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INVESTIGATION OF THE THERMAL BEHAVIOUR FOR THE DISC-PAD ASSEMBLY OF A MINE HOIST BRAKE USING COMSOL MULTIPHYSICS

Andrei ANDRAȘ, Ildiko BRÎNAȘ, Sorin Mihai RADU, Florin Dumitru POPESCU, Valentin POPESCU, Daniela-Ioana BUDILICĂ (ANDREI)

Abstract: *This paper presents an investigation of the temperature variation of the two most important components of the braking system of a mine hoist, the disk and the pads respectively. Based on the complete model of the brake system created at 1:1 scale in SolidWorks, by taking into consideration only the disk, it's mounting surface and the brake pads, the temperature variation was determined using the Heat Transfer Module of the COMSOL Multiphysics software in the case of an emergency braking. The study highlights the possibilities offered by COMSOL in the investigation of the heating and cooling effects in various devices, components or processes.*

Key words: *mine hoist, brake disc, brake pads, braking temperature, convection, radiation.*

1. INTRODUCTION

Mine hoists are heavy machines operating at vertical shaft underground mines for the transportation of personnel and equipment into the mine and raising of material to the surface. Depending on the depth, mining conditions and country traditions, three types of mine hoists are used: drum hoists, friction hoists and Blair hoists. The present paper focuses on a multi-rope friction hoist model [1, 2] widely used in Romanian coal mines, with a standard configuration as shown in figure 1.

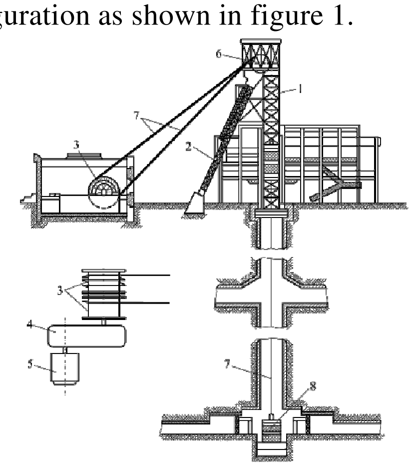

Fig.1. Multi-rope friction mine hoist (1 – head-frame, 2 - buttress, 3 – friction wheel, 4 – gearbox, 5 – drive engine, 6 – head sheave, 7 – ropes, 8 – conveyance)

Due to the masses and speeds of operation, as well as the existing safety regulations [3], the brake system of mine hoists must be able to meet three criteria: 1 - reduce and control the transportation speed continuously during normal hoisting; 2 - stop completely the hoist in the case of emergency situations as quickly as possible; 3 - hold the conveyances in a static position for loading and unloading. Modern mine hoists have disc brakes and pads operated by hydraulic cylinders (figure 2).

Fig.2. Mine hoist with disc and pad brake system

This technology is more reliable as it better withstands the high temperatures generated during braking. Studies have shown that high

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temperature can lead to deformation of brake components [4] and decrease of friction and braking capacity [5, 6], being one of the main reasons of a failure mine hoists [7].

2. LITERATURE REVIEW

There are numerous studies on the influence of frictional heat on the efficiency of braking, for both automotive brakes and mine hoists.

Usually software tools are used for simulations and numerical modeling using FEM, with SolidWorks [8], ANSYS [9, 10] and COMSOL [11, 12, 13] being the most common.

The difference between automotive and mine hoists is given by the high masses and decelerations in the case of mine hoists. This directly influences the stresses and temperatures [14] of the components of the braking system and dramatically decreases the tribological performance of pad materials [15]. Influence of the number and positioning of the brake pads were investigated in [16]. The location of the maximum braking temperature and stress was determined in [17], it was concluded in [18] that conductivity is better for the disc than for the pad and the maximum temperature and the time to reach it was determined in [19] for emergency braking.

3. THEORETICAL ASPECTS OF HEAT TRANSFER

The maximum temperature of the disc-pad assembly of the mine hoist depends on the amount of heat produced and the amount of heat transferred. Energy produced by the friction between disc and pads is not hard to evaluate, but the difficulty appears in the estimation of the transferred heat flux between the two. From theory [20] it is known that heat transfer can take place through thermal conduction, convection and radiation.

3.1. Conduction heat transfer

Thermal conduction is the leveling of different kinetic energies of the molecules, produced by their random motion in solid matter.

If the material has a regular, gapless structure like metals, this leveling happens very quickly. If the material has discontinuities and gaps like ceramics, the leveling is slower.

Conduction heat transfer takes place based on Fourier's law:

$$h = -n\frac{dq}{dt \cdot dA} = -\lambda \, grad\,\theta \quad (1)$$

where h is the specific heat flux in W/m^2, dq is the elementary heat amount in Ws, dA is the surface of elementary transmission in m^2, λ is the thermal conductivity in W/m·grd; θ is the temperature, t is the current time in s and $\hat{n}$ is the unit vector, perpendicular to the surface of transmission.

In the case of conduction heat transfer (figure 3), the vector of the specific heat flux $\bar{h}$ has an opposite direction to the unit vector $\hat{n}$, oriented in the temperature increase direction. Heat transfer takes place from surfaces with higher temperature (θ+dθ) to surfaces with lower temperatures (θ).

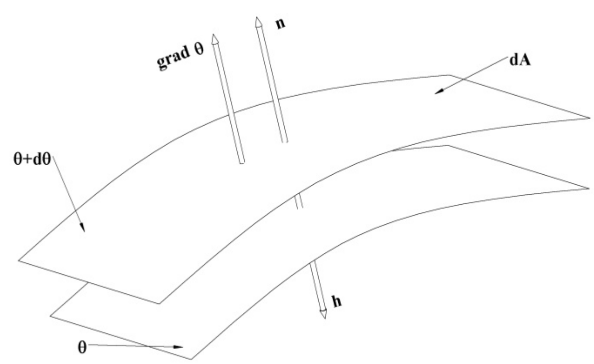


Fig.3. Heat conduction mechanism.

3.2. Radiation heat transfer

A body of temperature T higher than absolute zero transfers heat by electromagnetic radiation to neighboring bodies with lower temperatures. The specific heat flux transferred by radiation is given by the Stefan–Boltzmann law:

$$P_{1r} = K \cdot e_t (T_1^4 - T_2^4) \quad (2)$$

Where P_{1r} is the specific radiated heat flux in W/m^2, K is the Stefan–Boltzmann constant

($5.67 \cdot 10^{-8}$ W/m$^{2} \cdot$K^{4}), e_t is the total emissivity of the body depending on its the nature the processing and treatment of its surface, T_1 is the temperature of radiating solid surface, and T_2 is the ambient temperature.

Heat transfer from solid matter to fluids and liquids is always done through convection and radiation.

4. CONSTRUCTION OF THE MODEL

In order to conduct the thermal analysis, a complete model of the friction wheel for the MK5x2 mine hoist was designed [21] in SolidWorks (figure 4). The friction wheel was represented together with the brake discs mounted on its two sides.

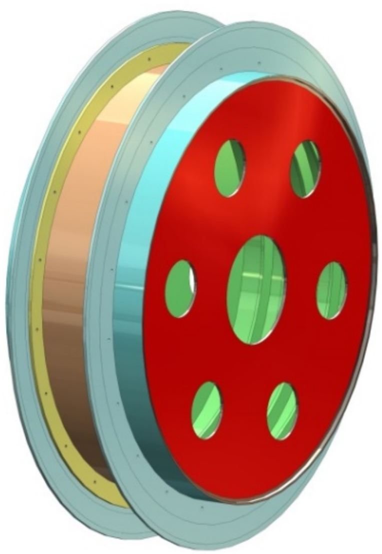


Fig. 4. Model of the friction wheel with the brake discs

The model was built at 1:1 scale, using the dimensions provided by the manufacturer in the technical documentation (figure 5). All diameters and thicknesses of the brake disc, mounting surface on the friction wheel and brake pads are given in table 1.

Table 1

Dimensions of brake components

Part	Inner Diameter	Outer Diameter	Thickness
Disc	5200	5900	40
Pad	-	220	60
Mounting surface	4750	-	40

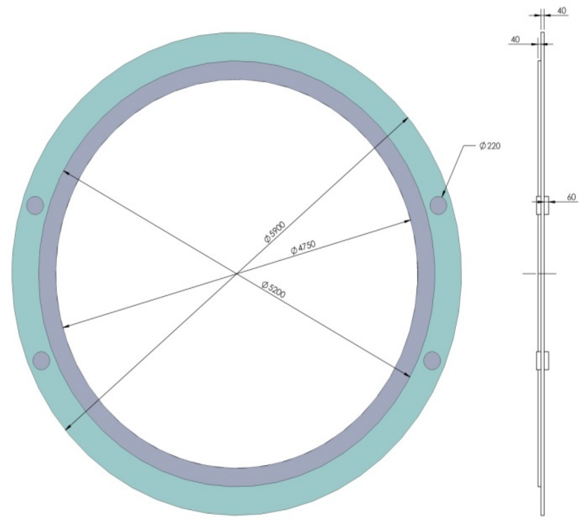


Fig. 5. Comsol model at 1:1 scale

5. SIMULATIONS IN COMSOL

In order to reduce the processing time, a simplified model - containing only one brake disc, four brake pads and the mounting surface of the disc on the friction wheel - was imported in COMSOL Multiphysics [22].

Using the *Model Builder* menu (figure 6), for the imported model, definitions and properties are set. Under the *Components* tree, the geometries of the parts are selected and grouped (disc faces, pad faces, contact surface, external surfaces and boundaries).

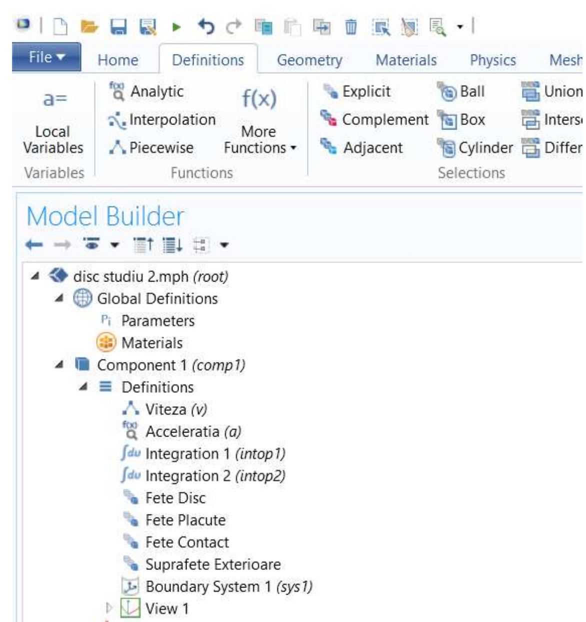
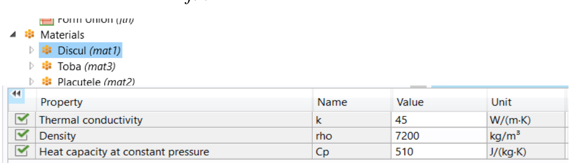


Fig. 6. Model builder of COMSOL

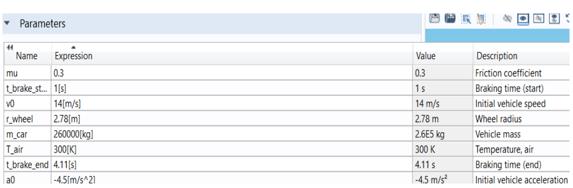
For each part resulted by grouping, the material properties (figure 7) are then defined: density, thermal conductivity and heat capacity at constant pressure. Under *Heat transfer in solids* option, the domain selection, motion type and coordinates, heat equations for flux and diffuse surfaces, boundaries, ambient temperatures are defined. Finally, under the *Global Definitions* tree, the parameters of the movement for simulation are defined (figure 8). Based on the properties defined and the model setup, the FEA mesh is created (figure 9).

The simulation parameters defined for the movement, impose a speed variation tachogram (figure 10) according to which the mine hoist moves with a constant vertical speed of v_{max}=14m/s in the time interval t_0–t_1=0..1s. At this point the emergency braking starts, meaning that in the time interval t_1–t_2=1..4.1s the mine hoist completely stops, with a deceleration (figure 11) automatically calculated by the software by derivation of the speed variation over time. The simulation will continue until t_{fin}=6s.



Property	Name	Value	Unit
Thermal conductivity	k	45	W/(m·K)
Density	rho	7200	kg/m³
Heat capacity at constant pressure	Cp	510	J/(kg·K)

Fig. 7. Defining material properties for parts



Name	Expression	Value	Description
mu	0.3	0.3	Friction coefficient
t_brake_st...	1[s]	1 s	Braking time (start)
v0	14[m/s]	14 m/s	Initial vehicle speed
r_wheel	2.78[m]	2.78 m	Wheel radius
m_car	260000[kg]	2.6E5 kg	Vehicle mass
T_air	300[K]	300 K	Temperature, air
t_brake_end	4.11[s]	4.11 s	Braking time (end)
a0	-4.5[m/s^2]	-4.5 m/s²	Initial vehicle acceleration

Fig. 8. Definition of simulation parameters

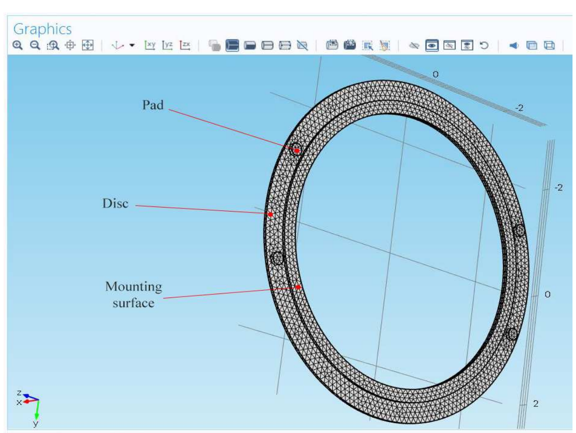


Fig. 9. FEA mesh of the model

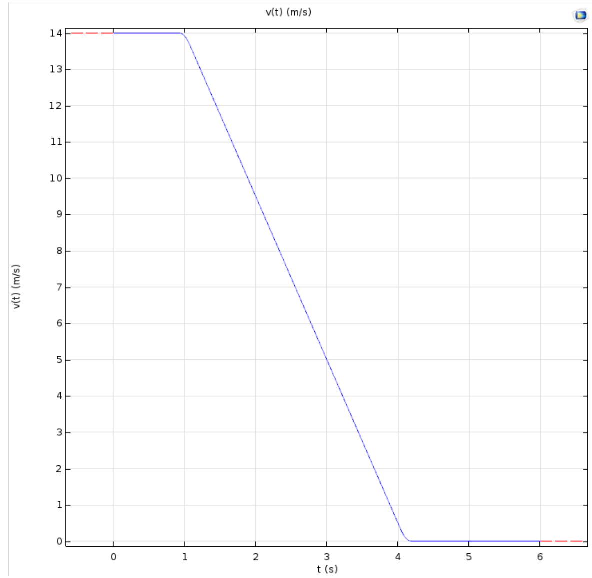


Fig. 10. Speed tachogram for simulation

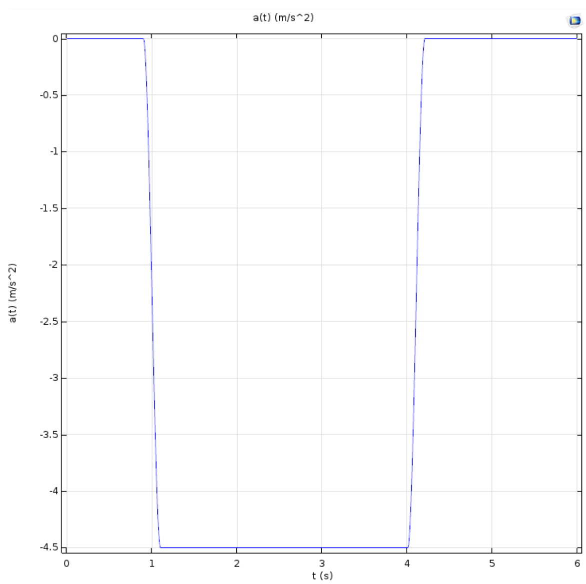


Fig. 11. Acceleration variation

6. RESULTS AND DISCUSSION

Based on the diameter of the brake disc and the vertical movement speed of the mine hoist, the number of rotations of a given point on the brake disc during the emergency braking until stop, can be estimated to 1.39 rotations.

As there are four pairs of brake pads and because their placement in relation to the circumference of the disc, the number of passes of a certain sections of the disc between the pads is different, resulting in an uneven temperature distribution at the contact surface of the pad and disc respectively.

Figure 12 shows the temperature distribution of the brake disc surface at the end of the emergency braking (t_2=4.1s), while figure 13 shows the temperature distribution of the brake disc surface at the end of the simulation (t_{fin}=6s). It can be observed that in the short period of 1.9s between the end of emergency braking and the end of the simulation, there is a temperature decrease of the disc as heat is dissipated into the atmosphere.

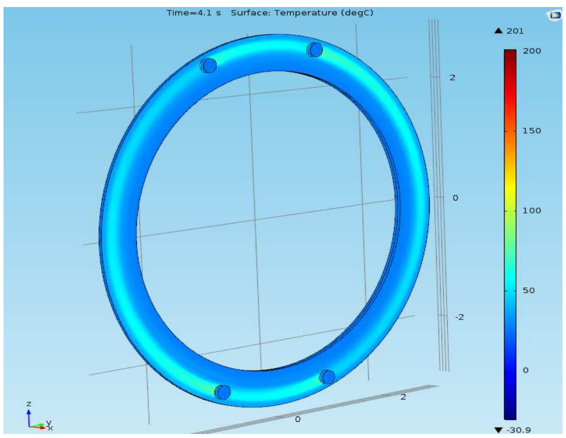


Fig. 12. Temperature distribution of the disc at (t_2=4.1s)

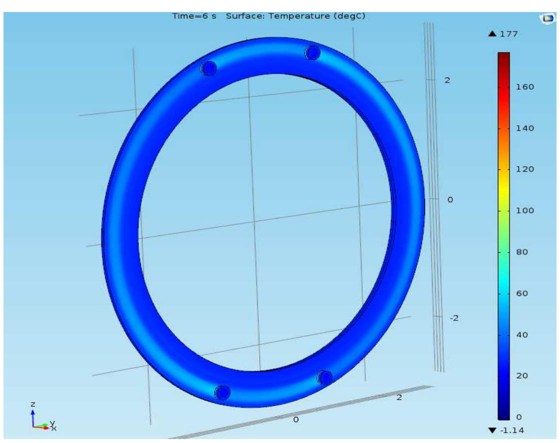


Fig. 13. Temperature distribution of the disc at (t_{fin}=6s)

The temperature distribution of the brake pad at the end of the emergency braking (t_2=4.1s) is shown in figure 14.

It can be observed that the distribution of temperature is uniform on the brake pad. This is expected, since the pad is in contact with the disc permanently during the braking, and the pad is fixed while the disc rotates until stop.

The temperature variation of a point on the surface of the disc pad during the emergency braking is plotted in figure 15.

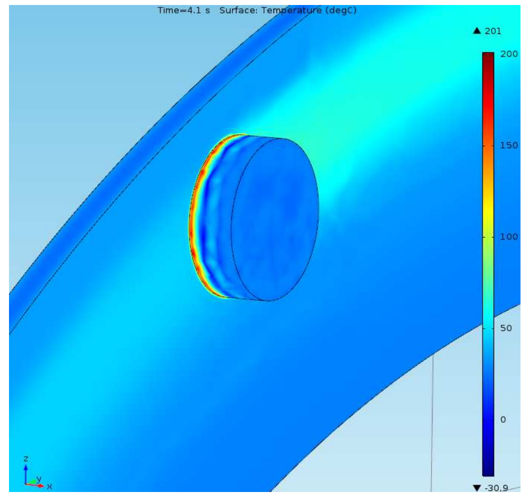


Fig. 14. Temperature distribution of the pad at (t_2=4.1s)

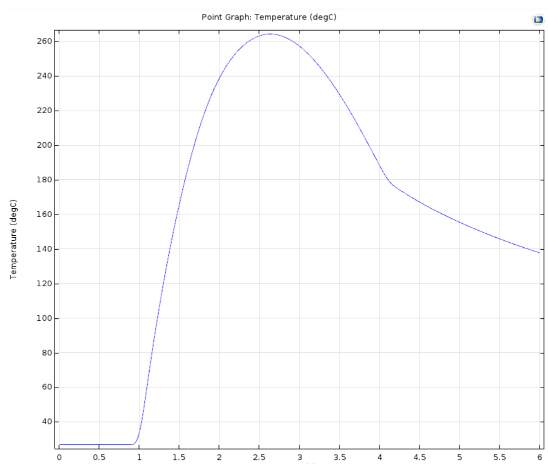


Fig. 15 Temperature variation of the brake pad during emergency braking

A comparison of the heat produced and the heat dissipated into the air during the emergency braking is shown in figure 16 (logarithmic scale).

The plot indicates that the resting time of the brakes must be long enough to properly dissipate all the generated heat. This is important because in case of emergency braking in a mine hoist, the brake pads are not released, but remain in contact with the disc for safety reasons, in order to hold the conveyances in place, unlike in automotive braking, where braking is applied multiple times.

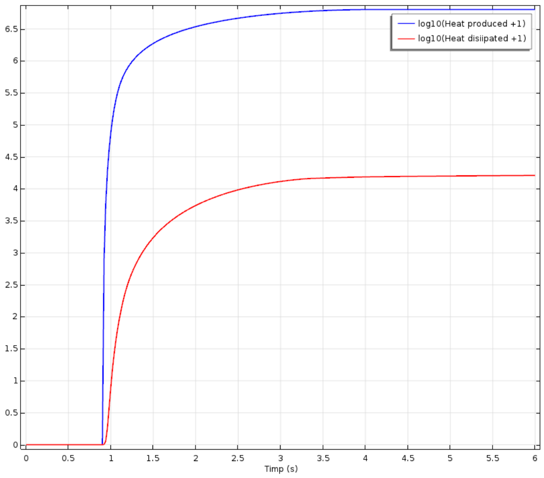


Fig. 16. Comparison of produced / dissipated heat

The surface temperatures of the disc and the pad vary with both time and position. The highest temperature is achieved at the contact surface between the pad and the disc, with the hot spot of the assembly being on the pad. This is also expected, as the pad is in permanent contact with the disc during emergency braking, and the disc better dissipates the heat because of its larger size and rotation movement.

Another investigation was then conducted in cross-section of the disc-pad assembly. First, a radial probe line was traced on the disc (Figure 17) and the temperature profile for the disc only along this line was plotted in figure 18. The maximum temperature of the disc is approximately 65°C. Using the same probe line, a cross-section plane through the disc-pad assembly was created (Figure 19) and the temperature distribution in the cross-section is shown in figure 20.

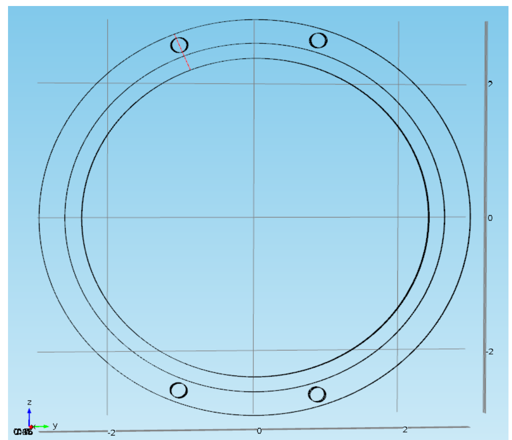


Fig. 17. Probe line location for cross-section investigation

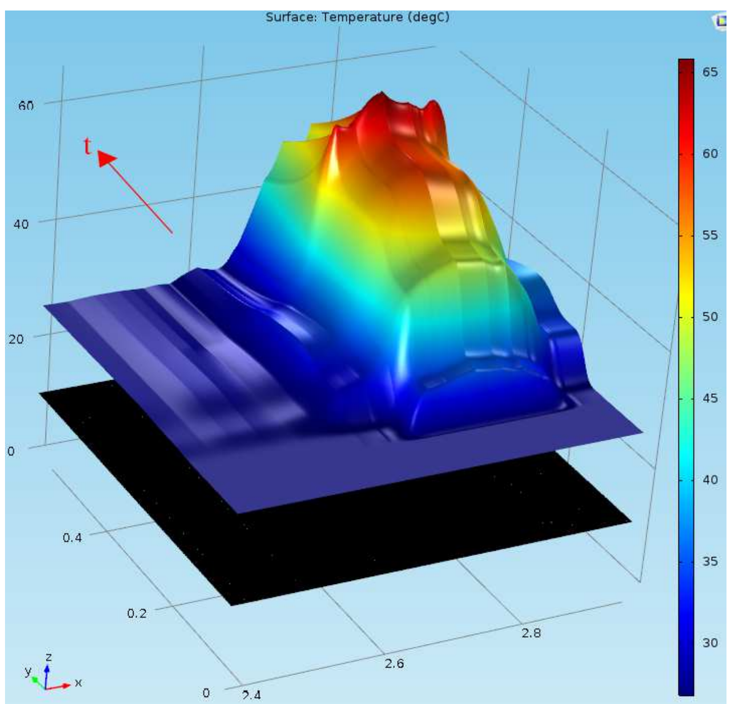


Fig. 18. Temperature profile of the disc along the probe line

It is visible that the hot point of the disc-pad brake assembly is situated on the outer edge of the pad that is in contact with the disc. The maximum temperature at this edge of the pad is slightly above 260°C at the end of the emergency braking (t_2=4.1s).

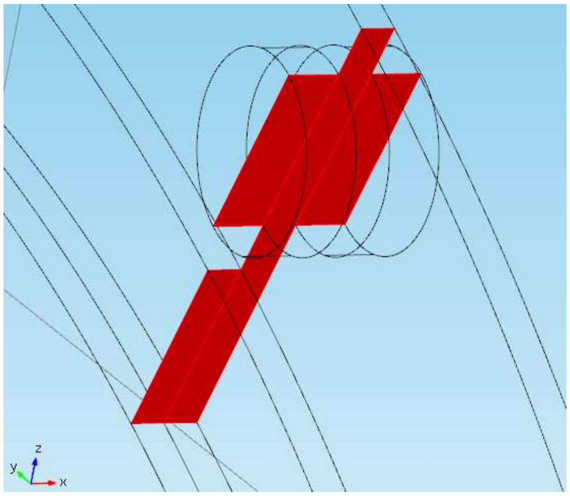


Fig. 19. Cross-section plane through the assembly

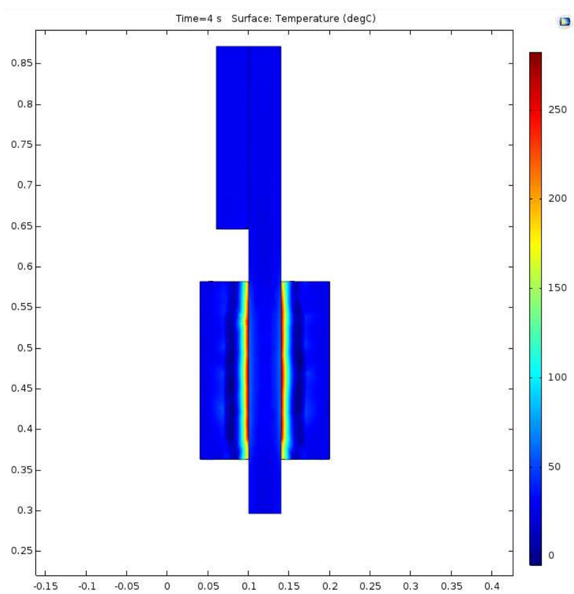


Fig. 20. Temperature distribution in cross-section

7. REFERENCES

[1.] Popescu, F.D.; Radu, S.M. *Vertical Hoist Systems, New Trends Optimizations*; LAP LAMBERT Academic Publishing: Saarbrucken, Germany, 2013.

[2.] Popescu, F.D. *Instalaţii de Transport pe Vertical*; Editura Focus: Petroșani, Romania, 2010.

[3.] Galy, B., Giraud, L. *Mine Hoist Safety: Regulations and Proposed Improvements to Risk-Mitigation Strategies.* CIM Journal; 7(4), 2016.

[4.] Mackin, T.J., Noe S.C., Ball K.J., et al. *Thermal cracking in disc brakes.* Eng Fail Anal; 9, pp. 63–76, 2002.

[5.] Orłowicz, A. W., Mróz, M., Wnuk, G., Markowska, O., Homik, W., Kolbusz, B. *Coefficient of Friction of a Brake Disc-Brake Pad Friction Couple*. Archives of Foundry Engineering, 16(4), pp.196–200, 2016.

[6.] Limpert, R. *Brake Design and Safety, 3rd ed.;* SAE International: Warrendale PA, USA, 2011.

[7.] Giraud, L., Galy, B. Fault tree analysis and risk mitigation strategies for mine hoists. Safety Science, 110, pp. 222–234, 2018.

[8.] Satope, S.; Bote, A.K.; Rawool, S.D. *Thermal Analysis of Disc Brake.* Int. J. Innov. Res. Sci. Technol. 3, pp. 68–73, 2017.

[9.] Belhocine, A.; Abu Bakar, A.R.; Bouchetara, M. *Thermal and structural analysis of disc brake assembly during single stop braking event.* Aust. J. Mech. Eng. 14, pp. 26–38, 2016.

[10.] Belhocine, A.; Abdullah, O.I. *A thermomechanical model for the analysis of disc brake using the finite element method in frictional contact.* J. Therm. Stresses, 43, pp. 305–320, 2019.

[11.] Singh, H.; Shergill, H. *Thermal Analysis of Disc Brake Using Comsol*. Int. J. Emerg. Technol. 3, pp. 84–88, 2012.

[12.] Bashir, M.; Qayoum, A.; Saleem, S. *Analysis of frictional heating and thermal expansion in a disc brake using COMSOL.* J. Phys. Conf. Ser. 1240, 012094, 2019.

[13.] *Heat Generation in a Disc Brake Created in COMSOL Multiphysics 5.6.* Available online: https://www.comsol.com/model/download/818061/models.heat.brake_disc.pdf (accessed on 28 December 2020).

[14.] Wang, D.; Wang, R.; Zhang, J. *Dynamic brake characteristics of disc brake during emergency braking of the kilometer deep coal mine hoist*. Adv. Mech. Eng. 12, pp. 1–23, 2020.

[15.] Bao, J.; Li, Z.; Hu, D.; Yin, Y.; Liu, T. *Frictional Performance and Temperature Rise of a Mining Nonasbestos Brake*

Material during Emergency Braking. Adv. Mater. Sci. Eng. 867549, 2015.
[16.] Yang, Y.; Ye, X. *Research and Optimization on Thermal Performance of Brake Disc for Ultra Deep Mine Hoist*. Proceedings of ICMTMA, 10th edition. Changsha, China, 10–11 February 2018; pp. 48–51.
[17.] Wang, D.; Wang, R.; Heng, T.; Xie, G.; Zhang, D. *Tribo-Brake Characteristics between Brake Disc and Brake Shoe during Emergency Braking of Deep Coal Mine Hoist with the High Speed and Heavy Load.* Energies, 13, 5094, 2020.
[18.] Peng, Y.; Zhu, Z.; Chen, G.; Bao, J.; Liu, B.; Li, Y. *Temperature Field of Disc Brake for Mine Hoist*. Adv. Sci. Lett. 4, pp. 2380–2384, 2011.
[19.] Popescu, F.D.; Radu, S.M.; Andraş, A.; Brînaş, I. *Numerical Modeling of Mine Hoist Disc Brake Temperature for Safer Operation.* Sustainability. 13, art. 2874, 2021.
[20.] Rusan, P.R.; Blebea, I. *Theoretical Study of Thermal Convection and Thermal Radiation.* ACTA TECHNICA NAPOCENSIS - Series: APPLIED MATHEMATICS, MECHANICS, and ENGINEERING, 58 (3), 2015.
[21.] Kurowski, P.M. *Engineering Analysis with SOLIDWORKS Simulation*, CRC Press, 2015.
[22.] COMSOL Multiphysics Users Guide, “Heat Transfer Module”, 2017.

Investigarea comportamentului termic al ansamblului disc-plăcuță de frână în cazul unei instalații de extracție folosind aplicația COMSOL Multiphysics

Rezumat: În lucrare este investigată variația temperaturii a două componente ale sistemului de frânare ale unei instalații de extracție, respectiv discul și plăcuța de frână. Pornind de la un model complet al tobei de fricțiune pe care sunt montate discurile și plăcuțele de frână, construit la dimensiune reală în SolidWorks, s-a importat în COMSOL Multiphysics o variantă simplificată a modelului constând doar în disc, plăcuță și locația de montaj a discului pe tobă. Pentru acest model s-au determinat variațiile de temperatură pentru disc și pentru plăcuța de frână, atât la suprafața lor cât și în secțiune, în cazul frânării de urgență a instalației de extracție de la viteza nominală de transport de 14 m/s. Studiul subliniază posibilitățile oferite de aplicația COMSOL în general și a modulului Heat Trasnfer al acesteia, în investigarea efectelor pe care încălzirea și răcirea le au asupra componentelor, dispozitivelor și proceselor mecanice.

Andrei ANDRAŞ, PhD Eng., Assoc. Prof., University of Petroșani, Department of Mechanical, Industrial and Transport Engineering, andrei.andras@gmail.com, 0722366653, 20 Universității street, 332006, Petroșani, HD
Ildiko BRÎNAŞ, PhD Eng., Lecturer, University of Petroșani, Department of Mechanical, Industrial and Transport Engineering, kerteszildiko@ymail.com, 0726703067, 20 Universității street, 332006, Petroșani, HD
Sorin Mihai RADU, PhD Eng., Professor, University of Petroșani, Department of Mechanical, Industrial and Transport Engineering, sorin_mihai_radu@yahoo.com, 0722642340, 20 Universității street, 332006, Petroșani, HD
Florin Dumitru POPESCU, PhD Eng. Habil., Professor, University of Petroșani, Department of Mechanical, Industrial and Transport Engineering, fpopescu@gmail,com, 0723719303, 20 Universității street, 332006, Petroșani, HD
Valentin POPESCU, PhD student, University of Petroșani, vpv.popescu@gmail.com, 20 Universității street, 332006, Petroșani, HD
Daniela-Ioana BUDILICĂ (ANDREI), PhD student, University of Petroșani, danalupulescu@yahoo.com, 20 Universității street, 332006, Petroșani, HD