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ENHANCING ENERGETIC AND ECONOMIC EFFICIENCY OF HEATING COAL MINES BY INFRARED HEATERS

Purpose. To increase the energy and economic efficiency of heating coal mines with infrared heaters through energy saving measures, taking into account the dynamics of the discount rate. To achieve this goal, the task was to conduct an energy audit of the heating system of the mine during its reconstruction according to an improved method, taking into account the dynamics of the discount rate and measures that are not feasible at the same time.

Methodology. When using infrared heating systems, local heating of the working area is provided. As a result, the necessary temperature conditions in the mines are maintained and there is a possibility of creating a local microclimate. A multifactorial experiment was performed and the research results were graphically and analytically described. Furthermore, the method of energy audit, taking into account the effect of complex interaction of factors and the dynamics of the degree of discount, is applied.

Findings. According to the results of the experiment, a nomogram of the temperature regime of the irradiation area with an infrared heater was constructed, which was approximated by the analytical dependence. The optimal profit from the introduction of energy-saving technologies during operation is EUR 379.2 under the following conditions: replacement of the heating system from stationary to variable with automation; installation of a different number of infrared heaters NL-12R with power $Q = 1200$ W each; application of the effect of complex interaction of factors.

Originality. The conducted energy audit of the radiant heating system with the use of infrared heaters during the underground reconstruction showed that non-stationary heating is efficient because it saves energy and has the lowest payback period.

Practical value. The expediency of using infrared heaters in variable mode in both energy and technical and economic aspects has been proved. These measures will provide comfortable conditions in the mine and have a significant economic effect.

Keywords: *heating system, energy saving, energy audit, thermal renovation, infrared heaters, variable mode*

Introduction. Issues of energy saving, energy accounting and improving the ecological situation in the environment are extremely relevant. In the context of an acute energy crisis and environmental degradation in general, the careful use of energy sources and the application of energy-efficient heating systems are important priorities of economic policy of European countries. Energy saving tasks in Ukraine appear from a comprehensive perspective and cover aspects of both heat and energy and environmental one and are based on the legal basis and technical innovations. A large amount of energy is spent on providing microclimatic conditions in production facilities, in particular in coal mines. Ensuring regulatory air parameters that create a comfortable microclimate in a closed isolated room is an important task in terms of energy, ecology and human comfort [1, 2]. High concentration of CO_2 and other gases in the production room leads to deterioration of health and reduced efficiency of staff [3].

There is no doubt that the energy consumption for the needs of heating system of the production premises must be reduced as a result of energy efficiency measures. One such measure is the use of infrared heaters [4, 5], which allow partially heating different areas of the production facility purposefully.

To achieve the maximum effect, it is necessary to determine a cost-effective level of thermal protection of the heating system based on infrared heaters. This level should be optimal in both thermal and economic aspects. The choice of energy-saving methods for operating the existing heating systems should be made taking into account economic factors [6, 7], which allows establishing the most acceptable options of operation of heat supply system in production facilities.

In infrared heating of premises, one of the important tasks is to create an intensive heat exchange [8]. At the same time the normalized temperature in a working area has to be provided. This value is normalized for different types of premises, including for coal mines, and failure to comply with this condition can cause both deterioration of human health and affect the operation of equipment. The selection of infrared heaters depends on the purpose of the premises, technological processes that occur in them and the design features of external fences [9].

Literature review. When designing heating systems for coal mines, the main task is to create comfortable conditions for people who are there. The microclimate in the production premises affects the work efficiency and quality of manufactured products. It is known that the dynamic mode in the premises has a positive effect on human well-being and efficiency of its work. However, in production facilities, such as coal mines, for the adaptation of the thermoregulation apparatus, improving the well-being and reducing fatigue of employees, it is hygienically justified to change by the periodic law one of the parameters, for example, air temperature, that is, to create a dynamic microclimate.

The use of energy for heating and ventilation is considered in [10]. When calculating the air temperature mathematically and by measuring this parameter, they obtained certain results. This proves the fact that temperature is an important variable parameter in creating a dynamic microclimate.

Various schemes of infrared heating systems in industrial premises and their efficiency are given in [9]. However, the analysis of the provision of regulatory parameters in the production facilities showed that this is a rather difficult task.

There are a large number of different designs of heaters and emitters with high heat transfer, which are infrared heaters

[11]. In [9] the question of radiation power entering the working area is considered. The efficiency of radiators without or with poor insulation of the radiating screen is 45–55 %. As a result, the installed heating capacity must be twice as big as the calculated heating load. The influence of the reflector as an additional structural element of the infrared heater was considered in [12, 13]. The reflector not only refocuses the directional radiant flux of the burner, but also participates in heat exchange with flue gases and emits additional infrared flux.

In coal mines, the issue of exhaust ventilation and the use of exhaust air heat remain relevant. It is recommended to use low-temperature heat for further needs of the mine heating system [14]. The article [15] considers methods of waste heat utilization and its use for industrial processes. When choosing the design of the infrared heater, attention should be focused on the combination of infrared heating and exhaust ventilation, whose work is regulated by a complex of automation.

When choosing the type of infrared heaters, one must take into account the geometric dimensions of the room, the geometric location of the equipment, heat sources, location of working areas [16, 17]. However, the issue of automatic regulation of the radiation temperature of all surfaces by changing the thermal power of the heater remains unresolved.

Usually for production premises there are difficulties in maintaining the air temperature in the working area at a stable level [18, 19]. In this case, heaters with a high heat transfer coefficient and a sufficient heat transfer surface are effective. Due to the use of radiant heating, it is possible to increase the intensity of heat transfer [20].

Along with providing comfortable conditions in the coal mine, the technical and economic assessment of the efficiency of the infrared heating system plays an important role. The latest concept of the economy is developed in the UNIDO recommendations (United Nations Industrial Development Organization) [6], which presents a modern method for assessing the economic efficiency of thermal renovation measures. However, these recommendations provide an algorithm only for those measures that can be applied simultaneously and does not take into account the effect of complex interaction of factors, as well as the dynamics of the discount rate.

Unsolved aspects of the problem. Based on a review of the literature, it can be generalized that there is a need to increase the energy efficiency of the heating system by creating a dynamic microclimate when installing automation, as well as improving the methodology of energy audit of the heating system of the production facility during its reconstruction, taking into account measures that are not implemented simultaneously, and the dynamics of the discount rate.

Purpose. The purpose of the work is to increase the energy and economic efficiency of heating coal mines with infrared heaters due to energy saving measures taking into account the dynamics of the discount rate.

To achieve this goal, the task was set to conduct an energy audit of the heating system of the coal mine during its reconstruction according to the improved method, taking into account the dynamics of the discount rate and measures that are not feasible simultaneously.

Materials and methods of research on infrared heaters in stationary and variable mode. It should be noted that infrared heaters (Fig. 1) have a characteristic design feature.

When using infrared heating systems, local heating of the working area is provided. As a result, the necessary temperature conditions are maintained in coal mines and there is a possibility of creating a local microclimate.

The infrared heater for coal mines works as follows. After the device is switched on from the surface of the rectangular ceramic plate *1*, heat fluxes are emitted. In this case, with the help of a reflector *2* made of a mirror metal sheet, the heat rays are directed to the working area. Simultaneously with heating, polluted air is localized and removed from the working area by the exhaust outlet *3*. It is removed from the working area

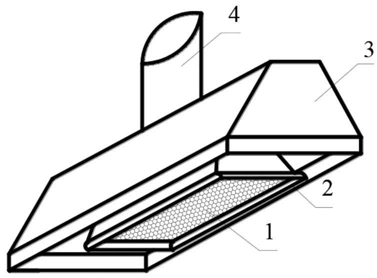

Fig. 1. Infrared heater:

1 – ceramic plate; 2 – reflector; 3 – exhaust outlet; 4 – exhaust pipe

through the exhaust pipe *4*, which is connected with the air duct to the exhaust ventilation system.

A model for creating a dynamic microclimate in the room with the help of automation has been developed. This makes it possible to change the thermal power of the device. This provides a dynamic microclimate in the working area, which makes it possible to improve sanitary and hygienic conditions in the premises (Fig. 2).

Results. An experimental study was performed to determine the radiation temperature of the irradiation area with an infrared heater. It was based on research on the floor surface's temperature as the largest surface of the irradiation area. To ensure the universality of the obtained calculations, the factors influencing this temperature were taken into account, namely: the intensity of irradiation of the infrared heater, the height of its installation and the blackness degree of the floor surface.

Graphs of the distribution of temperature fields on the surface of the heated floor with different blackness degrees of the surface ε_{floor} were demonstrated. Measurements were performed for the floor surface made of black metal sheet – $\varepsilon_{floor} =$ $= 0.92$; for the surface with sawdust – $\varepsilon_{floor} = 0.75$ and for the peat surface – $\varepsilon_{floor} = 0.3$ (Fig. 3).

The research results were summarized to determine the relative temperature of the floor surface. The relative temperature allows taking into account the value of the ambient temperature t_{am}, exploring its impact on the value of the studied temperature. The relative value makes it possible to obtain a universal value of surface temperature. It is determined by the formula

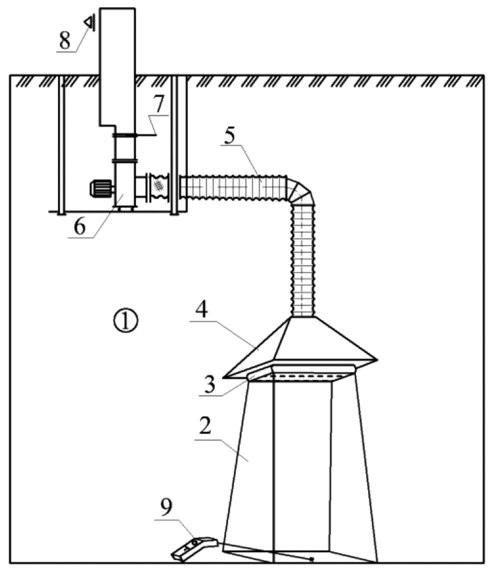

Fig. 2. Scheme of the system of providing the microclimate parameters in the coal mine:

1 – coal mine; 2 – irradiation area; 3 – infrared heater; 4 – exhaust outlet; 5 – exhaust air duct; 6 – exhaust fan; 7 – gate; 8 – air removal; 9 – measuring device

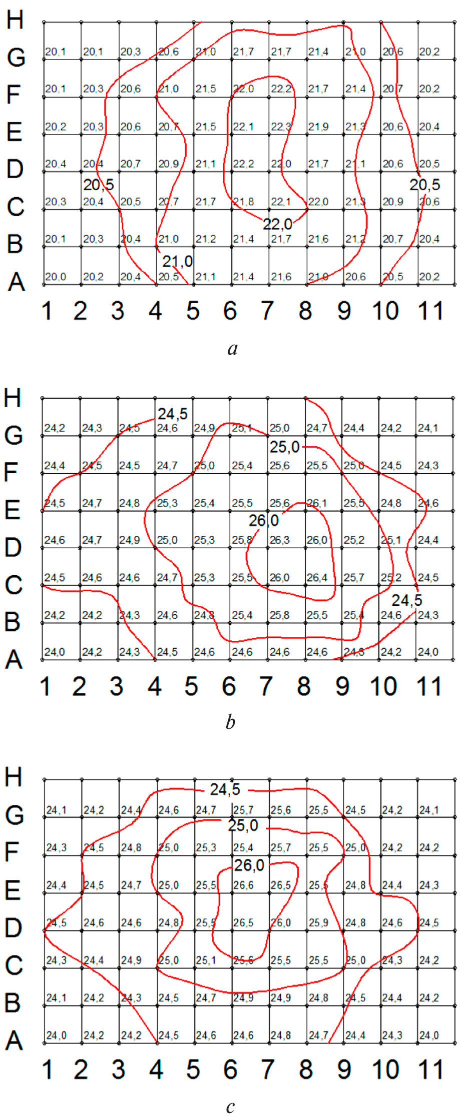

Fig. 3. *Temperature distribution on the floor surface, t_{floor}, °C at the power of the emitter Q = 800 W and at:*

a – t_{am} = 17.5 °C, ε_{floor} = 0.92; *b* – t_{am} = 21 °C, ε_{floor} = 0.75; *c* – t_{am} = 24 °C, ε_{floor} = 0.3

$$\bar{t}_{floor} = \frac{t_{floor}}{t_{am}}, \quad (1)$$

where t_{floor} is the surface temperature of the heated floor, determined experimentally, °C; t_{am} is air temperature in the coal mine, °C.

According to the experiment results, a monogram was constructed, shown in Fig. 4. It was approximated by an analytical dependence.

$$\bar{t}_{floor} = \left(0.18 \cdot \varepsilon_{floor} + 0.058\right) \cdot \left(-3H + 0.002 \cdot Q + 5.2\right)^2 + \\ + \left(0.45 \cdot \varepsilon_{floor} + 0.3\right) \cdot \left(-3 \cdot H + 0.002 \cdot Q + 5.2\right). \quad (2)$$

From the graph (Fig. 4) it is seen that the thermal power of the infrared heater NL-12R Q, W has the greatest influence on the value of the relative temperature of the irradiation surface. At constant values of the height of the heater, the blackness degree of the irradiation surface, and when the thermal power of the heater is doubled, the relative temperature of the irradiation surface will increase to 10 %.

Energy audit of the heating system using infrared heaters. During the reconstruction of the heating system, two alternative options for the use of infrared heaters NL-12R with a

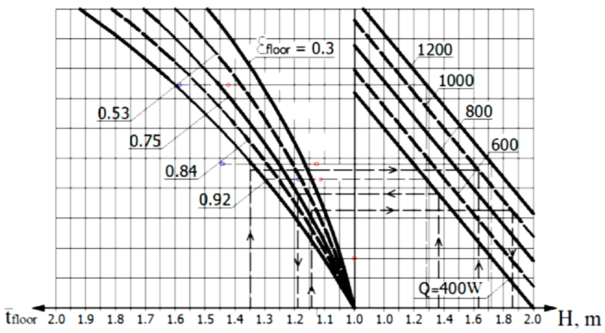

Fig. 4. *The dependence of the relative surface temperature of the heated floor on the thermal power of the heater NL-12R Q, W, the height of its installation H, m and the blackness degree of the underlying surface ε_{floor}*

power of Q = 1200 W were selected: in the number of 1 piece and 2 pieces. The following three energy saving measures were considered, taking into account the effect of integrated interaction of factors: *A* – changing the mode of operation of the heating system from stationary to variable when installing automation; *B* – installation of infrared heaters NL-12R in the amount of 1 piece with a total power Q = 1200 W; *C* – installation of infrared heaters NL-12R in the number of 2 pieces with a total power of Q = 2400 W.

The following solution algorithm is proposed:

1. Determination of annual energy consumption for the needs of the heating system Q_h, MJ/year for the basic version.

2. Selection of a list of simple thermal renovation measures for this system.

3. Determination of energy efficiency ΔQ_i of each of the simple thermal renovation measures, as $\Delta Q_i = Q_h - Q_i$, and hence – annual savings K_i, Euro/year. The cost of thermal energy (value of P_t) in Ukraine is 2000–2400 UAH per 1 Gcal, [7], i.e. P_t = 17 Euro/GJ (2350 UAH/Gcal). The cost of electricity P_e is 194 kop/kWh (voltage class II up to 27.5 kV for industrial and similar consumers with a capacity of up to 750 kVA). P_e = 16.3 Euro/GJ. When installing infrared heaters, savings are obtained due to the difference between the cost of heat and electricity.

The results of the calculations are given in Table. 1.

4. Determination of indicators of each measure (Table 2) under different values of the discount rate in Ukraine: r = 0.18 (2019), and r = 0.11 (2020).

Table 3 illustrates the dynamics of funds by years for the period of 15-year operation of measure A: "change in the operating mode of the heating system from stationary to variable when installing automation" taking into account the discount rate r = 0.11 and r = 0.18.

The data in Table 3 show that increasing the discount rate leads to an increase in the payback period, where *NPVR* = 0, when r = 0.18. This value exceeds *SPBT* = 1.2 years (Table 2) at

Table 1

Characteristics of energy saving measures

No	Measures	Energy consumption according to the "basic" variant, Q_h, GJ/year	After changing Q_i, GJ/year	Energy saving ΔQ_i $\Delta Q_i = Q_h - Q_i$, GJ/year	Savings funds K_i $K_i = \Delta Q_i\ (P_t - P_e)$ Euro/year
1	A	100	90	10	170
2	B	100	80	20	14
3	C	100	60	40	28

Table 2

Economic indicators of thermal renovation measures

No	Measures	I_i	K'_i	$SPBT_i$	$NPVR_i$ $r = 0.18$	$NPVR_i$ $r = 0.11$
		Euro	Euro/year	year	Euro	Euro
1	A	200	170	1.2	+12.5	+332.9
2	B	26.6	14	1.9	−9.1	+17.3
3	C	58.8	28	2.1	−23.8	+29.0

$r = 0$. The maximum value of $NPVR = +398.8$ Euro ($r = 0.11$) is obtained at $t = 10$ years.

Based on Table 3, a graph is constructed (Fig. 5) to visualize the current dynamics of funds.

The Net Present Value Ratio (*NPVR*) is determined by formula

$$NPVR = \frac{Kt}{\left(1+r\right)^t} - I, \quad (3)$$

where *K* is the cost of energy saving from annual savings, Euro; *I* is investment costs, Euro; *r* is the discount rate; *t* is time, years.

Let us denote it as a function of *Y*. As can be seen from Fig. 5, the nature of the function *Y* provides a point of maximum. To find this point, let us differentiate the function *Y* by determining its derivative with respect to time *t* at the discount rate $r = \text{const}$

$$Y' = \frac{K\left(1+r\right)^t - \left(1+r\right)^t \ln(1+r)Kt}{\left(1+r\right)^{2t}}. \quad (4)$$

Equating the result to zero ($Y' = 0$), we can obtain

$$\ln(1+r)t = 1. \quad (5)$$

The function has a maximum at a point with the following coordinate

$$t = \frac{1}{\ln\left(1+r\right)}. \quad (6)$$

It is obvious that as the discount rate *r* increases, the payback period decreases. This is confirmed by the results obtained by (6): at $r = 0.11$ $t = 10$ years, and at $r = 0.18$ $t = 6$ years, which is satisfactorily consistent with the graph (Fig. 5) and Table 3.

Since the standard service life of the equipment before overhaul is 15 years, there is a marginal discount rate, at which the function *Y* will still have a maximum point.

Given a value of $t = 15$, determine the marginal discount rate

$$r = e^{\frac{1}{15}} - 1. \quad (7)$$

According to the result (7), $r = 0.07$. This means that at a discount rate of less than $r = 0.07$, the function *Y* will grow monotonically and there will be no maximum point.

It is interesting to determine the maximum degree of discount at which a certain measure will be profitable, not unprofitable. This value is called the Internal Rate Ratio (*IRR*) and is determined by formula

$$IRR_i = \left(\frac{15K_i}{I_i}\right)^{\frac{1}{15}} - 1. \quad (8)$$

From (8) we obtain the value IRR_i. If the value of *r* is less than IRR_i, then this thermal renovation measure is profitable, and if it is greater, then such a measure is unprofitable (Table 2).

Based on this, it is possible to draw a conclusion if the measure of "change in the mode of operation of the heating system from stationary to variable when installing automation" is profitable. This statement is valid for the cumulative effect of measures, that is, for each option, including the effect of the complex interaction of factors (Table 4).

5. Carrying out optimization of aggregate thermal renovation options (Table 4). Given the effect of complex interaction of factors in Table 4, four thermal renovation variants with the corresponding marks + and – are composed. It should be noted that thermal renovation measures: *B* – "installation of infrared heaters NL-12R in the number of 1 piece with a total power of $Q = 1200$ W" and *C* – "installation of infrared heaters NL-12R in the number of 2 pieces with a total power of $Q =$ $= 2400$ W" are independent (options II and III). This demonstrates the effect of complex interaction of factors. That is, their combined effect is taken into account as a thermal renovation option IV.

An option with a positive *NPVR* value is profitable, and a negative option is unprofitable. The final choice is the choice of the thermal renovation option in which the value of *NPVR* is maximum. In Table 4 it is indicated in bold.

Analyzing Table 4, it should be noted that the effect of complex interaction of factors leads to an increase in the value of *SPBT*. The choice of the final option is significantly influenced by the value of *r*. At $r = 0.11$ all options are profitable, and at $r = 0.18$ profitable ones are options I and II, options III and IV are unprofitable.

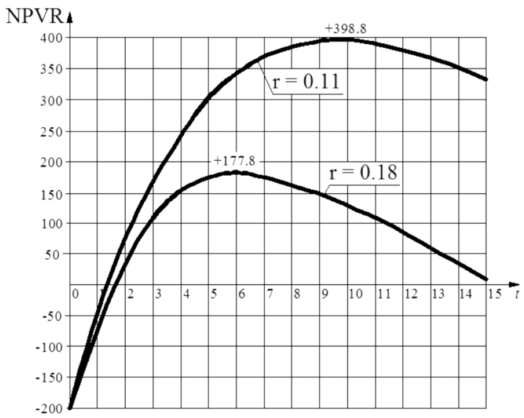

Fig. 5. Current cost dynamics

Table 3

Dynamics of funds by years

t	0	1	2	3	4	5	6	7
NPVR ($r = 0.11$)	−200	−46.8	+76.0	+172.8	+248.0	+304.5	+345.5	+373.2
NPVR ($r = 0.18$)	−200	−55.9	+44.2	+110.4	+150.7	+171.5	**+177.8**	+173.6
t	8	9	**10**	11	12	13	14	15
NPVR ($r = 0.11$)	+390.1	+398.1	**+398.8**	+393.7	+382.9	+369.6	+352.2	+332.9
NPVR ($r = 0.18$)	+161.8	+145.0	+124.8	+102.8	+79.9	+57.0	+34.6	+13.0

Table 4

Optimization of aggregate thermal renovation options

No	Measures	Options			
		I	II	III	IV
1	A	+	+	+	+
2	B	–	+	–	+
3	C	–	–	+	+
1	*I* (Euro)	200	226.6	258.8	285.4
2	*K* (Euro)	170	184	198	212
3	*SPBT* (year)	1.2	1.23	1.3	1.35
4	*NPVR* (Euro) $r = 0.18$	+12.5	+3.4	–10.7	–19.7
5	*NPVR* (Euro) $r = 0.11$	+332.9	+350.2	+361.9	**+379.2**
6	IRR	0.186	0.182	0.178	**0.175**

The maximum value of *NPVR* = 379.2 Euro is obtained from the introduction of energy-saving technologies under option IV. The effect is obtained through the introduction of the following thermal renovation measures: changes in the operation of the heating system from stationary to variable, installation of infrared heaters NL-12R in the amount of 3 pieces with a total power of $Q = 3600$ W.

Thus, the feasibility of using in the energy and technical and economic aspects of the use of infrared heaters NL-12R in variable mode is proved. These measures will provide comfortable conditions in the coal mine and get an economic effect.

The research results can be used in the design of energy-saving radiant heating systems using infrared heaters for coal mines.

Conclusions.

1. The use of infrared heaters NL-12R, equipped with automation, will allow designing energy-saving radiant heating systems for coal mines with provision of normative parameters of air in a variable mode.

2. The technique of energy audit has been improved taking into account the effect of complex interaction of factors and the dynamics of the discount rate.

3. An energy audit of the radiant heating system with the use of infrared heaters during its reconstruction was carried out. The event showed that non-stationary heating is efficient because it saves energy and has the lowest payback period. The optimal profit from the introduction of energy-saving technologies during operation is EUR 379.2 under the following conditions: replacement of the heating system from stationary to variable with automation, installation of infrared heaters NL-12R in the number of 3 pieces with a total power of $Q = 3600$ W.

References.

1. Savchenko, O., Voznyak, O., Myroniuk, K., & Dovbush, O. (2020). Thermal Renewal of Industrial Buildings Gas Supply System. *Lecture Notes in Civil Engineering*, *2021*, 100 LNCE, 385-392. https://doi.org/10.1007/978-3-030-57340-9_47.

2. Lis, A., & Spodyniuk, N. (2019). The quality of the microclimate in educational buildings subjected to thermal modernization. *11th Conference on Interdisciplinary Problems in Environmental Protection and Engineering EKO-DOK, E3S Web of Conferences 100,* 00048, 8. https://doi.org/10.1051/e3sconf/201910000048.

3. Kapalo, P., Vilceková, S., Domnita, F., Bacotiu, C., & Voznyak, O. (2017). Determining the Ventilation Rate inside an Apartment House on the Basis of Measured Carbon Dioxide Concentrations – Case Study. *The 10th International Conference on "Environmental Engineering", Selected Papers,* (pp. 30-35). Vilnius, Lithuania, 2017. https://doi.org/10.3846/enviro.2017.262.

4. Spodyniuk, N., & Lis, A. (2020). Research of temperature regime in the module for poultry growing. *Lecture Notes in Civil Engineering, LNCE 100*, 451-458. https://doi.org/10.1007/978-3-030-57340-9_55.

5. Trokhaniak, V.I., Rogovskii, I.L., Titova, L.L., Luzan, P.H., Popyk, P.S., & Bannyi, O.O. (2020). Computational fluid dynamics investigation of heat-exchangers for various air-cooling systems in poultry houses. *Bulletin of the University of Karaganda-physics, 1*(97), 125-134. https://doi.org/10.31489/2020PH1/125-134.

6. Gokul, M., Ponraj, S., Rohan, S., Venkatesh, M., Prince Winston, D., & Praveen Kumar, B. (2017). Energy Audit for Industries and Institution. *International Journal of Advanced Research in Management, Architecture, Technology and Engineering (IJARMATE)*, *3*(2), 199-205. ISSN: 2454-9762.

7. 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.

8. Sayeng, A. M., Danielewicz, J., Nannou, T., Miniewicz, M., Jadwiszczak, P., Piekarska, K., & Jouhara, H. (2016). Trends of European research and development in district heating technologies, Renew. *Renewable and Sustainable Energy Reviews*, *68*, 1183-1192. https://doi.org/10.1016/j.rser.2016.02.023.

9. Dudkiewicz, E., & Szałański, P. (2020). Overview of exhaust gas heat recovery technologies for radiant heating systems in large halls. *Thermal Science and Engineering Progress, 18*, 10552. https://doi.org/10.1016/j.tsep.2020.100522.

10. Kowalski, P., Szałański, P., Kaźmierczak, B., Kutyłowska, M., Piekarska, K., & Zdybek, A. (2017). Computational and the real energy performance of a single-family residential building in Poland – an attempt to compare: a case study. *E3S Web Conferences, 17*, 00045. https://doi.org/10.1051/e3sconf/20171700045.

11. Sarbu, I., & Tokar, A. (2018). Numerical modeling of high-temperature radiant panel heating system for an industrial hall. *International journal of advanced and applied sciences, 5*(5), 1-9. https://doi.org/10.21833/ijaas.2018.05.001.

12. 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.

13. Maznoy, A., Minaev, S., Markova, A., Pichugin, N., & Yakovlev, E. (2018). A study on the effects of porous structure on the environmental and radiative characteristics of cylindrical Ni-Al burners. *Energy*, *160*. https://doi.org/10.1016/j.energy.2018.07.017.

14. Huang, F., Zheng, J., Baleynaud, J.M., & Lu, J. (2017). Heat recovery potentials and technologies in industrial zones. *Journal of the Energy Institute*, *90*(6), 951-961. https://doi.org/10.1016/j.joei.2016.07.012.

15. Jouhara, H., Khordehgah, N., Almahmoud, S., Delpech, B., Chauhan, A., & Tassou, A. (2018). Waste heat recovery technologies and applications. *Thermal Science and Engineering Progress*, *6*, 268-289. https://doi.org/10.1016/j.tsep.2018.04.017.

16. Semenov, B.A., Pashchenko, D.I., & Mitenev, S.A. (2018). Mathematical modelling of heat transfer in a gas radiant of "dark" type. *Journal of Physics: Conference Series*, *1111*, 012008. https://doi.org/10.1088/1742-6596/1111/1/012008.

17. Linhoss, J.E., Purswell, J.L., Davis, J.D., & Fan, Z. (2017). Comparing Radiant Heater performance using spatial modeling. *Applied Engineering in Agriculture*, *33*(3), 395-405. https://doi.org/10.13031/aea.12108.

18. Amanowicz, Ł., & Wojtkowiak, J. (2018). Experimental investigations of thermal performance improvement of aluminum ceiling panel for heating and cooling by covering its surface with paint. *E3S Web Conferences*, *44*, 00002. https://doi.org/10.1051/e3sconf/20184400002.

19. Ermolaev, A.N., Khaustova, O.V., & Turaev, I.A. (2018). Simulating a convectional heat transfer in buildings with radi-

ant gas heating. *MATEC Web Conferences*, *194*, 10-13. https://doi.org/10.1051/matecconf/201819401025.
20. Kuznetsov, G. V., Kurilenko, N. I., & Nee, A. E. (2018). Mathematical modelling of conjugate heat transfer and fluid flow inside a domain with a radiant heating system, *International Journal of Thermal Sciences*, *131*, 27-39. https://doi.org/10.1016/j.ijthermalsci.2018.05. 010.

Підвищення енергетичної та економічної ефективності опалення вугільних шахт інфрачервоними обігрівачами

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Мета. Підвищення енергетичної та економічної ефективності опалення вугільних шахт інфрачервоними обігрівачами за допомогою енергозберігаючих заходів з урахуванням динаміки дисконтної ставки. Для досягнення цієї мети було поставлено завдання провести енергетичний аудит системи опалення шахти під час її реконструкції за вдосконаленою методикою з урахуванням динаміки дисконтної ставки та заходів, що не є одночасно здійсненними.

Методика. При використанні інфрачервоних систем опалення передбачається локальне опалення робочої зони. У результаті на шахтах підтримуються необхідні температурні умови та існує ймовірність створення місцевого мікроклімату. Був проведений багатофакторний експеримент, і результати дослідження були графічно та аналітично описані. А також був застосований метод енергетичного аудиту з урахуванням ефекту складної взаємодії факторів і динаміки ставки дисконтування.

Результати. За результатами експерименту була побудована номограма температурного режиму зони опромінення інфрачервоним нагрівачем, що була апроксимована аналітичною залежністю. Оптимальний прибуток від упровадження енергозберігаючих технологій під час роботи становив 379,2 євро за таких умов: заміна системи опалення зі стаціонарної на змінну з автоматикою; установка різної кількості інфрачервоних обігрівачів NL-12R потужністю Q = 1200 Вт кожен; застосування ефекту складної взаємодії факторів.

Наукова новизна. Проведений енергетичний аудит системи променевого опалення з використанням інфрачервоних обігрівачів під час реконструкції шахти показав, що нестаціонарне опалення є ефективним, оскільки воно економить енергію та має найнижчий термін окупності.

Практична значимість. Доведена доцільність використання інфрачервоних обігрівачів у змінному режимі як в енергетичному, так і в технічному та економічному аспектах. Ці заходи забезпечать комфортні умови на шахті й дозволять отримати значний економічний ефект.

Ключові слова: *система опалення, енергозбереження, енергоаудит, термореновація, інфрачервоні обігрівачі, змінний режим*

Повышение энергетической и экономической эффективности отопления угольных шахт инфракрасными обогревателями

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Цель. Повышение энергетической и экономической эффективности отопления угольных шахт инфракрасными обогревателями с помощью энергосберегающих мероприятий с учетом динамики ставки дисконтирования. Для достижения этой цели была поставлена задача провести энергетический аудит системы отопления шахты во время ее реконструкции по усовершенствованной методике с учетом динамики ставки дисконтирования и мероприятий, которые не являются одновременно осуществимыми.

Методика. При использовании инфракрасных систем отопления предполагается локальное отопление рабочей зоны. В результате на шахтах поддерживаются необходимые температурные условия и существует вероятность создания местного микроклимата. Был проведен многофакторный эксперимент, и результаты исследования были графически и аналитически описаны. А также был применен метод энергетического аудита, с учетом эффекта сложного взаимодействия факторов и динамики ставки дисконтирования.

Результаты. По результатам эксперимента была построена номограмма температурного режима зоны облучения инфракрасным нагревателем, которая была аппроксимирована аналитической зависимостью. Оптимальная прибыль от внедрения энергосберегающих технологий при работе составила 379,2 евро при следующих условиях: замена системы отопления со стационарной на переменную с автоматикой, установка различного количества инфракрасных обогревателей NL-12R мощностью Q = 1200 Вт каждый, применение эффекта сложного взаимодействия факторов.

Научная новизна. Проведенный энергетический аудит системы лучистого отопления с использованием инфракрасных обогревателей во время реконструкции шахты показал, что нестационарное отопление является эффективным, поскольку оно экономит энергию и имеет низкий срок окупаемости.

Практическая значимость. Доказана целесообразность использования инфракрасных обогревателей в сменном режиме как в энергетическом, так и в техническом и экономическом аспектах. Эти меры обеспечат комфортные условия на шахте и позволят получить значительный экономический эффект.

Ключевые слова: *система отопления, энергосбережение, энергоаудит, термореновации, инфракрасные обогреватели, сменный режим*

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