SIMULATION OF THERMAL LOADINGS OF WROUGHT WHEELS

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ABSTRACT

Actually used diagnostic systems do not allow to evaluate fairly enough the background of loading of an object, to identify those states which are characterized by absence of a defect, but at the same time warn of a mature environment for its formation. That is, they do not provide a full assessment of risks and the residual operation life of an object. The main disadvantage is a fact that they do not permit to analyze the kinetics of transient processes related to operational or technological impact. The paper clarifies approaches to evaluation of kinetics of transient thermal processes in a running wrought wheel (the system «wheel-shoe») on the basis of original methodology established by authors and of the results of computer simulation.

ENGLISH SUMMARY

Background. *During operation railway wheels are subject to two main types of loading: mechanical loading, related to the transfer of load from a car on a track, and thermal loading that occurs while braking in the system «wheel-shoe». Analysis of data on failures of wrought wheels (hereinafter- WW) shows that the largest number of defects in recent years accounted for chips of tread surface (up to 40%) and defects of braking-related origin (skidded, scaled wheels, etc. – up to 25%).*

Noteworthy is the fact that the share of damages by cracks in the total number of failures over the past 20 years has increased by 2 times and remains stable for a long time. There are three types of cracks differentiated: a) by bright spots, flats, scaled wheels b) by fatigue cracks; c) by thermal cracks on a tread surface of a wheel rim. All of them are the result of the thermal and mechanical impact on WW, are «local damage in the form of chipping of a metal of a wheel tread» [1] and fairly reflect the totality of complex transient processes.

It should be noted that if the mechanical impact on WW leads mainly to deformation processes in the boundary layer of a wheel tread, then thermal effects, associated with braking, can lead to complex transient processes of heat transfer, structural and phase transformations, kinetics of a strain-stress state arising at a stage of heat treatment after quenching and subsequent tempering, accumulation of plastic deformation at tread surface as well as in the zone of transition from a rim to a disc plate. Kinetics of thermal processes during braking in the boundary layers can lead to a significant reduction in the mechanical properties of a metal of a wheel that affects the growth of the intensity of plastic deformations occurring as a result of mechanical loadings in these areas and formation of local defects of a fatigue character.

Objective. *The objective of the authors is to investigate thermal processes (in particular, thermal loading), which occur in wrought wheels.*

Methods. *The authors use simulation method, mathematical calculations and analysis.*

Results.

Method of calculating heat input

With modern state of the art transient thermal deformation processes in WW cannot be analyzed by instrumental methods. The assessment of their impact on the current state, reliability, failure-free operation, maintainability of a wheel can be obtained only by computer simulation of nonlinear transient heat transfer processes, structural and phase transformations, and problems of thermo-, visco-, elasto-plasticity considering the kinetics of phase and structural state, as well as a whole complex of properties.

The basic provisions of the methods of analysis of parameters of thermal effects on WW during braking rest on conventional approaches outlined in the works of a number of researchers [2, 3, 4].

Conversion of kinetic energy of a train into thermal energy is at the heart of braking process. Heat generated in the contact zone of a wheel with a brake shoe, is distributed among them. The amount of heat supplied to a wheel depends on a type of a brake shoe. In case of composition brake shoes 95% of heat generated during braking at contact surfaces of rubbing friction pair is perceived only by a wheel rim [5]. In case of iron brake shoes, coefficient of thermal flows partition is assumed to be equal to 0,8 for a wheel and 0,2 for a shoe with one-sided braking pads and respectively 0,6 and 0,4 for two-side braking [4].

We have developed a calculation assessment of the intensity of heat release in a pair «wheel-shoe» [6] based on the following provisions.

In determining the actual deceleration time of a train and amount of heat generated during braking, we take into account:

– initial and final speed of a train in a calculation interval $V_н$ and $V_к$, km/h;

– main specific running resistance ω_{ox}, kgf/t;

– gradient of a track i,‰;

– deceleration of a train under the influence of specific retarding force ξ;

– mode of air distributor (laden, medium, empty);

– axial load q_0, t;

– calculated ratio of brake shoes friction $\varphi_к$;

– pressing force of brake shoes, actual $K_д$ and calculated K_p, tf;

– type of brake shoes (cast-iron, composite type);

– type of a car (freight, passenger);

– number of brake shoes per one wheel;

– calculated ratio of braking pressure of a train ϑ_p, tf/t;

– weight of a train;

– type of braking (emergency, full service, step of braking);

– specific braking force b_m, kgf/t;

– and other parameters.

The actual braking distance is calculated by summing braking distances, determined by intervals of speed at a constant braking force, specific train

Table 1

Values of pressing force on a brake shoe for a four axle open car, tf

Type of brake shoes	Mode of an air distributor		
	laden	medium	empty
composite	2,4	1,48	0,82
cast-iron	3,8	2,3	1,26

resistance and gradient in the accepted range of velocities [7].

$$\Delta S_{\partial} = \sum \frac{500 \cdot \left[V_{н}^{2} - V_{к}^{2}\right]}{\xi \cdot (b_{m} + \omega_{ox} + \omega_{i})}, \quad (1)$$

where $V_{н}$ and $V_{к}$ are initial and final speeds of a train in the accepted calculated range of velocities;

ξ – deceleration of a train under the influence of specific retarding force;

b_m – specific braking force at an average speed in each interval, kgf/t;

ω_{ox} – specific running resistance at an average speed in each interval, kgf/t;

ω_i – specific decelerating or accelerating force caused by a train weight when driving on a gradient railway track, kgf/t.

Acceleration a_i is determined by dependence:

$$a_{i} = \frac{V_{н}^{2} - V_{к}^{2}}{2 \cdot 3,6^{2} \cdot \Delta S_{\partial}}. \quad (2)$$

The total braking time is made up of actual braking time $t_ф$ and preparatory $t_п$:

$$t_{общ} = t_{ф} + t_{п}. \quad (3)$$

During preparation time $t_п$ brakes do not work and a train passes a preparatory length $S_п$. After this time brakes are activated immediately and a train passes the rest of a braking length with brake shoes pressed with a full force.

Therefore, to determine the amount of generated heat only a component $t_ф$ is taken into account, which is determined by the formula:

$$t_{ф} = \sum \frac{V_{н} - V_{к}}{3,6 \cdot a_{i}}. \quad (4)$$

As an example, we calculated braking length and braking time for trains of 50 loaded open cars with roller bearings and a two-section locomotive with accounting weight of 192 tons, at the site (i=0) of continuous welded rail. The value of ξ is taken equal to 120. The calculation results are presented in Tables 2 and 3.

Pressing force ($K_д$) for four axle open car was taken at laden mode of an air distributor (Table 1).

The data obtained for emergency braking from a speed of 120 km / h are summarized in Tables 2 and 3.

The values of the actual braking length obtained by the method of summation over the range of velocities, amounted to 1 054 m for composition brake shoes and to 1 894 m for cast-iron brake shoes. Preparatory length for a train with 200 to 300 axes with an initial speed of 120 km / h at the site of a track with a gradient i=0‰ is defined as 334 m. Accordingly, a full braking length with composition brake shoes is defined as 1388 m, and if recalculated for iron brake shoes as 2228 m.

According to nomograms shown in [6], a braking length of a freight train in emergency braking on the site with composition brake shoes ($\vartheta_p = 0,204$) is S ≈ 1390 m, with iron brake shoes ($\vartheta_p = 0,297$) is S ≈ 2100 m.

Thus, the error of calculated data varies from values from nomograms by less than 6%.

Kinetics of transient processes

Kinetic energy of a train at braking is equal to:

$$\Omega = \frac{m \cdot V^{2}}{2}, \quad (5)$$

where m is weight of a train, t; V is initial speed of braking, m/s.

Average power during braking is equal to:

$$q = \frac{\Omega}{t}, \quad (6)$$

where t is actual time of braking, s.

Average power of heat generated during braking, using composition and iron brake shoes is determined as:

$$q_{к} = \frac{\Omega}{t_{к}}, \quad (7)$$

$$q_{ч} = \frac{\Omega}{t_{ч}}, \quad (8)$$

where $t_к, t_ч$ are periods of braking time for corresponding type of braking shoes.

As an example of a computational assessment of heat generation intensity in the pair «shoe-wheel» we will take emergency braking of a freight train of 4892 t (two-unit locomotive VL80k – accountable weight 192 tf, a number of auto-brake axes – 8), consisting of 50 four axle open cars from a speed of 120 km/h at the site (i=0) of a continuous welded rail. In calculation of heat inputs we take actual time of braking equal to 60 s for composition brake shoes and 101 s for iron brake shoes (Tables 2 and 3). Initial speed $V = 120\ \text{km}/\text{h} = 33,33\ \text{m}/\text{s}$.

Then a kinetic energy of a train at braking will be:

$$\Omega = \frac{4892 \cdot 10^{3} \cdot 33,33^{2}}{2} = 2717234,249\ \text{kJ}. \quad (9)$$

Average power during braking period with the use of composite and iron brake shoes is:

$$q_{к} = \frac{2717234,249}{60} = 45287,238\ \text{kW}; \quad (10)$$

$$q_{ч} = \frac{2717234,249}{101} = 26903,31\ \text{kW}. \quad (11)$$

Intensity of a heat flow on each wheel will be:

$$q_{к}^{1} = \frac{q_{к}}{m_{л} + m_{в} \cdot n} = \frac{45287,238}{16 + 8 \cdot 50} = 108,86\ \text{kW}; \quad (12)$$

$$q_{ч}^{1} = \frac{q_{ч}}{m_{л} + m_{в} \cdot n} = \frac{26903,31}{16 + 8 \cdot 50} = 64,67\ \text{kW}. \quad (13)$$

If we apply efficiency output η =0,95 for a composite brake shoe and η =0,8 for an iron brake shoe, then *(p.34)**:*

Table 2

Data to determine actual braking distance when using cast-iron brake shoes

Vн	Vк	ϕк	Кд	ϕкр	Кр	ωо	ωх	ωох	ΣК	Q	ϑ	bт, kgf/t	tф	Sд
120	110	0,076	3,8	0,086	3,358	2,394	8,06375	2,616157	1455	4892	0,297	25,580	10,6398	339,8824
110	100	0,078	3,8	0,089	3,358	2,168	7,20375	2,365724	1455	4892	0,297	26,341	10,4504	304,8033
100	90	0,081	3,8	0,092	3,358	1,960	6,41375	2,134391	1455	4892	0,297	27,235	10,21465	269,5533
90	80	0,084	3,8	0,095	3,358	1,768	5,69375	1,922159	1455	4892	0,297	28,299	9,926714	234,3808
80	70	0,088	3,8	0,099	3,358	1,594	5,04375	1,729027	1455	4892	0,297	29,587	9,579611	199,5752
70	60	0,093	3,8	0,105	3,358	1,436	4,46375	1,554996	1455	4892	0,297	31,179	9,164856	165,4766
60	50	0,099	3,8	0,112	3,358	1,296	3,95375	1,400065	1455	4892	0,297	33,194	8,671923	132,4877
50	40	0,107	3,8	0,120	3,358	1,172	3,51375	1,264235	1455	4892	0,297	35,830	8,087484	101,0936
40	30	0,117	3,8	0,133	3,358	1,066	3,14375	1,147506	1455	4892	0,297	39,424	7,394286	71,88889
30	20	0,133	3,8	0,150	3,358	0,977	2,84375	1,049877	1455	4892	0,297	44,616	6,56945	45,62118
20	10	0,157	3,8	0,177	3,358	0,904	2,61375	0,971349	1455	4892	0,297	52,774	5,581836	23,25765
10	0	0,201	3,8	0,227	3,358	0,849	2,45375	0,911922	1455	4892	0,297	67,459	4,387801	6,094167
													100,7	1894,11

Table 3

Data to determine actual braking distance when using composite brake shoes

Vн	Vк	ϕк	Кд	ϕкр	Кр	ωо	ωх	ωох	ΣК	Q	ϑ	bт	tф	Sд
120	110	0,232	2,4	0,251	2,216	2,394	8,064	2,616	998	4892	0,204	51,232	5,571173	177,968
110	100	0,236	2,4	0,255	2,216	2,168	7,204	2,366	998	4892	0,204	52,038	5,514327	160,8345
100	90	0,240	2,4	0,259	2,216	1,960	6,414	2,134	998	4892	0,204	52,938	5,447344	143,7494
90	80	0,245	2,4	0,264	2,216	1,768	5,694	1,922	998	4892	0,204	53,951	5,369288	126,7749
80	70	0,250	2,4	0,270	2,216	1,594	5,044	1,729	998	4892	0,204	55,099	5,279079	109,9808
70	60	0,256	2,4	0,276	2,216	1,436	4,464	1,555	998	4892	0,204	56,411	5,175452	93,44567
60	50	0,263	2,4	0,284	2,216	1,296	3,954	1,400	998	4892	0,204	57,925	5,056913	77,2584
50	40	0,271	2,4	0,293	2,216	1,172	3,514	1,264	998	4892	0,204	59,691	4,921672	61,5209
40	30	0,280	2,4	0,303	2,216	1,066	3,144	1,148	998	4892	0,204	61,778	4,767561	46,35129
30	20	0,291	2,4	0,315	2,216	0,977	2,844	1,050	998	4892	0,204	64,282	4,591922	31,88834
20	10	0,305	2,4	0,330	2,216	0,904	2,614	0,971	998	4892	0,204	67,343	4,391444	18,29768
10	0	0,323	2,4	0,349	2,216	0,849	2,454	0,912	998	4892	0,204	71,170	4,161952	5,78049
													60,2	1053,85

Table 4

Ratios of intensity of heat inputs in the contact area of a brake shoe with a wheel rim, distributed by speed ranges

Speed rage	Ω_i , kJ	t_{ik} , s	q_{ik} , kW/cm²	$t_{iч}$, s	$q_{iч}$, kW/cm²
120–110	8341,049	5,5	74,39	10,6	32,8
110–100	7615,741	5,5	68,62	10,4	30,49
100–90	6890,432	5,4	62,85	10,2	28,22
90–80	6165,123	5,3	57,05	9,9	25,99
80–70	5439,815	5,3	51,2	9,6	23,76
70–60	4714,506	5,2	45,26	9,2	21,52
60–50	3989,198	5,1	39,2	8,7	19,25
50–40	3263,889	4,9	32,95	8,1	16,89
40–30	2538,58	4,8	26,46	7,4	14,36
30–20	1813,272	4,6	19,62	6,6	11,55
20–10	1087,963	4,4	12,31	5,6	8,16
10–0	362,6543	4,2	4,33	4,4	3,46
Sum	52222,22	60,2	-	100,7	-

$$q_к^2 = q_к^1 \bullet \eta = 108,86 \bullet 0,95 = 103,417\,\text{kW}; \quad (14)$$

$$q_ч^2 = q_ч^1 \bullet \eta = 64,67 \bullet 0,8 = 51,736\,\text{kW}. \quad (15)$$

To determine total area of the impact of a heat flow on a wheel tread we take into account width of a brake shoe and wheel geometrical parameters (taking into account the current state of wear). According to [8] width of an iron brake shoe is 0,08 m. According to a technical standard 2571–028–00149386–2000 scribe line 25610-N a width of a composite brake shoe is also equal to 0,08 m. Surface area of the heat input to a wheel tread is calculated as S=2πr • h , where r is a radius of a wheel, equal in that case to 0,475m, and h is a width of a brake shoe, m. So the surface area (S) is of 0,239 m².

$$q_к^{2ср} = \frac{q_к^1 \bullet \eta}{S} = \frac{103,417}{0,239} = 432,71\frac{\text{kW}}{\text{m}^2} = 43,27\frac{\text{W}}{\text{cm}^{2;}} \quad (16)$$

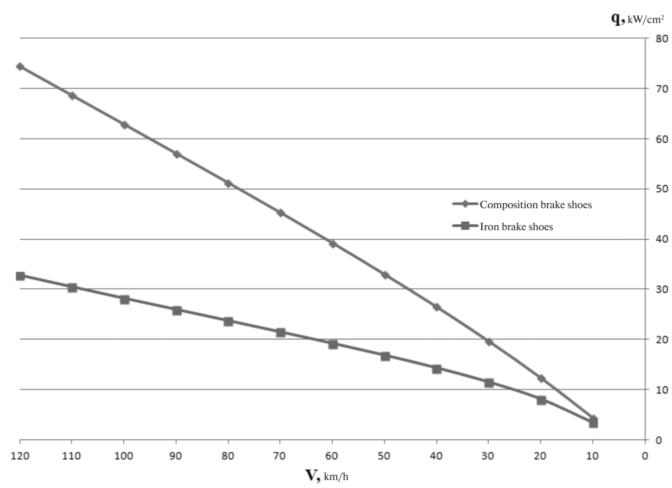
$$q_ч^{2ср} = \frac{q_ч^1 \bullet \eta}{S} = \frac{51,736}{0,239} = \ldots = 21,65\frac{\text{W}}{\text{cm}^{2;}}. \quad (17)$$

Since a weight of a locomotive as compared to a weight of an entire train is small, it is acceptable

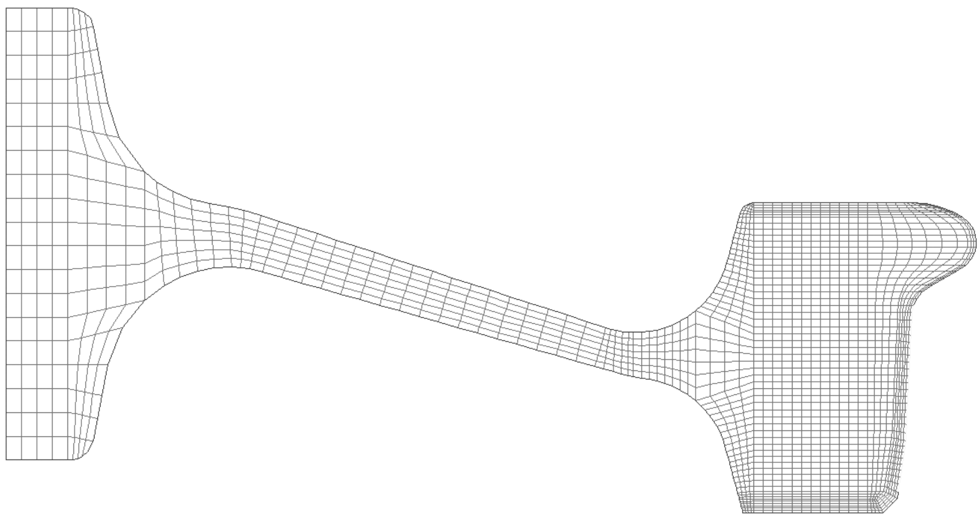
Table 5

Ratio of heat input power, constant on an entire range of braking

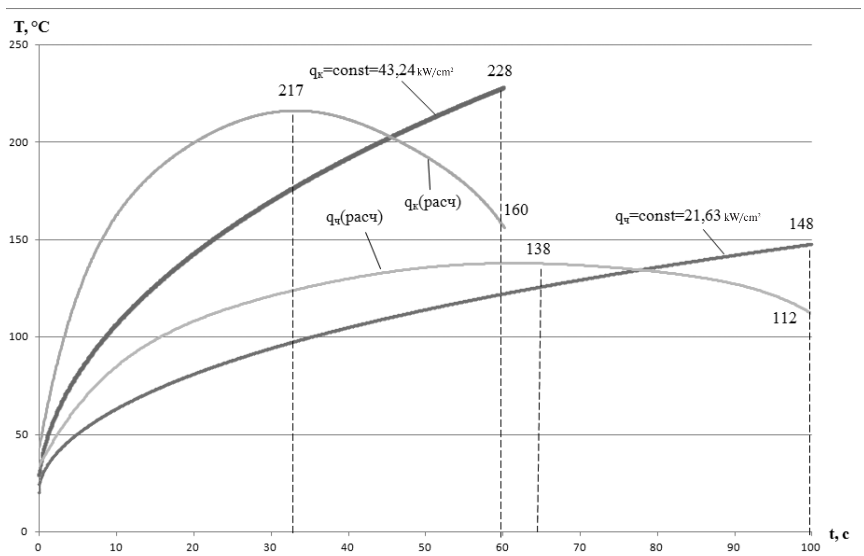
Initial braking speed, km/h	Values of an average ratio of heat input power, W/ cm²	
	Composite brake shoes	Iron brake shoes
120–0	43,07	21,7
110–0	39,88	20,39
100–0	36,65	19,07
90–0	33,39	17,72
80–0	30,07	16,34
70–0	26,7	14,91
60–0	23,26	13,42
50–0	19,73	11,85
40–0	16,09	10,14
30–0	12,34	8,26
20–0	8,43	6,09
10–0	4,33	3,46



Pic. 1 Change in values of power of heat inputs in WW, depending on a current speed of a car at braking with account for a brake shoe type.



Pic. 2. Axisymmetric model of a wrought with a rectilinear disc plate.



Pic. 3. Distribution of values of maximum temperatures on a wheel tread at different ratios of heat input power.

to carry out a calculation of intensity of a heat flow in relation to a car.

In this case, the kinetic energy of a car is:

$$\Omega = \frac{m \bullet V^2}{2} = \frac{94 \bullet 10^3 \bullet 33{,}33^2}{2} = 52211{,}778 \text{ kJ}. \qquad (18)$$

Estimated time of emergency braking is taken depending on the material of brake shoes: 60 s for composition brake shoes and 101 s for iron brake shoes.

$$q_к = \frac{\Omega}{t} = \frac{52211{,}778}{60} = 870{,}196 \text{ kW}; \qquad (19)$$

$$q_ч = \frac{\Omega}{t} = \frac{52211{,}778}{101} = 516{,}948 \text{ kW}. \qquad (20)$$

On each of eight wheels of a four axle power is:

$$q_к^1 = \frac{q_к}{8} = \frac{870{,}196}{8} = 108{,}775 \text{ kW}; \qquad (21)$$

$$q_ч^1 = \frac{q_ч}{8} = \frac{516{,}948}{8} = 64{,}62 \text{ kW}. \qquad (22)$$

With implied efficiency output η =0,95 for a composite brake shoe and η =0,8 for an iron brake shoe we get:

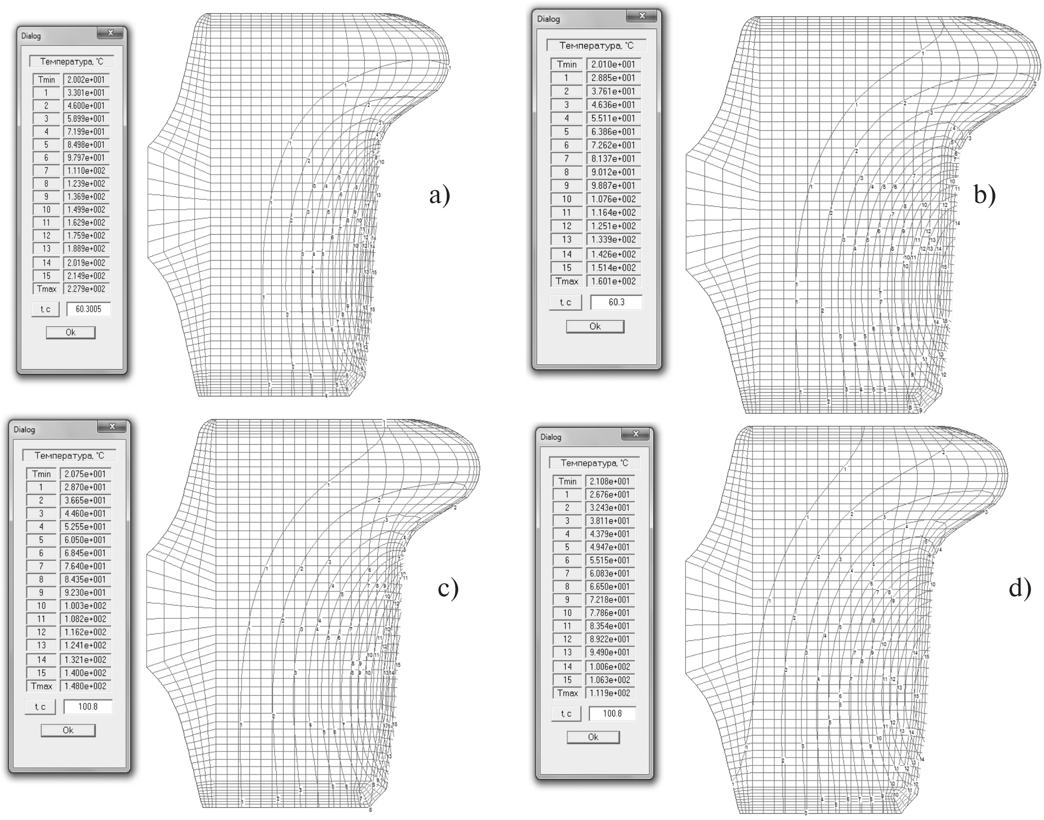
$$q_к^2 = q_к^1 \bullet \eta = 108{,}775 \bullet 0{,}95 = 103{,}336 \text{ kW}; \qquad (23)$$

$$q_ч^2 = q_ч^1 \bullet \eta = 64{,}62 \bullet 0{,}8 = 51{,}696 \text{ kW}. \qquad (24)$$

Specific power, generated per unit of a site surface in the contact area wheel-shoe is determined as:

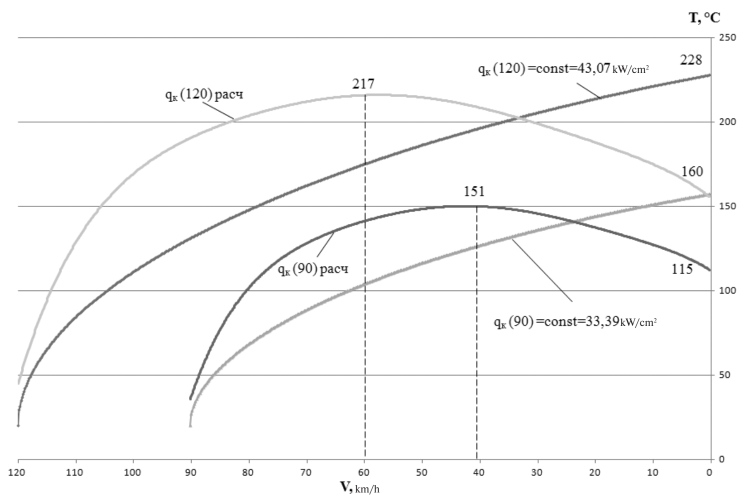
$$q_к^{2ср} = \frac{q_к^1 \bullet \eta}{S} = \frac{103{,}336}{0{,}239} = \ldots = 43{,}24 \frac{\text{W}}{\text{cm}^2}; \qquad (25)$$

$$q_ч^{2ср} = \frac{q_ч^1 \bullet \eta}{S} = \frac{51{,}696}{0{,}239} = \ldots = 21{,}63 \frac{\text{W}}{\text{cm}^2}. \qquad (26)$$



Pic. 4. The temperature distribution in a wheel rim at the time of emergency braking: heat input power ratio – constant (a – composite brake shoes, b – cast-iron brake shoes), heat input power ratio depends on a current speed of a car (c – composite brake shoes, d – cast-iron brake shoes).

Pic. 5. Kinetics of maximum temperatures on a tread surface of a wheel rim during braking from 120 km / h and 90 km / h, composite brake shoes.



Comparing the results obtained from the formulas (14) – (15) and (25) – (26) we can conclude that an error does not exceed 1%, and it is permissible to carry out a calculation of heat inputs in a wheel in relation to one car (assuming that a train consists of cars of the same type).

As a result, the obtained values of average heat inputs into a wheel q^{2cp} and $\sum t_i$ are initial data for the analysis of the kinetics of thermal processes in WW at braking.

It should be noted that while studying thermal effects on a wheel, the power of thermal loadings was previously assumed to be constant throughout braking – from the beginning to the end. However, this approach can be considered approximate, because during braking intensity of heat, generated in the pair of «wheel-shoe» depends on the wheel speed (speed of movement), and varies with time.

A distinctive feature of a developed technique is a differentiated assessment of the intensity of thermal *loads on a wheel, depending on a current speed. When calculating a real braking distance, actual time of braking and intensity of heat flows, velocity intervals of every 10 km / h are considered.*

In this case:

$$\Omega_i = \frac{m\bullet(V_i^2 - V_{i+1}^2)}{2} \qquad (27)$$

$$q_i = \frac{\Omega_i}{t_i}, \qquad (28)$$

where Ω_i *is kinetic energy in a given range of speeds of braking, kJ;*

t_i *is a braking time in a given range of speeds of braking, s;*

V_i, V_{i+1} *are respectively initial and final speeds of braking in a given range, m/s.*

The implementation of a demonstrated approach is presented at an example of the results of calculation of heat inputs during braking of a car (see Table 4).

The sum of kinetic energy, counted according to speed ranges, coincides with the kinetic energy, calculated by the formula (18), if speed is not rounded to 33,33 m / s.

Pic. 1 shows a diagram of change in intensity of heat inputs, depending on the current speed of a freight car at braking, obtained for 10 km/h intervals of braking.

Table 5 shows values of ratio of heat input power in WW, constant on an entire interval of braking with different initial maximum speed calculated by the method we used.

Modeling of heating of a wheel rim

For analysis of the kinetics of thermal processes in WW at braking an axisymmetric finite element model has been developed, which is shown in Pic. 2. Dimensions correspond to those indicated in State standard 10791–2011. The model consists of 2000 nodes, number of four-nodal elements is 1864.

Pic. 3 shows the curves of changes in the values of maximum temperatures on a wheel tread during emergency braking for a considered option with the use of ratio of heat input power: constant during entire braking (43,24 W / cm² – composite brake shoe, 21,63 W / cm² – iron brake shoe), and variable with account of a current speed.

Analysis of the curves indicates that the use of a constant value of ratio of heat input power during the entire braking mode provides a rise of maximum temperatures during an entire braking interval with maximum values at the end of braking (228 ˚C for composite brake shoes, 148 ˚C – for iron brake shoes).

If for computer simulation running values of heat input power ratio are used depending on a current speed of a car, we note maximum values of temperature on a wheel surface not at the end of braking, as it was previously, but at an intermediate stage of braking. This can be explained by the fact that with a decrease in speed of a car the intensity of a heat flow emitted in a wheel decreases in the presence of intense heat transfer processes in a wheel rim from a wheel tread.

Pic. 4 shows the temperature distribution in a cross section of a wheel rim at the end of emergency braking.

Then we can consider the results of modeling of thermal processes in WW during braking with different initial speed and the use of composite brake shoes.

Pic. 5 shows the results of computer simulation using a constant heat input power ratio (33,39 W / cm² and 43,07 W / cm²) and a variable heat input power ratio (data shown in Table 5).

Conclusion. *Analysis of simulation results, presented in Pic. 5, demonstrates that the use in the formation of the boundary conditions of a variable ratio of heat input power depending on a current speed of a car leads to obtaining of maximum values of temperatures on a wheel thread not at the end of braking, but in its middle part. It is a fundamentally important result which is of particular importance not in the analysis of thermal processes by modeling results of an entire braking cycle from a maximum speed to a full stop, but in simulation of successive cycles of incomplete braking that occurs in the operation of a train's movement.*

Keywords: railway, rolling stock, the system «wheel-shoe», braking, thermal loading, kinetics, wrought wheel, intensity of thermal loadings.

REFERENCES

1. Classifier of faults of car wheelsets and their elements, JSC «Russian Railways» [*Klassifikator neispravnostey vagonnyh kolesnyh par i ih elementov, OAO «RZhD»*]. Moscow, 2007, 100 p.

2. Zharov, I. A. Application of thermal models for the analysis of processes in the system «shoes-wheelset-rails». Works of VNIIZhT. Contact-fatigue damage of wheels of freight cars [*Primenenie teplovyh modeley dlya analiza protsessov v sisteme «kolodki–kolesnaya para–rel'sy». Trudy VNIIZhT. Kontaktno-ustalostnye povrezhdeniya koles gruzovyh vagonov*]. Ed by. S. M. Zakharov. Moscow, Intekst publ, 2004, 160 p.

3. Petrov, S. Yu. Material properties of tribosystems shoe-wheel-rail [*Svoystva materialov tribosistem kolodka-koleso-rel's*]. Moscow, MIIT, 2000, 210 p. (Dep. TsNIITI MPS № 6309).

4. Anisimov, P.S., Yudin, V.A., Shamakov, A.N., Korzhin S. N. Calculation and design of pneumatic and mechanical parts of brakes of cars. Educational guide [*Raschet i proektirovanie pnevmaticheskoy i mehanicheskoy chastey tormozov vagonov*]. Ed by P. S. Anisimov, Moscow, Marshrut publ., 2005, 248 p.

5. Wrought wheels. Manufacturing, maintenance, repair, reliability [*Tsel'nokatanye zheleznodorozhnye kolesa. Izgotovlenie, ekspluatatsiya, vosstanovlenie, obespechenie nadezhnosti*]. Ed by S. N. Kiselev, Moscow, Pechat'-Servis-XXI vek publ., 2009, 265 p.

6. Grebenyuk, P.T., Dolganov, A.N., Skvortsova, A. I. Traction calculation. Directory [*Tyagovye raschety: Spravochnik*]. Ed by P. T. Grebenyuk, Moscow, Transport publ., 1987, 272 p.

7. State standard 1205–73 «Iron brake shoes for cars and tenders of broad gauge railways. Design and basic dimensions» [*GOST 1205–73 «Kolodki chugunnye, tormoznye dlya vagonov i tenderov zheleznyh dorog shirokoy kolei. Konstruktsiya i osnovnye razmery»*].

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