Сподинюк[1], *О. Возняк*[2], *О. Савченко*[2], *І. Сухолова*[2], *М. Касинець*[2]

1 – Національний університет біоресурсів і природокористування України, м. Київ, Україна, e-mail: n_sponduniuk@meta.ua

2 – Національний університет «Львівська політехніка», м. Львів, Україна

Мета. Оптимізація енергетичної та економічної ефективності системи опалення наземних споруд вугільних шахт інфрачервоними обігрівачами завдяки раціональному вибору технічних параметрів опалювальних пристроїв і умов їх експлуатації, а саме інтенсивності опромінення підлоги q, теплової потужності нагрівача Q, ступеня чорноти поверхні підлоги ε і висоти розташування H інфрачервоних обігрівачів. Для досягнення мети було поставлено завдання провести теоретичні та експериментальні дослідження інфрачервоних обігрівачів NL-12R системи опалення надшахтної будівлі під час її термомодернізації.

Методика. При застосуванні систем променистого опалення інфрачервоними обігрівачами забезпечується локальне опалення робочої зони надшахтної будівлі. Унаслідок цього у наземних спорудах вугільних шахт підтримуються необхідні температурні умови та існує ймовірність створення локального мікроклімату. Було реалізовано багатофакторний експеримент з урахуванням взаємодії факторів. Результати дослідження представлені у графічному та аналітичному вигляді. Крім цього, було застосовано аналітичний метод оптимізації параметрів і умов експлуатації системи променистого опалення інфрачервоними обігрівачами NL-12R, а також оптимізована їх кількість у системі комбінованого опалення наземних споруд вугільних шахт.

Результати. За результатами експерименту визначена залежність відносної температури підлоги від інтенсивності опромінення підлоги q, теплової потужності нагрівача Q, ступеня чорноти поверхні підлоги $\varepsilon_{\text{підл}}$ і висоти розташування H інфрачервоних обігрівачів. Результати представлені у вигляді графіків і номограми, а також апроксимовані аналітичними рівняннями. Річний економічний ефект за оптимального варіанту комбінованої системи опалення за рахунок застосування максимальної кількості інфрачервоних обігрівачів NL-12R складає 39,4 Euro/рік за умови встановлення інфрачервоних обігрівачів NL-12R потужністю Q = 1200 Вт у кількості 5 шт.

Наукова новизна. Оптимізація енергетичної та економічної ефективності системи опалення наземних споруд вугільних шахт інфрачервоними обігрівачами NL-12R, завдяки раціональному вибору технічних параметрів опалювальних пристроїв і умов їх експлуатації, проведена аналітичним методом.

Практична значимість. Результати оптимізації теплових і економічних параметрів роботи комбінованої системи опалення надшахтних будівель зі встановленням інфрачервоних обігрівачів NL-12R потужністю Q = 1200 Вт засвідчили ефективність комбінованого опалення наземних споруд вугільних шахт і досягнення річного економічного ефекту 39,4 Euro/рік.

Ключові слова: *система опалення, надшахтні будівлі, енергоощадність, термомодернізація, інфрачервоні обігрівачі*

The manuscript was submitted 29.07.21.