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A Thermal Analysis of Crane Brakes with Two Shoes

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The main characteristic of the work of brake represents conversion of the mechanical energy into the heat resulting into warming-up and temperature increment of frictional areas. According to the researches carried out there is a negative influence of the increased temperature on both the frictional linings lifetime and reliability of the brakes. If a warm-up level of frictional areas is known at the early stage of design, this will decrease problems of designing and brakes selection to use. This paper gives a possible solving approach of a mentioned problem using examples of cranes with two brake shoes. During analysis of unsteady temperature fields (temperature calculation on the braking drum), this mathematical model is solved by use of numerical procedures (finite volume method). The simulation is showing real working conditions of the brakes. Developed computer program provides an ability to supervise temperature changes at the braking drum for randomly chosen period of crane work. This gives an opportunity to determine ratio between temperatures of sliding surfaces immediately after brake or during the brake (depending on the brakes purpose) and the temperatures at the end of the braking cycle. This analysis is concerned about work of brakes for stopping and brakes for lowering cargo. After simulation of equal brakes working conditions, temperature evaluation of the calculation results and measured results has been done. This has verified developed computer program and process presented.

Toplinska analiza dizaličnih kočnica s dvije papuče

Izvornoznanstveni članak

Rad kočnica karakterizira pretvorba mehaničke energije u toplinu što za posljedicu ima zagrijavanje i povećanje temperatura dijelova koji se taru. Istraživanja su pokazala da povećana temperatura negativno utiče na vijek trajanja frikcionih obloga ali i na pouzdanost kočnica. Poznavanje stupnja zagrijanosti tarnih površina u ranoj fazi projektiranja smanjuje poteškoće vezane za projektiranje i izbor kočnica. U ovom radu je dat mogući pristup rješavanju navedenog problema na primjerima dizaličnih kočnica s dvije papuče. Kod analiziranja nestacionarnih temperaturnih polja (izračunavanje temperatura na bubnju kočnice) postavljeni matematički model je riješen numeričkim putem (metoda konačnih volumena). Simulacijom su obuhvaćeni realni uvjeti rada kočnice. Razvijeni računalni program osigurava praćenje promjena temperatura na kočnice bubnja za proizvoljno dug period rada dizalice. To daje mogućnost da se ustanovi odnos između temperatra kliznih površina neposredno nakon kočenja ili u toku kočenja (zavisno od namjene kočnice) i temperatura na kraju ciklusa. Analizom je obuhvaćen rad zaustavnih kočnica i kočnica za spuštanje tereta. Procjene temperatura dobijenih proračunom su upoređivane s izmjerenim vrijednostima, na ispitnom stolu, simulacijom jednakih uvjeta rada kočnice. Time je izvršena verifikacija razvijenog računarskog programa i prezentiranog postupka.

1. Introduction

The main goal of brakes, the crane brakes as well is to make move control of individual mechanisms. To rich this goal, all conditions in which that mechanism works must be fulfilled. Brakes are introduced awhile, but are still the object of research and development. It is due to enlargement of object purposes, making new requests, introduction of new materials, technologies as well as methods of calculation. The most often, research directions are toward: brake design [1-6], temperature evaluation and thermo-mechanic behavior of brake discs [7-9], waste of frictional materials and conditions during brake [10-12]. All mentioned research is related to car brakes [1, 10-12] and railway brakes [3-9]. The need for this and related research is evident having the main

Symbols/Oznake

A_P	- sliding surface of the braking shoe, m^2 - klizna površina papuče
C_{12}	- radiation constant, $W/(m^2\ K^4)$ - konstanta zračenja
c	- specific heat, J/(kg K) - specifična toplina
F_{Wv}'	- constant driving resistance, N - otpor ustaljene vožnje
J_R	- reduced inertia momentum at the brakes shaft, kg m^2 - reducirani moment inercije na vratilu kočnice
M_k	- moment of breaking, Nm - moment kočenja
m_T	- cargo mass, kg - masa tereta
n	- revolution per minute of the braking drum, min^{-1} - broj okretaja bubnja kočnice
p_{sr}	- uniformly spaced average pressure, Pa - ravnomjerno raspoređen srednji tlak
q	- specific heat flow (thermal flux thickness), W/m^2 - specifični toplinski protok (gustina toplotnog fluksa)
q_b	- heat that is transferred to the drum, W/m^2 - toplina koja se predaje bubnju
q_p	- heat that is transferred to the shoes, W/m^2 - toplina koja se predaje papučama
q_B	- heat that is transferred to the environment, W/m^2 - toplina koja se predaje okolini
q_{max}	- specific heat flow at the beginning of braking, W/m^2 - specifični toplinski protok na početku kočenja
q^{konv}	- heat that is transferred to the environment through convection, W/m^2 - toplina koja se prenosi na okolinu konvekcijom
q^{zr}	- heat that is transferred to the environment through radiation, W/m^2 - toplina koja se prenosi na okolinu zračenjem
S	- total cell surface, m^2 - ukupna površina ćelije
S_e, S_w, S_n, S_s	- surfaces that limit one cell, m^2 - površine koje ograničavaju jednu ćeliju
s_k	- braking path, m - put kočenja
T	- temperature, K (°C) - temperatura
T_P	- temperature in a centre of cell, °C - temperatura u centru ćelije
T_E, T_W, T_N, T_S	- temperatures in the centers of neighboring cells, °C - temperature u centrima susjednih ćelija
T_O	- temperature of the environment, °C - temperatura okoline
T_p	- temperature at the start, °C - početna temperatura
T_B	- temperature at the surface of the object, °C - temperatura na površini tijela
t	- time, s - vrijeme
t_{kz}	- braking time, s - vrijeme kočenja
V	- cell volume, m^3 - volumen ćelije
v_s	- movement speed of cargo, m/s - brzina spuštanja tereta
v	- sliding velocity, m/s - brzina klizanja
W_{k1}	- work of a braking, J - rad jednog kočenja
α	- contact angle, rad, (°) - obuhvatni kut
α	- coefficient of heat transition, $W/(m^2\ K)$ - koeficijent prijelaza topline
α_p	- coefficient of heat transition in forced air flow, $W/(m^2\ K)$ - koeficijent prijelaza topline kod prisilnog strujanja zraka
α_s	- coefficient of heat transition at the free flow of air, $W/(m^2\ K)$ - koeficijent prijelaza topline kod slobodnog strujanja zraka
δt	- time step, s - vremenski korak
δx_e, δx_w, δy_n, δy_s	- center distance of neighboring cells, m - rastojanja centara susjednih ćelija
η	- degree of utilization - stepanj iskorištenja
φ_{k1}	- angle of drum rotation during the braking, rad - kut za koji se zakrene bubanj tokom jednog kočenja
λ	- coefficient of heat conducting, W/(m K) - koeficijent provođenja topline
μ	- friction coefficient - koeficijent trenja
$\mu\ p_{sr}\ v_0$	- specific braking power, W/m^2 - specifična snaga kočenja
ω_{K0}	- angle velocity at the beginning of braking, s^{-1} - kutna brzina na početku kočenja
ρ	- specific mass, kg/m^3 - specifična masa

goal more secure brake work. Crane brakes are exposed to different work conditions. Those conditions depend of brake appliance as well as of mechanisms that the brakes are built on. While designing crane mechanisms, these brakes are picked out of commercially available range, rather than designed from the beginning, relied on experienced positive solutions. That way all difficulties related to heat transfer problems (worming brake parts) are trying to be avoid, but solutions are not always optimal. It is well known that the temperature on sliding areas reaches the maximum temperature in some phase of braking (dependant on brake purpose) and then is decreasing. Using common methods it is not possible to predict the instantaneous temperature value or the increased temperature time of duration. Those maximum temperatures may influence the brake security as well as the linings life time. In this paper the procedure that might predict temperature on contact surfaces of drum and braking shoes is developed. It considered the brake working conditions (braking frequency, average cargo mass, braking duration etc.) and the brake purpose (lowering the cargo, stopping mechanisms). Computer program, developed upon the presented mathematical model, is providing simulation of brake work for desirable long period of crane work. During that period, the temperature on brake's drum can be evaluated. For simulation model are used: the brake with two braking shoes and as the brake's drum standard elastic ring clip made of steel alloy EN: X27CrMoV51 is used [13].

2. Temperature evaluation with two-dimensional model

Analyzes of unsteady temperature fields (temperature calculations on the braking drum) were done using the finite volume method (FVM). With assumption that the temperature exchange is not done on the edge of braking drum [7, 9], the clip in radial direction and small angle was chosen, as shown on figure 1a. The problem came up to two dimensional. The purpose was to avoid complexity of three-dimensional model, as well as to achieve the request for getting enough precise calculation results [7]. Space discretization was comprised of numerical mesh definition in a way that observed space-clip (2D domain of calculation) divided on final number of control volumes (CV) adapted to the domain of shape calculations. In center of each CV the calculation point was installed as shown on Figure 1b and 2. For discretization, the orthogonal numerical mesh was used. In the area of more intensive temperature exchange the numerical mesh is denser.

While calculating problem of heat conduction within the body, using finite volume method, it's started of energy equation written as integral [14, 15]

$$\frac{\partial}{\partial t}\int_V \rho c T \, \mathrm{d}V = \int_S \lambda \frac{\partial T}{\partial x_j} n_j \, \mathrm{d}S + \int_V q_i \, \mathrm{d}V \tag{1}$$

Where: t - time, V - cell volume, ρ - material density, c - specific heat, T -temperature, S - total cell surface, x_j - spatial coordinates of the point, λ - coefficient of heat conduction, n_j – unit vector of external normal on the surface S, q_i - specific heat volume that appears or plunge in measure of time.

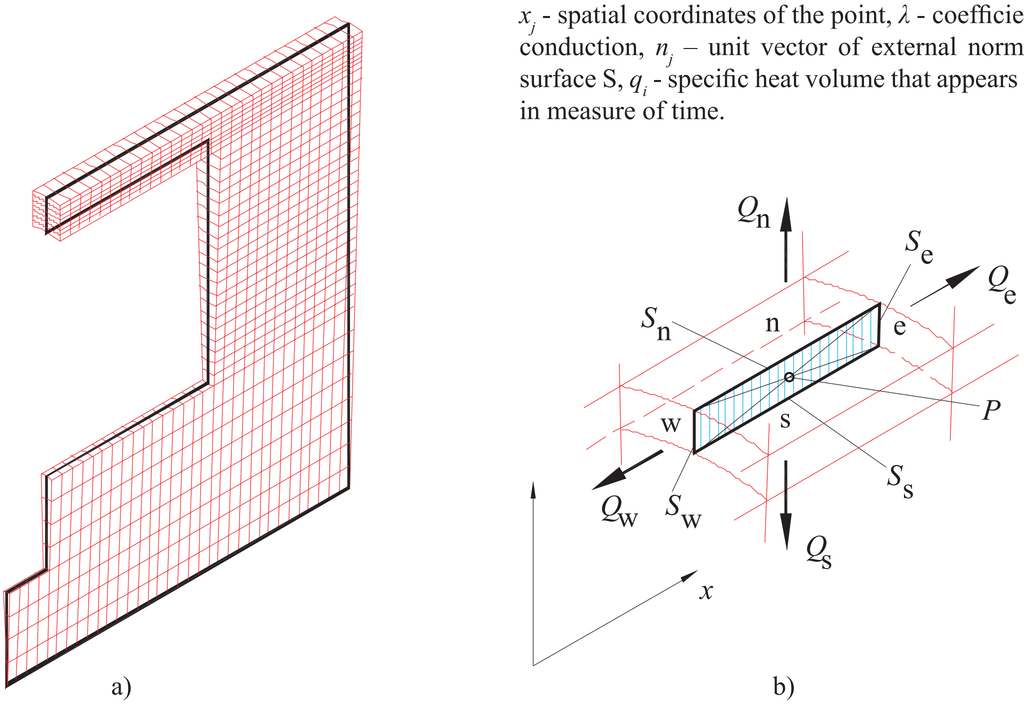

Figure 1. 2D calculation domain: a) numerical mesh, b) control volume

Slika 1. 2D domen rješavanja: a) numerička mreža, b) kontrolni volumen

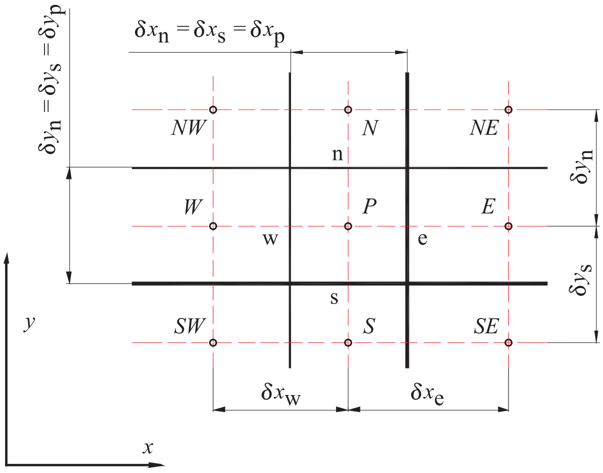

Figure 2. Two-dimensional CV, compass define chart

Slika 2. Dvodimenzionalni KV, šema kompasnog označavanja

Due to integration of equation (1), on each control volume (CV) [14-15], system of algebraic equation is achieved:

$$a_P T_P = \sum_K a_K T_K + b\,, \quad (K = E, W, N, S)\,. \tag{2}$$

Where (according to Figure 1 and 2)

$$a_P = \sum_K a_K + \left[\frac{V}{\delta t}(\rho c)_P\right], \quad (K = E, W, N, S)\,, \tag{3}$$

$$a_E = \lambda \frac{S_e}{\delta x_e}; \quad a_W = \lambda \frac{S_w}{\delta x_w}; \quad a_N = \lambda \frac{S_n}{\delta y_n}; \quad a_S = \lambda \frac{S_s}{\delta y_s} \tag{4}$$

$$b = q_{iP} V + \left[\frac{V}{\delta t}(\rho c T)_P^{m-1}\right]\,. \tag{5}$$

2.1. Modeling work of brakes

The amount of mechanical energy that converts into the heat (on the brake due to friction) depends of crane (mechanism) purpose and working conditions. In further description, brake work of brakes for lowering cargo and stopping brakes is simulated. Independently of brake purpose, it can be said that the energy that brake takes onto during the single brake is equal to break work:

$$W_{k1} = M_k\, \varphi_{k1} \tag{6}$$

Where: M_k - brake moment that the selected brake can achieve and φ_{k1} - the angle that drums achieved during single brake.

With the assumption that distribution of contact pressure between drum and the shoe is uniform. Frictional coefficient has the constant value which at the stopping brakes causes constant deceleration and linear heat flux decreasing from beginning to the end of braking (Figure 3b).

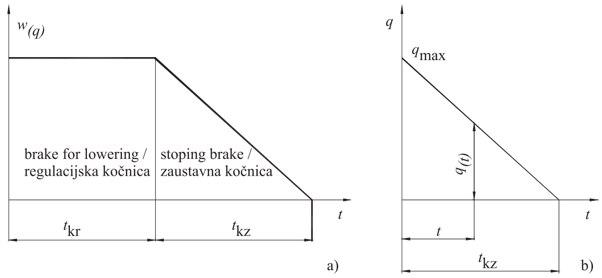

Figure 3. Diagram for determination of brake angle φ_k and heat flux q(t)

Slika 3. Dijagram za određivanje kuta kočenja φ_k i toplotnog fluksa q(t)

2.1.1. Brakes for lowering cargo

Amount of mechanical energy converted into the heat that is transferred on the brake per unit of time, presented per unit of surface (heat flux) is:

$$q = q_b + q_P = \frac{\eta\, m_T\, g\, v_s}{2 A_p} = \frac{M_K\, \varphi_{K1}}{2 A_p\, t_{kr}} = \mu\, p_{sr}\, v\,. \tag{7}$$

Where: q_b - heat transferred to the drum, q_P - heat transferred to shoes, A_p - contact surface among drum and one shoe, m_T - cargo mass, v_s - speed of lowering cargo, μ - frictional coefficient, p_{sr} - average pressure value on contact surface among drum and shoe and v - skating speed.

In calculation, according to [16], is assumed that all heat is transferred to the drum:

$$q = q_b + q_p \cong q_b\,. \tag{8}$$

2.1.2. Stopping brakes

Stopping brakes are incorporated on mechanism for elevating cargo and on mechanism for bridge driving or winch. Considering the equal speed change, the equation for heat flux for brakes of elevating cargo mechanisms (according to Figure 3b) has the form:

$$q(t) = \left(\frac{J_R\, \omega_{K0}^2}{2} \pm \eta\, m_T\, g\, s_k\right) \frac{t_{kz} - t}{A_p\, t_{kz}^2} = q_{max} \frac{t_{kz} - t}{t_{kz}}\,. \tag{9}$$

While at stopping brakes for driving mechanisms is:

$$q(t) = \left(\frac{J_R\, \omega_{K0}^2}{2} - \eta\, F_{Wv}'\, s_k\right) \frac{t_{kz} - t}{A_p\, t_{kz}^2} = q_{max} \frac{t_{kz} - t}{t_{kz}}\,. \tag{10}$$

Where: J_R - reduced inertia momentum at the brakes shaft, F_{Wv}' - driving resistance, s_k - braking path, q_{max} - specific heat flow at the beginning of braking.

2.2. Initial and boundary conditions

Knowledge of initial conditions considering knowledge of start temperature field of observed field. While resolving this problem it is assumed that the start temperature T_p is uniform (constant) and equal to the environmental temperature T_0, so for t =0:

$$T(x, y, 0) = T_p = T_O \tag{11}$$

Boundary conditions are defined by temperature exchange between body surface and the environment, so the limited temperature flux is:

$$q_B = -\lambda \left(\frac{\partial T}{\partial n} \right)_B = q^{konv} + q^{zr} \tag{12}$$

Where: $(\partial T/\partial n)_B$ - temperature gradient on body surface, q^{konv} - heat that is transferred to the environment through convection and q^{zr} - heat that is transferred to the environment through radiation.

Convective temperature exchange, either done by free or forced air fluid, is defined by Newton law of temperature exchange [17-18]:

$$q^{konv} = \alpha \left[T_B - T_O \right] \tag{13}$$

Where: α – coefficient of heat transition, T_B - temperature at the surface of the object, T_O - air temperature on further distance from body surface.

Part of temperature released by radiation is:

$$q^{zr} = C_{12} \left[\left(\frac{273 + T_B}{100} \right)^4 - \left(\frac{273 + T_O}{100} \right)^4 \right]. \tag{14}$$

Where: C_{12} - radiation constant [16].

While defining the boundary conditions, working cycle is divided on operations and each of them is analyzed separately. The operation of breaking is also divided, so two segments a) period of observed surface sliding on friction material and b) period while it moves among two shoes, are analyzed separately. It is assumed that the speeds of empty and loaded beckets are equal, driving bridge conditions are almost equal. During the crane work when brake's drum is rotating, boundary conditions are defined on Figures 4. and 5. While observed mechanism of the analyzed brake is resting, boundary conditions are defined on Figure 6.

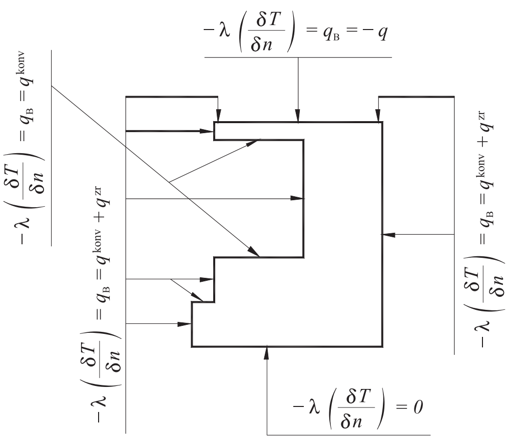

Figure 4. Boundary conditions during sliding of observed surface on shoe linings

Slika 4. Granični uvjeti u vrijeme klizanja površine po oblogama papuča

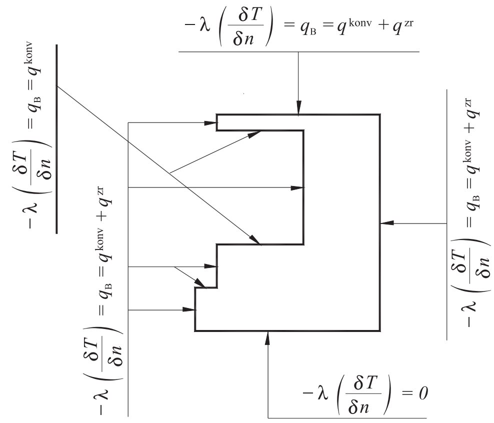

Figure 5. Boundary conditions while surface moves between two shoes, period of elevating cargo and elevating and lowering the empty hook

Slika 5. Granični uvjeti za vrijeme putovanja površine između dvije papuče, vrijeme dizanja tereta te dizanja i spuštanja prazne kuke

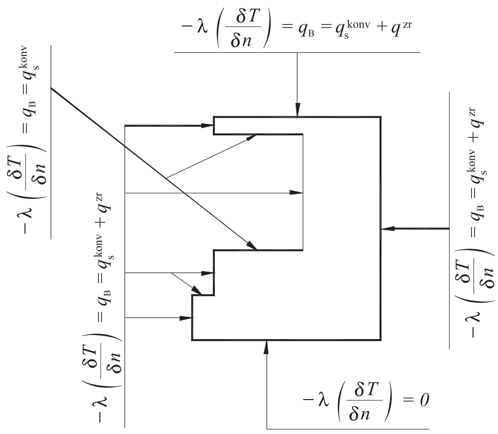

Figure 6. Boundary conditions while observed brake drum is resting

Slika 6. Granični uvjeti u vrijeme mirovanja bubnja

In defining these conditions, for speeds $v_i \geq 0{,}8\ ms^{-1}$, the temperature flux from definition (13) is calculated with temperature exchange coefficient [16]:

$$\alpha = \alpha_p = 7{,}14\, v^{\,0{,}78}\,. \qquad (15)$$

Where for speeds $v_i \geq 0{,}8\ ms^{-1}$, temperature exchange coefficient is $\alpha = \alpha_s$ [16].

2.3. Computer program

For resolving the problem, using described method, computer program is developed that working chart as diagram is shown on Figure 7. Program gives the opportunity for simulation of randomly long brake's working period. As may be seen on diagram, each operation during crane work period is analyzed separately, each cycle of brake drum as well as period while the observed surface is in contact with drum lining or it moves between two shoes. For defining the time steps, δt periods of contact among brake lining and observed surface, as well as moves of the surface between the shoes (while lowering cargo - braking) have been divided on larger number of equal intervals. At all other operations, the time step has been equal the time of single drum cycle. System of algebraic equation type (2) has been calculated using iterative method [14-15].

3. Calculation results

3.1. Brake for lowering cargo

Calculation needed data are presented in pervious paragraph. Data related to working conditions are: environmental temperature 20 ºC, drum cycle number while lowering cargo 500 min^{-1}, duration of cargo lowering 10s, total time of cycle duration 160 s. It is assumed that the characteristics of material do not change with temperature change, and calculations were done with values achieved at temperature of 20 ºC. On Figures 8 and 9 were shown calculation results for the first crane work cycle. Results on Figure 8 present change of temperature distribution on generating line of drum sliding surface.

For easier presentation of calculation results, for longer period of crane work, have been chosen two points on drum sliding surface. Points are 10 mm apart of drum sliding surface ends (20 mm and 75 mm). Results were shown on Figure 10 and present temperatures after each cargo lowering and at the end of each cycle. From the figure it could be seen, that due to relatively small braking strength, after a long period the balance have been established among energy that on the brake is turned to heat and the heat that is released from the drum. On Figures 11 and 12 are presented temperature changes on sliding surface at the end of brake work observing period. It is shown that temperature distribution is repeating and that at the end of cycle is equal through all the drum width.

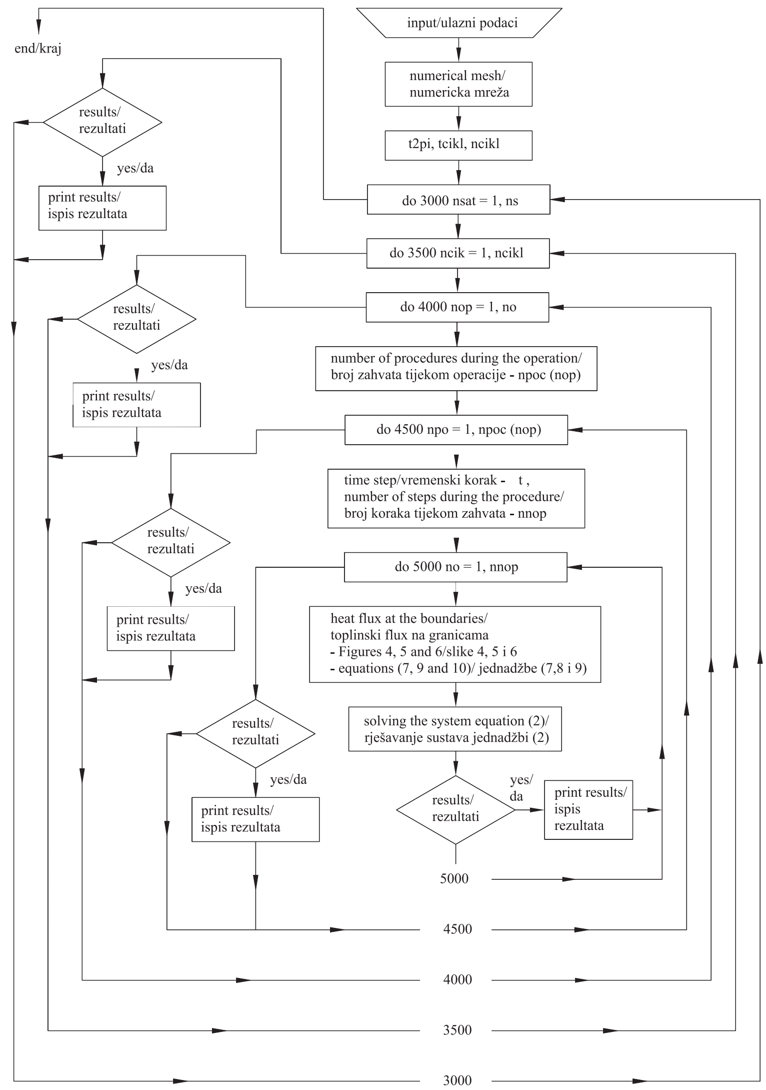

Figure 7. Flow of temperature calculations on brake drum while lowering cargo

Slika 7. Tok proračuna temperatura na bubnju kočnice kod spuštanja tereta

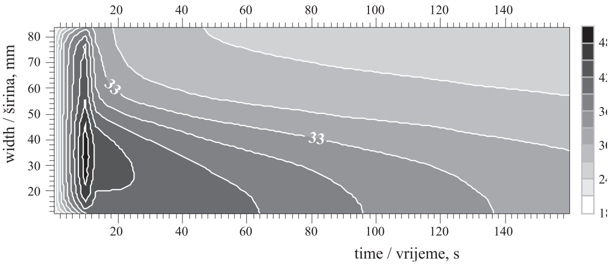

Figure 8. Temperature change on drum sliding surface during first cycle.

Slika 8. Promjena temperatura na kliznoj površini bubnja tijekom prvog ciklusa

3.2. Stopping brake

During calculations for stopping brakes, the same procedure is used as for lowering cargo brakes. Brake is incorporated with mechanism for bridge driving and can achieve braking moment of M_k =107,78 Nm. Number of drum cycles on beginning of braking was 960 min $^{-1}$. Temperature flux on beginning of brake work was $q_{max} = \mu\ p_{sr}\ v_0$ = 0,634 W/ mm ^{2}, and at the end of braking was close to zero (Figure 3). For purpose of not repeating the complete process, results of single braking were presented. Boundary conditions from Figures 4 and 5 were used in calculations. The only values that were measured while showing temperature changes are those at the end of observed surface contact with shoe lining. From the figure it can be seen faster arising of temperature at the brake beginning, and reaches the maximum value in the middle of braking. It is result of constant decrease of temperature flux during braking.

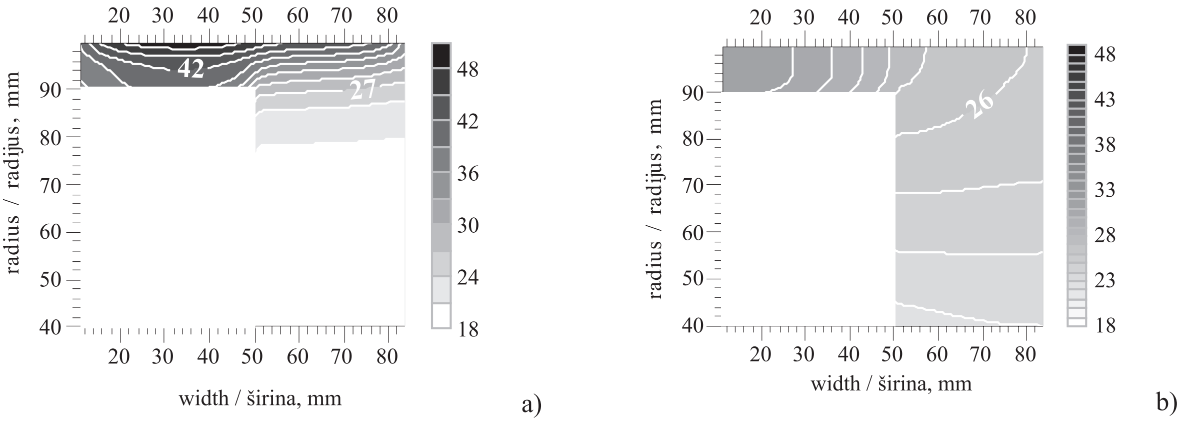

Figure 9. Temperature distribution, from inside the drum, after lowering cargo 10s (left) and on the end of the cycle 160s (right).

Slika 9. Raspored temperatura, u unutrašnjosti bubnja, nakon spuštanja tereta 10s (lijevo) i na kraju ciklusa 160s (desno)

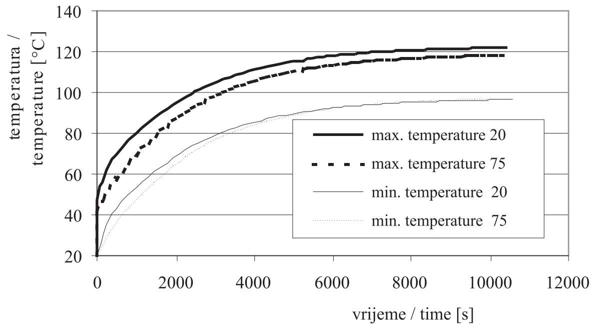

Figure 10. Temperature change, at points 20 mm and 75 mm, during 3 hours of crane work.

Slika 10. Promjena temperatura, u točakama 20 mm i 75 mm, tijekom 3 sata rada dizalice

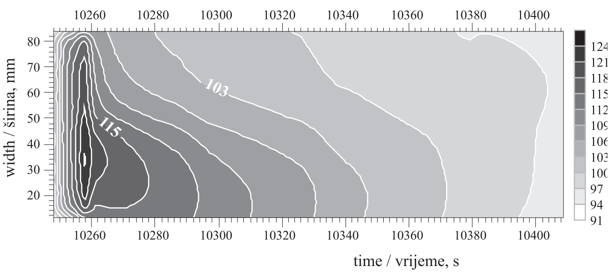

Figure 11. Temperature change on drum sliding surface during 21.st cycle on third hour of crane work.

Slika 11. Promjena temperatura na kliznoj površini bubnja tijekom 21. ciklusau trećem satu rada dizalice

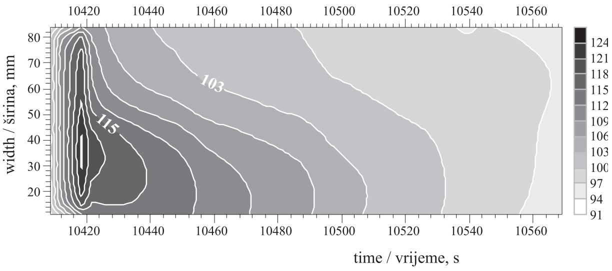

Figure 12. Temperature change on drum sliding surface during 22nd cycle at the end of third hour of crane work at TC = 160s

Slika 12. Promjena temperatura na kliznoj površini bubnja tijekom 22. ciklusa na kraju trećeg sata rada dizalice kod TC = 160s

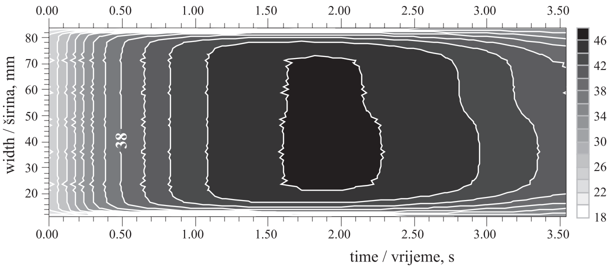

Figure 13. Temperature change on drum sliding surface during the braking of stopping brake on mechanism for bridge drive.

Slika 13. Promjena temperatura na kliznoj površini bubnja tijekom kočenja zaustavne kočnice mehanizma za vožnju mosta

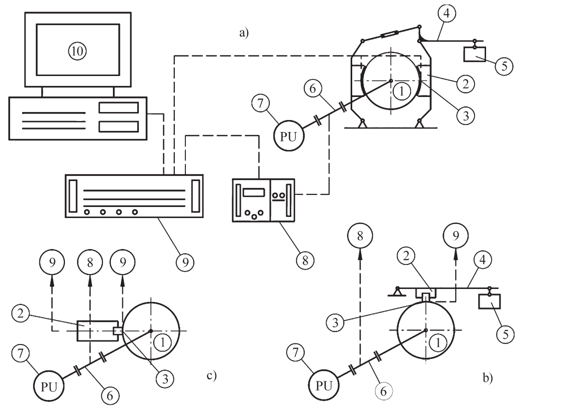

Figure 14. Presentation chart of the test stand (Working practice): 1-drum, 2- career and test tube (brake shoes linings), 3- thermocouple, 4- lever, 5.- weight, 6 – measuring beam, 7 –drive, 8 – digital indicator DA 24 and value amplifier MD 18 N, 9- multi-channel value amplifier DMC 9012 A, 10-personal computer.

Slika 14. Šematski prikaz ispitnog postolja (princip rada): 1-bubanj, 2-nosač i epruveta (papuča sa oblogom), 3-termopar, 4- poluga, 5-uteg, 6- mjerno vratilo, 7- pogon, 8- digitalni indikator DA 24 i mjerno pojačalo MD 18 N, 9- višekanalno mjerno pojačalo DMC 9012 A, 10- personalni računar

4. Experimental results check

4.1. Test stand

During research on brakes, the test stand was developed, that can check calculation results for temperature prediction on frictional areas of brake drum and its stability during brake work. By combination of certain parts and mechanisms, the test stand is used for determination of frictional material coefficient. Results achieved like this are used for temperature calculations on brake drum. Presentation chart of the test stand is on Figure 14. By rotating drum 1, the relative sliding speed towards the test tube is achieved (brake shoes linings) 2. Normal force, on contact place, is achieved by system of levers unequal legs 4 (a lever 4, Figure 14b) and weight 5 or spring 2 (Figure 14c).

On Figure 15. is presented dependency between frictional coefficient and sliding speed for two specific pressure values (0,1 MPa and 0,2 MPa). Measures were done at sliding surfaces temperatures with ≅ 60 °C (Figure 14b and 14c).

Further checking of frictional coefficient depending of sliding speed was done. The brake with medial pressure 0.075 MPa (Figure 14a) as well as temperature of sliding surfaces ≅ 80 °C (the same conditions as for brakes for lowering cargo) was tested. Results were shown on Figure 16 and there is a good correlation with results on Figure 15.

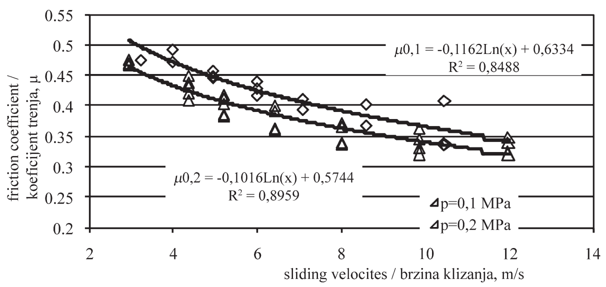

Figure 15. Dependency of frictional coefficient of sliding speed (for 0,1 MPa and 0,2 MPa)

Slika 15. Ovisnost koeficijenta trenja od brzine klizanja (za 0,1MPa i 0,2 MPa)

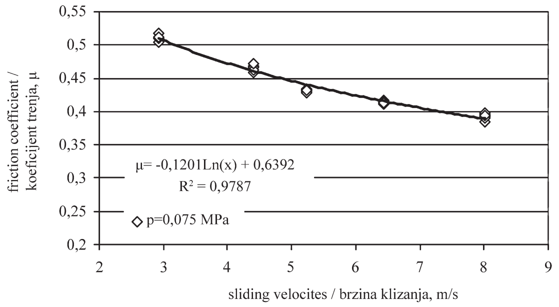

Figure 16. Testing the dependency among frictional coefficient and sliding speed.

Slika 16. Provjera ovisnosti koeficijenta trenja od brzine klizanja

4.2. Comparing the calculation results with tested values

For testing the presented procedure, for assumption of temperatures on brake drum, the comparison of achieved calculated results with tested results on the test stand (Figure 14a) using simulation of equal work conditions, was done. Using thermocouples, at previously defined points (20mm and 75mm) the temperatures were measured. Compared results between calculated and measured temperature values at brakes for lowering cargo were presented on Figure 17.

From presented results, it is obvious good correlation among calculated and measured values, considering possible obstacles during process performance as: time duration of each operation, manipulation while temperature measured, coefficient of heat transmission and so on. Considering all of these, presented way of calculation and temperature prediction on brake drum, gives sufficiently precise results. It is also simulated brake work with different work conditions as: different speed of linings sliding along ledge of brake drum. Results of these calculations are no different of presented examples.

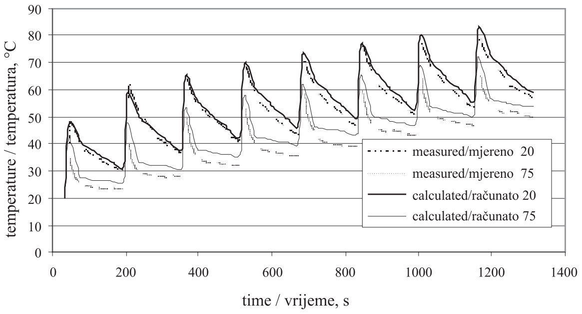

Figure 17. Compared results of temperatures achieved by calculation and measuring on the test stand for $n = 500 \text{min}^{-1}$ ($v = 5{,}2 ms^{-1}$)

Slika 17. Uporedni rezultati temperatura dobijenih proračunom i mjerenjem na ispitnom postolju za $n = 500 \text{min}^{-1}$ ($v = 5{,}2 ms^{-1}$)

5. Conclusion

Based upon the analyzes done in this work, it can be concluded that presented mathematical model and numerical procedure of resolving it may be used for temperature calculations on brake drum. Computer program provides ability to supervise temperature changes for randomly chosen time period of crane work. Analyzes show that using this kind of calculation it is possible to assume the influence of brakes working conditions on temperature of sliding surfaces, specially when their maximum values are considered (named: temperature picks). Experimental results confirm applicability of this procedure that may provide certain protection while projecting and make easier the choice of these brakes. The procedure might with some minor changes and adaptations be used at analyzing braking systems in highway traffic as well as at railroad traffic.

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