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DETERMINATION OF THE BRAKING CHARACTERISTICS IN CASE OF THE VARIATION DEPENDING ON THE TEMPERATURE OF THE MATERIAL PROPERTIES OF THE FRICTION COUPLING OF THE DISC BRAKE OF RAILWAY VEHICLES

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Abstract: *The safety of classic and high-speed rail vehicles depends on the mode of operation and the characteristics of their braking systems. Braking of railway vehicles (especially stopping braking) can be performed using brakes of the same system (for example, shoe brake or disc brake of the mechanical braking system) or by combining brakes of several systems (disc brake - mechanical braking system). mechanical, electromagnetic rail brake or resistive or regenerative electric brake - electric braking system). During stop braking, the friction elements of the main brake - the disc brake - reach quite high temperatures (especially when braking at high speeds: V > 160 km/h) which leads to the alteration of the physical- chemical and mechanical properties of the materials of these elements.*

This work presents the braking characteristics of railway vehicles (friction coefficient, braking space and deceleration when braking) in case of variation of the physical properties (specific heat and thermal conductivity) of the materials of the friction coupling elements of the railway. disc brake (friction pad and brake disc) as a function of temperature.

Key words: *Physical properties, Mechanical braking system, Pad, Brake disk, Brake stopping.*

1. INTRODUCTION

The determination method of the brake characteristics and the brake disk friction surface temperature, proposed by Hasselgruber [11-12], shows a series of deficiencies, such: physical properties of the friction coupling material elements (density, specific heat, thermal conductibility) were considered constant with temperature variation, fact which was not confirmed by the experimental trials done later on [2].

Taking into account these deficiencies, the author of this work considers the variation with temperature of the specific heat c_d , c_g and of the thermal conductibility λ_d and λ_g, of the disk and of the friction pad (*composite material*). Also, we consider a straight-line variation of the speed with period of braking at a brake stopping.

At the brake characteristics determination at a brake stopping with disk brake help, in this work were taken into account the next hypothesis:

- the vehicle speed varies straight-line depending on time at a brake stopping;
- the physical properties (specific heat and thermal conductibility) of the friction coupling material elements vary depending on temperature;
- the optimal time of braking was considered t_b= 60 s ,taking into account the brake spaces and decelerations admitted;
- the neglecting of the influence of the radiation and heat convection at brake stopping due to the small time of this;
- the densities of the materials from which are made the friction coupling elements were considered constant with temperature;
- the friction coefficient between the brake disk and friction pad (set) determined by the Karwatsky, [13], formula helping, for three pressure forces of the friction pad (set) on the disk: F_{b1} = 20 KN , F_{b2} = 45 KN , F_{b3} = 50

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KN, (Fb_2 force is the pressure force used in experimental testing, [2, 10];

- for brake characteristic calculation at brake stopping using the method proposed by the author were used the same types for friction coupling elements used in experimental trials (brake disk $\Phi \times b = 640 \times 110$ mm, friction pad Jurid 874 with friction surface 800 cm^2).

2. . MATERIALS AND METHODS

The physical properties of the friction coupling elements of the disk brake (*specific heat*, *thermal conductibility*) show a certain variation depending on temperature, and the nature of the structural constituents, fact which cannot be neglected at the brake characteristics determination of the disk brake and the friction surface temperature of the friction coupling elements.

As it was shown above, for highlight the according between the theoretical researches and those experimental, at brake characteristics calculation and of temperature, by the method proposed by the present work, were considered in calculation the same friction coupling material elements like those used in experimental trials namely:

- for the brake disk gray iron pearlite (Fc 250);
- for the friction pad a composite material JURID 874.

Theoretical and experimental researches shown in [15-16] demonstrate that the **density** (ρ) of the gray irons with a pearlite and ferritic matrix has a certain variation depending on temperature in high temperature range T > 1000° C (decreases straight-line from 1000° C to 1150° C, and pronounced increases to 1175° C and then decreases again straight-line over this temperature).

Taking into account that at a brake stopping from a speed of 200 km/h, in admitted deceleration limits, in 60 sec. time there are not temperature higher than 400° C of the disk brake friction surfaces, in calculation the density was considered constant ((ρ_d =7330 kg/m^3).

Concerning the friction pad material density, the experimental researches done by Ehlers, [13] put in evidence the next spreading range: ρ_g = (1000 - 2800) kg/m^3. Also, Ehlers established for the friction pad JURID 874, at a long brake a mass decrease almost negligible (0,5%) at temperatures under 150° C and an important decrease at temperature over 400° C. So, for the using friction pad, in calculation is used the density which was determined experimentally by Ehlers, shown in [13]: ρg = 2500 Kg/m^3.

Specific heat (c) of gray irons increase when the temperature increases (the transformation temperature $\alpha \rightarrow \gamma$ is about 720° C) (see [15-16]).

Choosing the gray iron like material for making the brake disk self-ventilated was done and because pearlite gray iron has the specific heat with approximates 60% higher than cast steel. This thing has a positive effect on the heat storage capacity of the brake disk made from gray iron.

Specific heat of the friction pad (*composite material*) was determined experimentally are shown in [15] this being bordering in spreading range: c_g = (628 - 2094) J/Kg·°C at temperature variation.

Using these specific heats of the friction coupling material elements (composite material), in specialty literature [15-16] were calculated the coefficients of the approximation polynomial of the functions: $c_d = f(T)$ şi $c_g = f(T)$, by the smallest squares method.

The coefficients of the approximation polynomial of m power:

$$c_1 + c_2 \cdot T_i + c_3 \cdot T_i^2 + \cdots + c_{m+1} \cdot T_i^m \qquad (1)$$

which approximates by the smallest squares method the points family (T_i, c_{di}) or (T_i , c_{gi}) i=1,.....,n, are obtained as solutions of the linear algebraic system:

$$\begin{cases} S_1 \cdot c_1 + S_2 \cdot c_2 + \cdots + S_{m+1} \cdot c_{m+1} = b_1 \\ S_2 \cdot c_1 + S_3 \cdot c_2 + \cdots + S_{m+2} \cdot c_{m+1} = b_2 \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ S_{m+1} \cdot c_1 + S_{m+2} \cdot c_2 + \cdot\cdot + S_{2m+1} \cdot c_{m+1} = b_{m+1} \end{cases} \qquad (2)$$

where:

$$S_k = \sum_{i=1}^{n} T_i^{k-1}, \quad k = 1, \dots, 2m+1$$

$$b_k = \sum_{i=1}^{n} cd_i \cdot T_i^{k-1} \; sau \; b_k = \sum_{i=1}^{n} cg_i \cdot T_i^{k-1} \;,\; k = 1, \ldots, m+1$$

Table 1 The approximation polynomial coefficients for specific heats

The polynomial approximation coefficients	**c_d = f (T) (m = 9)**	**c_g = f (T) (m = 9)**
c_1	533,988	$1{,}467\cdot10^{3}$
c_2	0,78761	-0,60434
c_3	- 0,00338	-0,03794
c_4	$5{,}736\cdot10^{-5}$	0,00117
c_5	$-9{,}814\cdot10^{-7}$	$-1{,}787\cdot10^{-5}$
c_6	$9{,}324\cdot10^{-9}$	$1{,}495\cdot10^{-7}$
c_7	$-5{,}065\cdot10^{-11}$	$-7{,}200\cdot10^{-10}$
c_8	$1{,}574\cdot10^{-13}$	$1{,}984\cdot10^{-12}$
c_9	0	$-2{,}90643415749037\cdot10^{-15}$
c_{10}	0	0

For a quick and exact solving of the linear system (2) it was used the utilitarian Mathcad.

By means of the coefficients which were determined and shown in table 1 we can write the approximation polynomial of the c_d = f (T) and c_g = f (T) functions.

$$cd_i = c_1 + c_2 \cdot T_i + c_3 \cdot T_i^2 + \cdots + c_{10} \cdot T_i^9$$

$$cg_i = c_1 + c_2 \cdot T_i + c_3 \cdot T_i^2 + \cdots + c_{10} \cdot T_i^9$$

In figures 1 and 2, there are represented the variation of the specific heat for the friction coupling material elements, for the range of temperature (0 - 350)° C, by means of cubic spline interpolation functions.

Analyzing the following figures we can observe a complete different variation with temperature of the specific heat for the two friction coupling materials (increasing carriage for the specific heat with temperature for the brake disk and a decreasing carriage for the specific heat with temperature for the friction pad material).

These variations of the specific heat have a large influence upon thermal regime of the friction surface of the friction coupling elements of the disk brake.

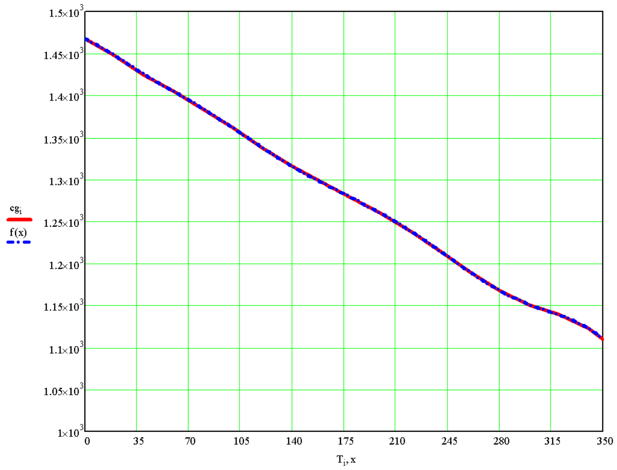

Figure 1. The variation of the friction pad material specific heat *vs*. the temperature.

Thermal conductibility (λ) of the gray irons is dependent both on metallic mass structure and on temperature. An important influence on gray iron thermal conductibility is given by the conductibility of the main structural constituents (pearlite, ferrite, graphite) and the aspects in which the graphite is in the structure (gray iron with flaked graphite has a larger thermal conductibility than gray iron with module graphite). on the gray iron thermal conductibility actuates even more the carbon content and the addition agent.

Thus, the increasing of the carbon content can produce a decreasing or an increasing of the thermal conductibility depending on the constituents, which of them are in advantage by this increasing.

For example, the increasing of the pearlite amount and cementite amount produces a decreasing of thermal conductibility, while the increasing of the graphite amount determines an increasing of the thermal conductibility.

The addition elements (silicon, mangan, aluminum, chrome, copper, nickel, tungsten, molybdenum, vanadium) have a different influence on thermal conductibility on determined temperature ranges [15] (silicon, mangan, aluminum, copper and nickel lead to a decreasing of the thermal conductibility).

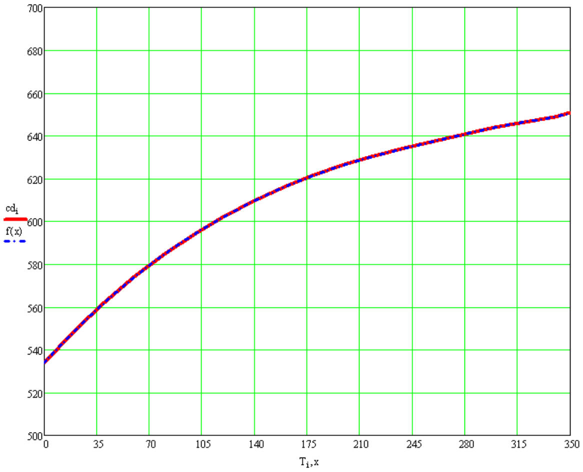

Figure 2. The variation of the disk brake specific heat *vs.* the temperature.

The thermal conductibility of the friction pad material (*composite material*) is framed at variation with temperature in the dispersion range: λ_g = (0,16282 - 1,01181) W/m·°C.

Using the thermal conductibility of the friction coupling material elements, for different temperatures, which are shown in specialty literature [15-19], were determined the approximation polynomial coefficients for the functions λ_d = f (T) and λ_g = f (T).using the smallest squares method.

The determination of the approximation polynomial coefficients is done using the next linear algebraic system (2), where:

$$S_k = \sum_{i=1}^{n} T_i^{k-1} \ , \quad k = 1\ , 2\ , ...\ , 2m+1$$

$$b_k = \sum_{i=1}^{n} \lambda d_i \cdot T_i^{k-1} \quad or \quad b_k = \sum_{i=1}^{n} \lambda g_i \cdot T_i^{k-1} \qquad k = 1\ , 2\ , \ ...\ , m+1$$

m = approximation polynomial power

By helping Mathcad computer program, were determined the values of the approximation polynomial coefficients, which are shown in table 2:

Table 2 The approximation polynomial coefficients for thermal conductibility

The approximation polynomial coefficients	λ_d = f (T) (m = 8)	λ_g = f (T) (m = 9)
c_1	49,988	0,88662
c_2	0,19636	0,00434
c_3	- 0,00301	$-2{,}533 \cdot 10^{-5}$
c_4	$1{,}496 \cdot 10^{-5}$	$-5{,}661 \cdot 10^{-7}$
c_5	$- 1{,}006 \cdot 10^{-7}$	$9{,}630 \cdot 10^{-9}$
c_6	$6{,}129 \cdot 10^{-10}$	$-6{,}692 \cdot 10^{-11}$
c_7	$-1{,}773 \cdot 10^{-12}$	$2{,}403 \cdot 10^{-13}$
c_8	$2{,}086 \cdot 10^{-15}$	0
c_9	0	0
c_{10}	0	0

In figures 3 and 4 there are shown the thermal conductibility variation for friction coupling material elements for the noted temperature ranges, using the cubic spline interpolation functions.

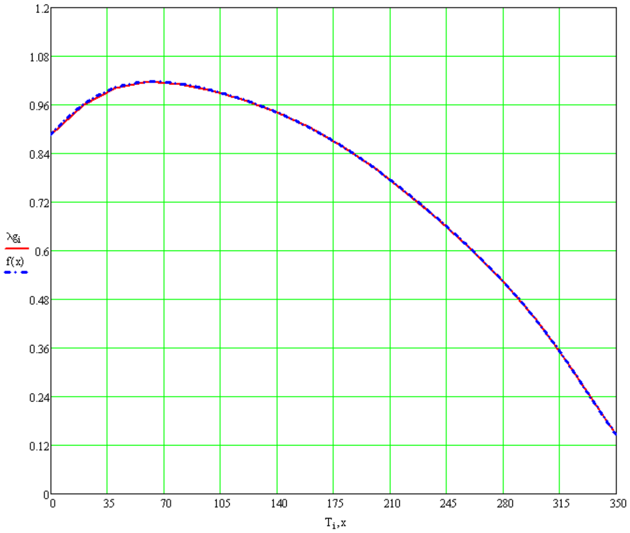

Figure 3. The variation of the friction pad thermal conductibility *vs.* the temperature

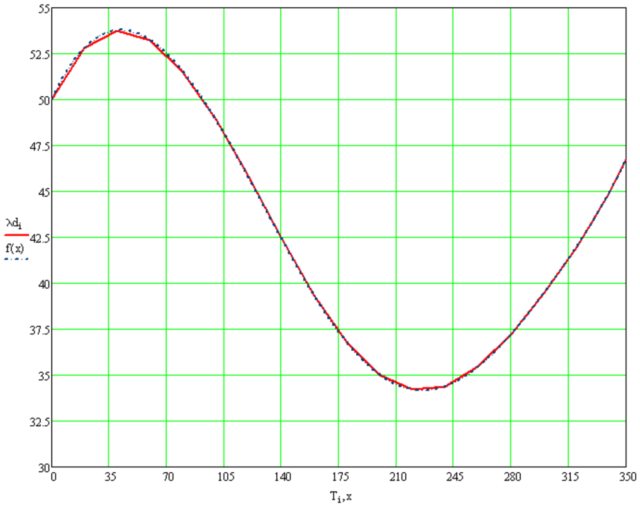

Figure 4. The variation of the brake disk material thermal conductibility *vs.* the temperature.

We can observe that there are different variations of the thermal conductibility depending on temperature, and this can lead at a variation of the material factor (f_m) depending on temperature with influences on thermal regime of the friction surfaces of the brake disk elements.

3. RESULTS AND DISCUSSIONS

The specific head and the thermal conductibility of the friction coupling material elements vary many with the temperature; this thing influences the brake characteristics and the value of the average temperature of the friction surfaces of the brake disk and of the friction pad.

Material factor f_m [10-12] which is considered constant with temperature it was reconsidered, keeping in to account of the modification of the specific heat (c) and of the thermal conductibility (λ) depending on temperature. Thus, the material factor f_m is not any longer constant with temperature but depended on it. The calculation relation of this is next:

$$f_m(T) = \frac{2}{1 + \frac{\sqrt{\rho g \cdot cg(T) \cdot \lambda g(T)}}{\sqrt{\rho d \cdot cd(T) \cdot \lambda d(T)}}} \quad (3)$$

where: c_g (T) , c_d (T) are the variation laws of the friction pad material (*composite*) specific heat and of the brake disk depending on temperature;

λ_g(T) , λ_d(T) are the variation laws of the friction pad material (*composite*) thermal conductibility and of the brake disk depending on temperature;

ρ_g , ρ_d are the densities of the friction pad material (*composite*) and of the brake disk consider constant depending on temperature variation.

Using relation (3) and the variation laws of the physical properties depending on temperature were determined de values for the material factor, for the temperature range (0 - 350)° C, shown in table 3, and in diagram in figure 5 it was represented the variation of this factor depending on temperature.

Table 3. The material factor values

Temperature [°C]	**Material factor f_m [dimensionless]**
0	1,7675546671
20	1,7692311740
40	1,7707183180
60	1,7718700944
80	1,7724014406
100	1,7721022945
120	1,7709978086
140	1,7695004282
160	1,7684867293
180	1,7692154797
200	1,7730164523
220	1,7807997443
240	1,7926605546
260	1,8079457788
280	1,8258685995
300	1,8463290917
320	1,8704250923
340	1,8999820460
350	1,9168198656

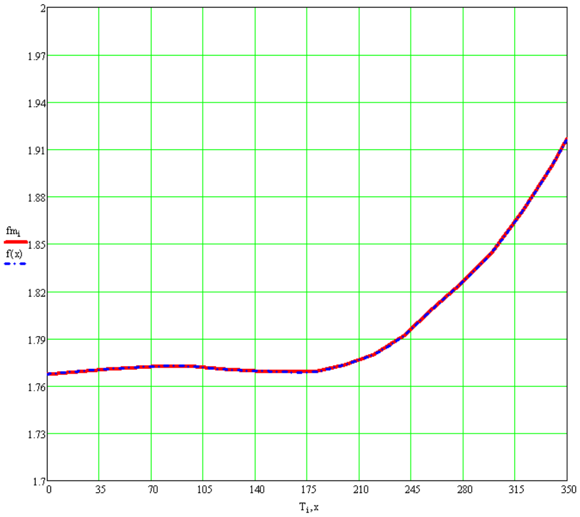

Figure 5 The variation of the material factor *vs*. the temperature

Having into account the experimental trials done with high speed trains shown in: [2, 3, 4, 12], it came out that at a brake stopping from the maximum speed, the train speed decreases approximate straight-line depending on time (brake time), thus, we can consider that the high speed train at a brake stopping performs an uniform deceleration motion, at which: V = a·t, where a = deceleration (constant).

If the speed at the beginning of the brake stopping is V = 200 Km/h and brake time t_b = 60 s, using the Mathcad computer program, were calculated the coefficients of the approximation polynomial for the function V = f (t) by the smallest squares method, and in figure 6 is represented this function using de cubic spline interpolation functions.

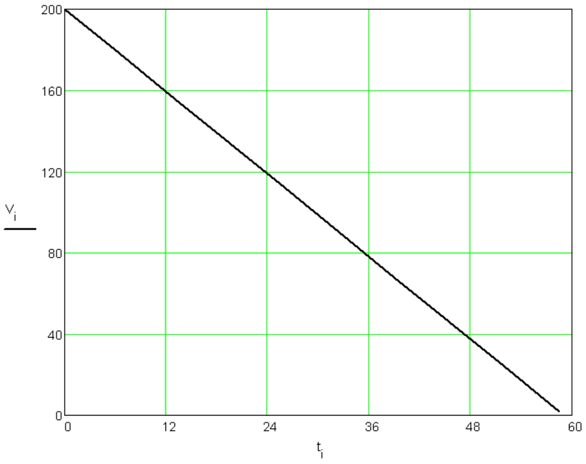

Figure 6. The variation of the circulation speed *vs.* the brake time

The brake space according with V (t) variation is given by relation:

$$Sf = \frac{3{,}93 \cdot (1+\gamma)\cdot V^2(t)}{g \cdot \mu s(t) \cdot \delta + rt} + \frac{V(t)\cdot tu}{7{,}2} \quad [\mathrm{m}] \qquad (4)$$

where: (1+γ) = a factor which take into account the revolving masses of the vehicle (in calculation 1+γ = 1,05);

g = gravity acceleration (it in calculation it is considered g = 9,80665 m/s^2);

δ = brake coefficient (in calculation δ = 0,35);

tu = time for filling the brake-cylinder with compressed air (in calculation tu = 4 s);

rt = specific train resistance of the considered vehicle (in calculation rt = 20 N/KN);

μ_s = friction coefficient between brake disk and friction pad (set).

For the determination of the brake space with relation (4) it was calculated with Karwatsky's formula, [13], the friction coefficient between brake disk and friction pad (set) for different pressure forces of the pad on the disk:

$$\mu s(t) = 0{,}1177 \cdot \frac{Fb + 200}{Fb + 80} \cdot \frac{V(t) + 171{,}8}{V(t) + 105} \qquad (5)$$

The values of the friction coefficient and of the brake space calculated for three different pressure forces (F_b = 20 KN, F_b = 45 KN and F_b = 50 KN) are presented in table 4.

Table 4 The values of the friction coefficient and of the brake space for different pressure forces of the friction pad (set) on the brake disk.

F_b = 20 KN

Speed V [Km / h]	**Friction coefficient μ_s**	**Brake space S_f [m]**
0	0,42214618	0
20	0,39603319	23,078
40	0,37712378	72,453
60	0,36279848	150,745
80	0,35157053	259,733
100	0,34253341	400,671
120	0,33510288	574,464
140	0,32888550	781,785
160	0,32360660	1023,144
180	0,31906859	1298,932
200	0,31512573	1609,457

Fb = 45 KN

Speed V [Km / h]	**Friction coefficient μ_s**	**Brake space S_f [m]**
0	0,37609387	0
20	0,35282957	24,519
40	0,33598301	78,498
60	0,32322046	164,867
80	0,31321738	285,613
100	0,30516612	442,138
120	0,29854620	635,453
140	0,29300708	866,309
160	0,28830406	1135,276
180	0,28426111	1442,791
200	0,28074838	1789,198

Fb = 50 KN

Speed V [Km / h]	**Friction coefficient μ_s**	**Brake space S_f [m]**
0	0,36900890	0
20	0,34618286	24,772
40	0,32965366	79,560
60	0,31713153	167,346
80	0,30731690	290,158
100	0,29941731	449,418
120	0,29299210	646,160
140	0,28748733	881,148
160	0,28287290	1154,961
180	0,27890611	1468,045
200	0,27545955	1820,749

Using the values calculated, in figures 7 and 8 are shown the variations of the friction coefficient depending on speed and the variation of the brake space depending on speed for the three pressure forces presented before:

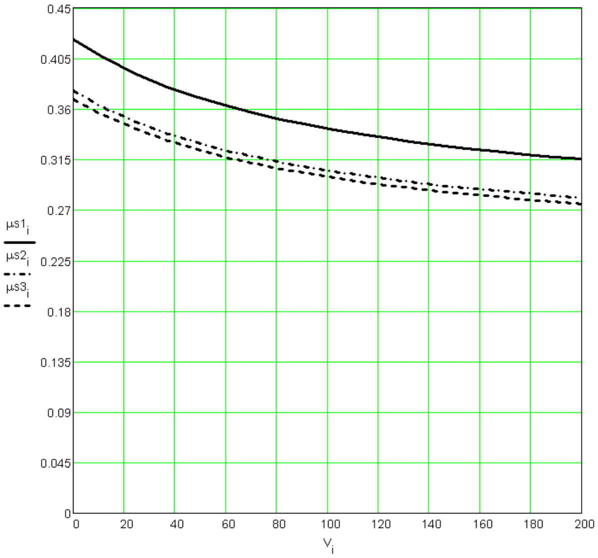

Figure 7. The variation of the friction coefficient between the brake disk and friction pad *vs*. the speed.

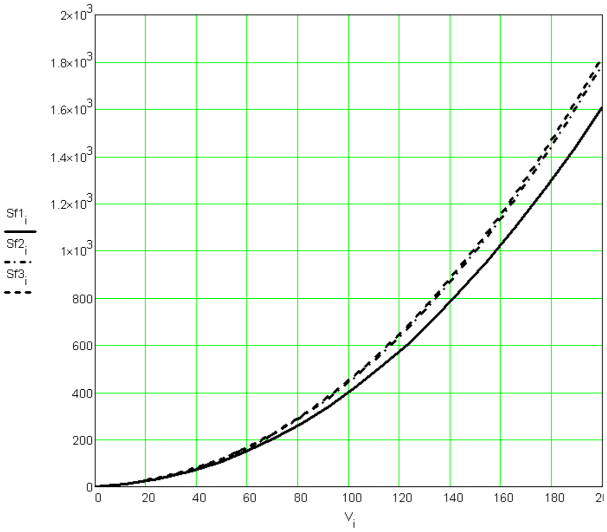

Figure 8. The variation of the brake space *vs*. the speed.

The decelerations which were used for getting these brake spaces, at a straight- line variation of the speed depending on time, are determined with relation:

$$a=\frac{\left(\frac{V(t)}{3,6}\right)^2}{2\cdot Sf}\qquad [\mathrm{m/s^2}] \qquad (6)$$

The deceleration values for the three pressure forces of the friction pad on the brake disk are presented in table 5.

Table 5. The deceleration values for the pressure forces

Speed V [Km / h]	**Deceleration a [m / s^2]**		
	F_b = 20 KN	**F_b = 45 KN**	**F_b = 50 KN**
0	0	0	0
20	0,668696	0,629382	0,62295
40	0,851978	0,78636	0,775866
60	0,921351	0,84243	0,829946
80	0,950643	0,864502	0,850962
100	0,962891	0,872583	0,858447
120	0,967085	0,874267	0,859779
140	0,962738	0,872867	0,858167
160	0,965314	0,869969	0,855141
180	0,962329	0,866377	0,851473
200	0,958839	0,862515	0,847569

Using the values from the table 5, in figure 9, are shown the brake decelerations for the three pressure forces of the brake pad (set) on the brake disk.

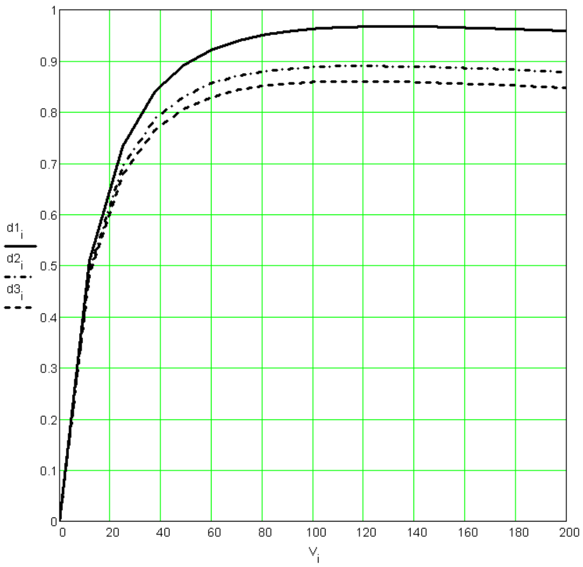

Figure 9. The variation of the brake deceleration *vs*. the speed

4. CONCLUSIONS

From the data analysis of the tables and diagrams presented in this work result the next conclusions:

- For the determination of the brake characteristics (friction coefficient between the friction coupling elements, brake space, brake deceleration) and of the brake disk and friction pad (set) friction surfaces average temperatures we must consider the variation depending on temperature of the physical properties of the materials which are used for the brake disk and friction pad (in disk brake case: friction pad-brake disk);

- Having in to account the experimental trials done with high speed trains shown in specialty literature, [2, 3, 4, 12], it was found that at a brake stopping from a maximum speed, the trains speed decreases almost straight-line depending on time (brake time), thus, we can consider that the high speed train, at a brake stopping executes an uniform deceleration motion, at which $V = a \cdot t$ where a = deceleration (constant);

- The material densities from which are manufactured the elements of the friction coupling (gray iron Fc 250, for disk and a ***composite material*** JURID 874 for friction pad) were considered constant with temperature range: 0 - 350° C, these vary insignificant with temperature;

- Using the values of the specific heat and of the thermal conductibility of the friction coupling material elements, for different temperatures, presented in specialty literature: [15-16], were determined the approximation polynomial coefficients for the functions: c_g (T) , c_d (T), $\lambda_d = f(T)$ and $\lambda_g = f(T)$, using the smallest squares method, and the graphic representation of these variations was done by the cubic spline interpolation functions;

- Analyzing the diagrams from figures 1 and 2 we can observe a complete variation different with temperature of the specific heat for the two materials of the friction coupling elements (the increasing allure with temperature of the brake disk material specific heat and a decreasing allure of the friction pad material specific heat), having a large influence upon brake characteristics and of the thermal regime of the brake disk and friction coupling elements friction surface;

- Material factor f_m [10-12] considered constant with temperature was reconsidered in this work, keeping in to account of the modification of the specific heat (c) and of the thermal conductibility (λ) depending on temperature (factor f_m is not constant any more with temperature but depending on this);

- We observe (see figure 8) that when we increase the pressure force of the friction pad on the brake disk, deceleration decrease (at 180 km/h and F_b = 20 kN, deceleration has d = 0,962329 m/s^2 value, and for F_b = 45 kN, deceleration decrease at d = 0,866377 m/s^2 value), situation which leads at a increasing of the brake space (from S_f = 1298,932 m to S_f = 1442,791 m) and to a thermal regime more “tolerable” for the elements of the friction coupling of the disk brake (friction pads and brake disk);

- Result, thus, the fact that the variation depending on temperature of the physical properties of the friction coupling material elements influences the brake characteristics of the disk brake, direct, by the friction coefficient obtained at certain speeds at the beginning of the brake, and, indirect, by the expression of this coefficient in the calculation relation of the brake space (for example: at a speed at the beginning of the brake of 200 km/h and a pressure force F_b = 45 kN, we obtain a friction coefficient μ_s = 0,28074838, which decreases at de value of μ_s = 0,27545955, at a bigger pressure force F_b = 50 kN, by cause of the high level for the temperature which is on the friction surface of the friction coupling elements of the disk brake).

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Determinarea caracteristicilor de frânare în cazul variației cu temperatura a proprietăților materialelor cuplei de frecare a frânei cu disc a vehiculelor feroviare

Rezumat

Siguranța circulației vehiculelor feroviare clasice și de mare viteză depinde de modul de funcționare și caracteristicile sistemelor de frânare ale acestora. Frânarea vehiculelor feroviare (în special frânarea de oprire) se poate face utilizând frâne din același sistem (de exemplu frâna cu saboți sau frâna cu disc din sistemul mecanic de frânare) sau combinând frâne din mai multe sisteme (frâna cu disc-sistemul mecanic, frâna electromagnetică pe șinăsau frâna electrică rezistivăsau recuperativă – sistemul electric de frânare). În timpul frânării de oprire elementele cuplei de frecare ale frânei principale – frâna cu disc, ating temperaturi destul de mari (în special la frânarea de la viteze mari V > 160 km/h) care conduc la alterarea proprietăților fizico-chimice și mecanice ale materialelor acestor elemente.

În această lucrare se prezintă caracteristicile de frânare ale vehiculelor feroviare (coeficientul de frecare, spațiul de frânare și decelerația la frânare) în cazul variației proprietăților fizice (caldura specifică și conductibilitate termică) ale materialelor elementelor cuplei de frecare ale frânei disc (disc de frână - plăcuță de frecare) cu temperatura.

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