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METHODOLOGY FOR DETERMINING THE HEAT DISTRIBUTION IN DISC BRAKES OF MINE HOISTING MACHINES

Purpose. To study the course of heat phenomena in disc brakes using modern computing systems in order to determine and substantiate the operating parameters for the hoisting machine components.

Methodology. The research uses software packages, with the help of which a computational-theoretical apparatus is developed for heat mode modeling processes. In particular, the mentioned function is used in the SolidWorks Simulation software with the ability to evaluate the errors of the calculation results.

Findings. In the course of the research, the dependence of the hoisting machine disc brake performance on the operating parameters of its components was determined. The research has led to a better understanding of the heat transfer processes in disc braking devices, as well as the ability to study the friction response of various materials and determine optimal parameters that help improve the performance of braking systems. The effectiveness has been proven of the proposed method for analyzing the heat distribution processes of the mine hoisting machine drum components under the influence of operating and emergency braking modes.

Originality. For the first time, a methodology for calculating the heating temperature distribution along the brake rim plane during a safety stop has been developed and substantiated. A method has also been developed for determining the temperature field arising under steady-state heating conditions, which occur after repeated operating braking and cooling of the device. In this case, when using the formula for determining the temperature on the brake rim surface, the sample length, the relative velocity between the friction components and the heat flow distribution coefficient are taken into account. The brake disc geometric model developed in the SolidWorks software package makes it possible to study the temperature change on the device rim in real time.

Practical value. The proposed design improvement based on the research results of heating processes should improve vehicle safety. The cost of braking systems is expected to be reduced through the use of optimal materials and production technologies. The software methods for modeling and analyzing the temperature influence on brake discs of the Mine Hoisting Machine (MHM) have been improved. Based on the research results, recommendations have been developed for the optimum braking process of machines in various operating conditions.

Keywords: *mine hoisting machine, disc brake, friction material, temperature, time*

Introduction. The investigations conducted by Ukrainian scholars in the domains of mining engineering and mechanical engineering, which encompass multifaceted aspects such as the design of mining and transportation machinery, shaft hoists, and the development of advanced diagnostic and monitoring methodologies for these systems, bear direct relevance to fostering an innovative economy. This economy is underpinned by scientific knowledge and cutting-edge technology, serving as a pivotal driver of competitiveness and economic expansion.

Advancing innovative technologies for mining engineering and machinery constitutes a critical objective for Ukrainian researchers. Their achievements bolster the quality of national products and enhance the efficiency of industrial processes in accordance with contemporary market demands. This progress lays the groundwork for sustained national development. The list of these directions is given below.

Innovations in design and structure of mining machinery: development of a concept for recursive metamodeling in mining machine design [1, 2]; analysis of diverse approaches to dynamic modeling of hoisting and transportation machines [3]; optimization of the tower crane tilting mechanism [4]; determining the load capacity of multilayer-wound rubber ropes [5], formulation of the theory for drum rope winding [6]; analysis of modern trends in shaft hoist design and engineering [7, 8]; development of an interaction model between brake pads and drums; justification of the algorithm for selecting elastic coating parameters [9]; safety and reliability of hoisting-transport systems and mining equipment [10, 11]; examination of mathematical models of vibration in mining equipment; establishing the conceptual framework for intensifying mining operations through monitoring and control of shaft hoist systems [12, 13]; analysis of risk formation processes during mining hoist operation [14]; testing of control systems for the smooth movement of skip hoists in mine shafts [15]; development of a methodology for assessing the operational life of welded screen structures [16]; design of efficient braking methods for mine diesel locomotives using hydromechanical transmissions [17, 18].

In summary, these studies illuminate the trajectory and progress of research in Ukrainian mining engineering, outlining a strategic direction for advancing the field while reinforcing national industrial competitiveness.

The summaries of international scholars' work on mine hoisting and mechanical engineering research underscore significant progress in this field. The primary components of these studies include a focus on drum design [19, 20] and optimization for mine hoists [21], optimization of hoisting machinery schedules in deep mines, design improvements in mining engineering, creation of energy-efficient and intelligent power supply systems for mining hoists [22], development of a structured and effective system for diagnosing equipment functions [23, 24], implementation of systems enhancing energy efficiency and intelligent equipment control [25, 26], and the advancement of fault detection methods to improve maintenance efficacy and operational safety [27].

Additionally, it is important to highlight research that investigates the three-dimensional transient thermal field of a friction lining and a sliding steel rope [28]. This study observed the influence of several parameters on the increase in rope temperature, revealing that a higher sliding speed correlates with a greater average temperature increase and fluctuations over time.

Among the limitations of this research, the model assumes an idealized smoothness of the rope and lining surfaces, disregarding surface roughness, which could constrain the real-world applicability of these findings. Moreover, the study only considers the thermal field of the friction lining, omitting that of the rope itself.

In this study, numerous assumptions and simplifications were made that could affect the overall accuracy of the model's performance.

The model's applicability to analyzing finite-sized bodies is limited due to the mathematical complexity and the necessity of extensive calculations.

A thematically related work analyzed the thermomechanical changes in braking systems during emergency stops of mine hoists using the finite element method (FEM). This study provided an in-depth examination of heat transfer processes in braking systems, underscoring the importance of various mechanisms such as convection, thermal conductivity, and radiation. The research relied on assumptions and simulated models, potentially failing to comprehensively reflect the actual operating conditions of braking systems in mine hoists.

The lack of comparative analysis between simulation results and empirical or experimental data reduces the ability to verify the predicted accuracy of the model. The scope of the study focused solely on the thermal aspects of the braking system, potentially overlooking other critical factors such as material fatigue and environmental influences on its functions. The use of a specific type of mine hoist (MK5×2) as the research subject may limit the universality and applicability of the results obtained.

Considering the strengths and weaknesses of the study [29], the need to continue and expand research on this topic becomes evident. Research on thermomechanical modeling processes in braking systems should encompass emergency stops of various types of mine hoists, rather than focusing on a single model. This broad approach would enable the generalization of results and expand the model's applicability.

Amid contemporary challenges in underground work safety, studying the thermomechanical characteristics of mine hoist braking systems is particularly relevant. The development of detailed, accurate, and universal models to analyze thermal fields in mine hoist braking systems is crucial for enhancing the safety and operational efficiency of mining equipment.

Literature review. Progress in the design of machines involves reducing their metal consumption, and, consequently, their weight. But at the same time, in the operation of these machines, the acceleration of idling of the working bodies increases, and the braking systems available there are set to create a certain braking force [22, 23].

Practice shows that such systems may not always provide the safety braking deceleration limits [26, 27], prescribed by the Safety Rules (at least 1.2–1.5 m/s^2 when lowering and not more than 5 m/s^2 when lifting the estimated load). In this case, there is a need to analyze the temperature change on the surfaces of disc braking devices of modern hoisting machines, when the mutual influence of elementary heating sources at the level of microcontacts should be taken into account. This is important in order to use effective friction materials that would meet the requirements of stability, wear resistance, mechanical strength, safety and other criteria [9].

One of the best ways to solve this problem is to use multi-modular axial disc braking devices (Fig. 1), in which the pads are hydraulically opened and spring-closed. These devices are equipped with automatic adjustment and safety braking systems instead of traditional braking mechanisms with radial clamping of pads to the wheel. Disc braking systems represent a logical step forward in the development of modern hoisting machines. American researchers F. P. Bowden and K. E. W. Ridler first tried to determine the friction temperature of surfaces in such systems, suggesting the theory of basic measurements. This theory was later developed by F. P. Bowden and D. Tabor, suggesting that the heat flow distribution coefficient is a value inversely proportional to the sum of heat conductivity coefficients.

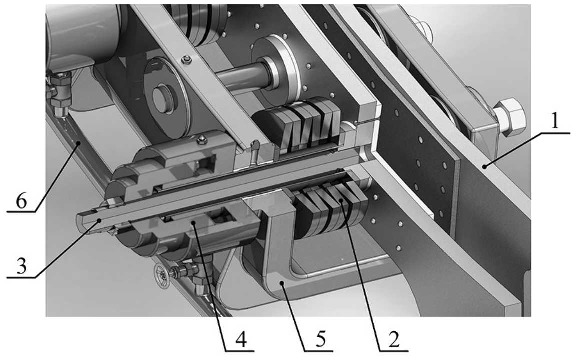

Fig. 1. General view of the hydraulic opening and spring closing of the brake pads:

1 – brake pads; 2 – disc spring; 3 – stem; 4 – hydrocylinder; 5 – bracket; 6 – pipeline

Subsequently, researcher M. P. Levytsky formulated an equation according to which the friction temperature is determined based on several parameters, such as the sample length, the relative movement velocity of the friction components, and the heat flow distribution coefficient.

Professor V. S. Shchedrov studied the thermal dynamics of friction by examining the influence of numerous microcontact heating sources. This scientist developed a methodology for measuring temperature using Fredholm integral equations, where the main focus was on the total amount of heat produced by all sources at the microcontact level. The proposed methods make it possible to calculate the average temperature value, but at the same time it is impossible to obtain accurate data about the contact zone real temperature. Each friction material must meet many criteria, including wear resistance, cost-effectiveness, easy handling ability, and operational safety. With the active development of technology and increasing safety requirements, selecting the right friction materials becomes an increasingly urgent task for engineers. It is known that the market constantly offers new materials, the use of which can increase the performance and durability of machines. Additional research into the braking system functions can help to make them more efficient and safer to operate under different operating conditions. Innovative technologies, including digital ones, also offer good opportunities for the development of more environmentally friendly and economical technical facilities. The choice of materials and technologies should always focus on creating safe conditions for users and the environment.

The research into frictional properties of friction pairs and the use of pressed friction materials in mechanical engineering has been the subject of many studies, in particular by M. P. Aleksandrov, A. V. Chichinadze, L. M. Pyzhevych, G. A. Georgievsky and other scientists. Today, the domestic market offers a large selection of materials with various friction properties [26]. These products are designed for use in braking systems to suit a wide range of operating conditions. It was proposed that all friction materials should be divided into the following groups: designed for light friction conditions (temperature up to 250 °C); materials for medium friction conditions (temperature up to 600 °C); those that can be in severe friction conditions (temperature up to 1,000 °C).

Results. When the machine stops moving, the brake linings are pressed against the disc brake, and under the influence of the friction forces that arise in this case, the kinetic energy of the hoisting machine is converted into heat. Since the heat conductivity of the disc is higher than the heat conductivity of the linings, it can be assumed that sources of variable heating power move on the surface of the first, and the generated heat spreads from the entire rim of the disc and is dissipated by convective heat exchange and radiation [28, 29].

To fulfill the formulated task, the following assumptions are made:

1. The entire heat flow generated by braking is concentrated only in the brake disc rim.

2. Given that the rim is thin, and both of its surfaces interact with the pads, neglecting the spread of heat through the component thickness, we will consider it as a surface (in the program it is a shell model with a specified thickness).

3. The ambient temperature is 20 °C.

4. To account for maximum heat loss intensity during radiation, the brake disc is considered to be an absolute black body.

5. The heat transfer coefficient due to convection into the environment is 6 $W/m^2 \cdot K$.

6. The interaction of the brake lining with the disc is modeled by a heating power source on a plane corresponding to the area of one lining.

7. The continuous thermal interference of the lining with the rim is modeled as a discrete process of moving the heating power source into each of the ten brake disc sectors, corresponding to the area of one lining.

8. The intensity of the heating power source at each discrete process step is defined as the difference in the kinetic energy values at the beginning and end of each step depending on its duration.

9. Safety braking occurs under steady-state deceleration conditions a.

During the process of safety braking, depending on the acceleration value, the drum performs several revolutions, and the heating power source passes over each sector of the disc the same number of times. In this case, the brake disc itself is considered as a combination of two rings, besides the external one, which is in contact with the brake lining, is divided into 10 equal sectors. For illustration (Fig. 2), given that the braking acceleration is 1 m/s^2, the sequence of steps of heating power discrete movement through each sector of the disc is shown.

Next, we study the heating processes occurring during a safety stop of a hoisting machine due to the action of a disc brake. Initial research data are as follows: effective load mass $m_{eff.load}$ = 25,000 kg; mass, which is reduced to the drum bypass of the hoisting machine moving parts $m_{machine}$ = 256,643 kg; outer rim diameter d_{outer} = 2,823 mm; inner rim diameter d_{inner} = 2,443 mm; linear velocity at the beginning of safety braking V_0 = 10 m/s, specified braking acceleration values $a_1 = 1$, $a_2 = 3$ m/s^2.

Given the 8^{th} assumption in our research, it can be seen that the amount of heat released during the disc brake operation at the i^{th} step of the discrete process of stopping the hoisting machine can be calculated using the following formula

$$K_i = \left[(V_{i-1})^2 - (V_i)^2\right] \cdot 0.5 m_{ins.}, \quad (i = 1 \ldots N),$$

where V_{i-1}, and V_i are linear velocity at the beginning and end of the i^{th} step.

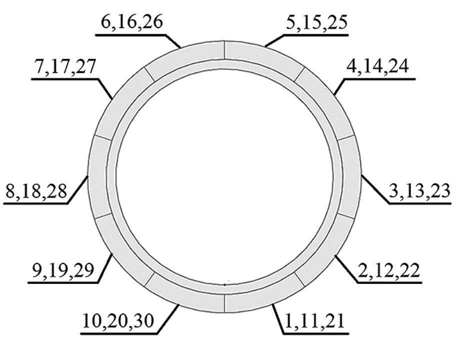

Fig. 2. Numbering of discrete heat movement steps through brake disc sectors

Given the 9^{th} assumption, the i^{th} step duration is

$$\Delta_i = \frac{V_{i-1} - \sqrt{(V_{i-1})^2 - 2 \cdot a \cdot L}}{a}, \quad (i = 1 \ldots N),$$

where L is the sector arc length, here

$$L = \frac{\pi \cdot (d_{ext} - d_{\text{int}})}{N}.$$

Disc sector heating power at the i^{th} step is

$$Y_i = \frac{K_i}{\Delta_i}, \quad (i = 1 \ldots N).$$

Using the given above dependences, the following algorithm for solving the problem is introduced: for a given acceleration, calculate the number of steps in the discrete braking process until disc N comes to a complete stop; then, using formulas above, it is possible to determine the duration of the i^{th} braking step, the amount of heat released at this step, and the heating power intensity.

Results. The developed algorithm is implemented using the MathCAD 14 program. As an example, the values of the discrete step duration (Fig. 3) and heating power (Fig. 4) depending on the step number are given, when braking acceleration is $a_1 = 1$ m/s^2.

It turned out that when the braking acceleration is $a_1 = 1$ m/s^2, the drum makes three revolutions until it comes to a complete stop, with the heating power source passing over each sector three times.

Fig. 5 shows the change in the heating source intensity values over the first sector at each step of the discrete braking process.

As a result of solving the problem set, the dependences of the heating source power values on time have been determined for

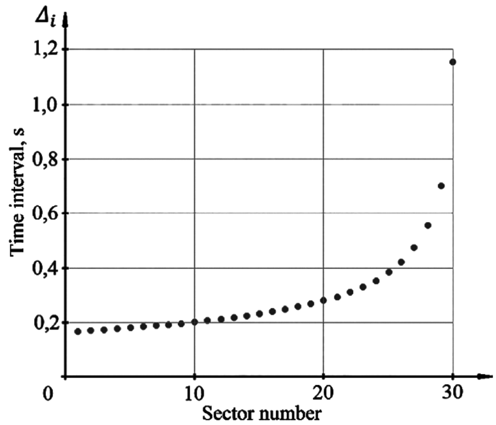

Fig. 3. Graph of changes in the discrete step duration depending on its number

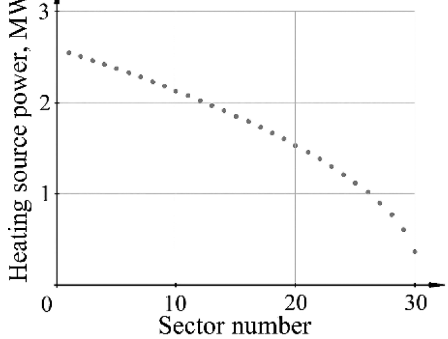

Fig. 4. Graph of dependency graph of the heating power on the brake disc on the step number

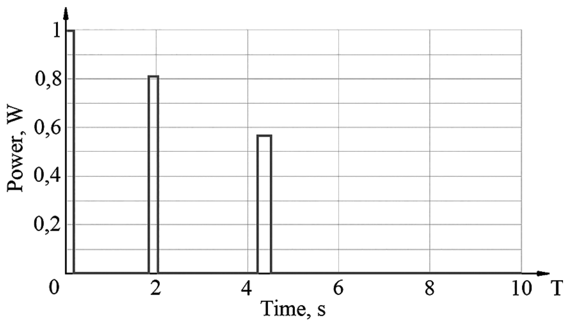

Fig. 5. Graph of changes in the heating source power in the first disc sector when the braking acceleration is 1 m/s^2

each brake disc segment, taking into account different braking acceleration values. The SolidWorks software has developed a geometric model for the disc based on the given parameters, consisting of two annular components with one divided into ten sectors (Fig. 2). Using the SolidWorks Simulation application (Kurowski, P. M., 2022), the following steps can be implemented:

1. A thermal study of the transient process, the duration of which corresponds to the moment the drum completely stops, has been conducted.

2. From the brake disc surfaces, two annular shells with a thickness of 50 and 40 mm, where the heating power values in each shell sector are taken into account (Fig. 6), the initial temperature of all parts of the disc at the level of 20 °C, the convection value, which is equal to 6 W/m^2·K and the radiation coefficient, which is unity (assuming that the disc is an absolute black body), have been modeled.

3. Finite-element calculation of acceleration values a_1 and a_2 has been conducted.

Figs. 6 and 7 show the temperature distribution on the brake disc surface at accelerations of 1 and 3 m/s^2.

To analyze the influence of radiation on the research results, the calculation is performed under the assumption that the radiation coefficient is zero. It has been determined that the difference in the maximum temperature values at the end of braking is 0.9 %.

Analyzing the data in Figs. 6 and 7, it can be concluded that, regardless of the acceleration value during braking, the temperature distribution in the brake disc can be considered axisymmetric, which is 40 °C with an error of 2.3 %.

The temperature field on the disc surface, which is formed under the influence of steady-state heating mode as a result of passing through successive stages of braking, has been calculated. The following conditions were considered:

1. The brake disc heats up symmetrically relative to its axis.

2. Braking occurs exclusively using the device of the same name.

3. It has been determined that braking lasts 10 s, and the period of lowering and lifting by the hoisting machine is 111 s.

The initial braking cycle characteristics at an acceleration of 1 m/s^2 are given above.

To calculate the temperature distribution under conditions when the machine is moving empty containers, let us examine the braking process (when disc is influenced by heating). This happens periodically, when braking lasts 10 s, and cooling continues for 110 s until the disc temperature stabilizes.

The process modeling sequence is as follows:

1. With the use of the MathCAD 14 program, the heating activity axisymmetric source characteristics are determined for each phase of braking during the transportation of empty containers by a machine.

2. With the use of the SolidWorks Simulation application, the state of the annular shell disc models is analyzed without dividing them into separate sectors.

Fig. 8 shows the dynamics of changes in the brake disc temperature during the mine hoisting machine operation.

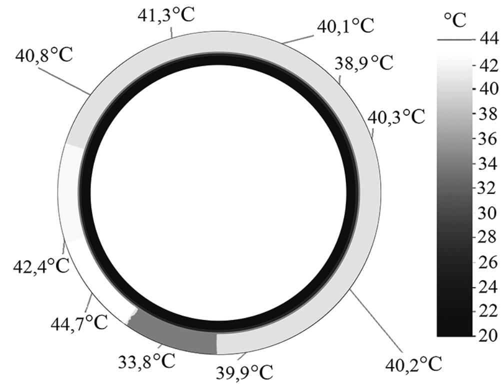

Fig. 6. Temperature distribution in disc sectors after braking at acceleration of 1 m/s^2

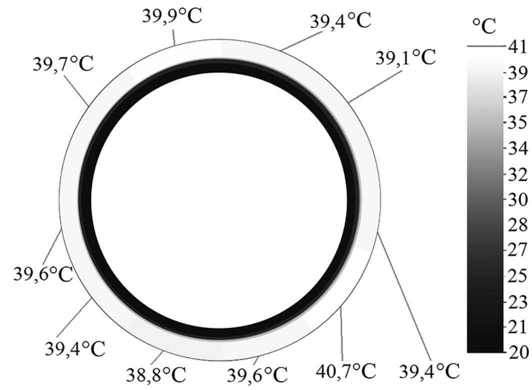

Fig. 7. Temperature distribution in disc sectors after braking at acceleration of 3 m/s^2

Analyzing these parameters, it can be concluded that the change in the maximum temperature in the specified object, depending on the duration of the hoisting machine operation, has a character similar to exponential one. It is important to note that after 2,600 s of the machine operation, the heating process stabilizes, and the temperature begins to reach 223 °C, as shown in the graph (Fig. 9).

It can be seen from the analysis of dependence in Fig. 9 that the temperature distribution in the radial direction of the brake disc is significantly uneven, so outside the brake pads the temperature is 56 °C, and within their boundaries – 223 °C.

The conducted analysis of the radiation influence suggests that ignoring this factor leads to an error in the calculation results at the level of 0.83 %.

To calculate the temperature distribution when lifting the load and the counterweight, let us examine the load braking cycle (when there is heating of the brake disc), which has the following time characteristics: braking is 10 s, lifting the counterweight is 110 s, braking the counterweight is 10 s, lifting the load (with disc cooling) is 110 s until the disc temperature stabilizes.

Next, the problem of studying the heating process can be solved using the following algorithm:

1. Using the MathCAD 14 program, we determine the temperature dependences of the axisymmetric heating source on all stages of braking, in particular when lifting the load and counterweight.

2. Using the SolidWorks Simulation application, we calculate the parameters of annular shell brake disc models without dividing them into separate sectors.

Fig. 10 illustrates the graph depicting the variation in the brake disc temperature during the process of transporting cargo with a counterweight. As can be seen, the dependence of the maximum temperature of this object on the duration of the hoisting machine operation is approximated in the form of an

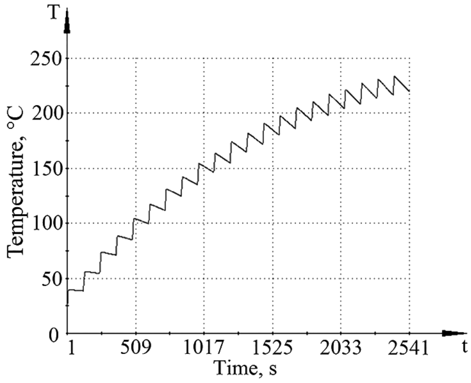

Fig. 8. Graph of dependency of brake disk temperature on the duration of the hoisting machine operation

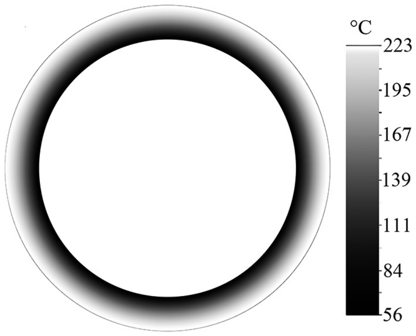

Fig. 9. Distribution of maximum temperature values of the disc in the steady-state heating process

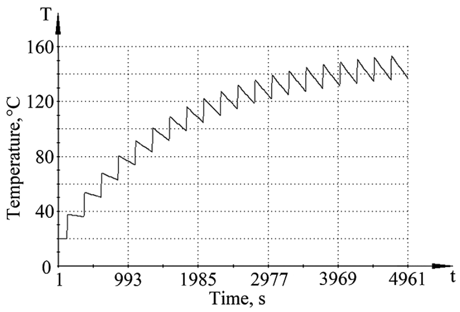

Fig. 10. Dependence of the brake disc temperature on the duration of the hoisting machine operation with the counterweight

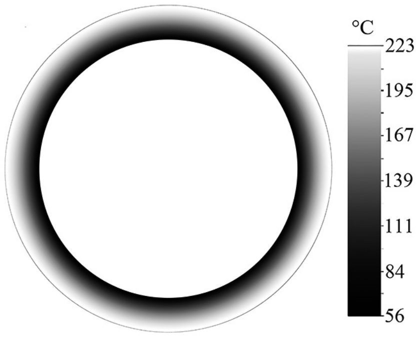

Fig. 11. Distribution of maximum temperature values of the brake disc in the steady-state heating process

exponential function. When the machine operates for 5,000 s, the heating process stabilizes and the temperature reaches 139 °C, as shown in the diagram (Fig. 11).

Analyzing the diagram in Fig. 11, we can see that the temperature distribution in the radial direction of the brake disk plane is uneven, so outside the brake pads the temperature is 56 °C, and in their middle – 139 °C.

Conclusions:

1. During the safety braking of a mine hoisting machine, regardless of the intensity of its deceleration, the temperature field of the brake disc rim is almost unchanged and is 40 °C with a deviation of 2.3 %.

2. In the case of a single lifting/lowering of empty containers by the machine, when only the disc brake operates, the temperature of its working body reaches 45 °C.

3. With repeated lifting/lowering of empty containers and operation of only the disc brake, temperature stabilizes after 25 cycles of machine operation, and the temperature of the working body increases to 220 °C.

4. In the calculations, the influence of radiation can be neglected, which gives a deviation of the result of 0.83 %.

5. When lifting a load using a counterweight and the disc brake alone, the temperature of its working body reaches 139 °C during the 21 operating cycles of the hoisting machine.

6. Neglecting the radiation coefficient in calculations gives an error of the result within 0.7 and 0.9 %.

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Методика моделювання розподілу температури в дискових гальмах шахтових підіймальних машин

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Мета. Використовуючи сучасні обчислювальні комплекси, дослідити перебіг теплових явищ у дискових гальмах, аби визначити й обґрунтувати робочі параметри елементів підіймальної машини.

Методика. У дослідженні застосовані програмні комплекси, за допомогою яких був сформований розрахунково-теоретичний апарат процесів моделювання теплових режимів, зокрема згадана функція була покладена на програмне забезпечення SolidWorks Simulation із можливістю оцінити похибки результатів обчислень.

Результати. У ході дослідження встановлена залежність працездатності дискового гальма підіймальної машини від робочих параметрів його елементів. Дослідження дають змогу глибше зрозуміти перебіг процесів теплової передачі в дискових гальмових пристроях, вивчити реакцію різних матеріалів на тертя й визначити оптимальні параметри, що сприяють підвищенню ефективності гальмівних систем. Була доведена ефективність запропонованого методу аналізу процесів розподілу нагрівання елементів барабанів шахтових підіймальних машин під впливом робочих і аварійних режимів гальмування.

Наукова новизна. Уперше була розроблена та обґрунтована методика розрахунку розподілу температури нагрівання за площиною гальмівного ободу під час запобіжної зупинки. Також розроблено спосіб визначення температурного поля, що виникає в умовах сталого теплового режиму, який настає після багаторазового робочого гальмування та охолодження пристрою. При цьому були враховані довжину зразка, відносна швидкість між тертьовими елементами й коефіцієнт розподілу теплового потоку, коли застосовували формулу визначення температури на поверхні гальмівного ободу. Розроблена геометрична модель гальмівного диску у програмному комплексі SolidWorks дозволяє досліджувати зміну температури на ободі пристрою в реальному часі.

Практична значимість. Запропоноване за результатами досліджень теплових процесів удосконалення конструкції має сприяти підвищенню безпеки транспортних засобів. Передбачено зниження вартості гальмівних систем за рахунок використання оптимальних матеріалів і технологій виробництва. Удосконалені програмні методи моделювання та аналізу впливу температури на гальмівні диски шахтових підіймальних машин. З урахуванням результатів дослідження розроблені рекомендації щодо оптимальності процесу гальмування машин у різних експлуатаційних умовах.

Ключові слова: *шахтова підіймальна установка, дискове гальмо, фрикційний матеріал, температура, час*

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