MODELING THERMAL EFFECTS IN BRAKING SYSTEMS OF RAILWAY VEHICLES

by

Miloš S. MILOŠEVIĆ*, Dušan S. STAMENKOVIĆ, Andrija P. MILOJEVIĆ, and Miša M. TOMIĆ

Faculty of Mechanical Engineering, University of Niš, Niš, Serbia

Original scientific paper
DOI: 10.2298/TSCI120503188M

The modeling of thermal effects has become increasingly important in product design in different transport means, road vehicles, airplanes, railway vehicles, and so forth. The thermal analysis is a very important stage in the study of braking systems, especially of railway vehicles, where it is necessary to brake huge masses, because the thermal load of a braked railway wheel prevails compared to other types of loads. In the braking phase, kinetic energy transforms into thermal energy resulting in intense heating and high temperature states of railway wheels. Thus induced thermal loads determine thermomechanical behavior of the structure of railway wheels. In cases of thermal overloads, which mainly occur as a result of long-term braking on down-grade railroads, the generation of stresses and deformations occurs, whose consequences are the appearance of cracks on the rim of a wheel and the final total wheel defect. The importance to precisely determine the temperature distribution caused by the transfer process of the heat generated during braking due to the friction on contact surfaces of the braking system makes it a challenging research task. Therefore, the thermal analysis of a block-braked solid railway wheel of a 444 class locomotive of the national railway operator Serbian Railways is processed in detail in this paper, using analytical and numerical modeling of thermal effects during long-term braking for maintaining a constant speed on a down-grade railroad.

Key words: *railway, braking, block-braked solid wheel, thermal load, friction generated heat*

Introduction

Thermal analysis is involved in almost every kind of physical processes and it can be the limiting factor for many processes. Therefore, its study is of vital importance, and the need for powerful thermal analysis tools is virtually universal. Furthermore, thermal effects often appear together with, or as a result of, other physical phenomena.

The modeling of thermal effects has become increasingly important in product design including areas such as electronics, automotive, aerospace, railway (*e. g.* wheel and rail rolling contact, braking systems, and so on), medical industries, *etc*. Computer simulation has allowed engineers and researchers to optimize process efficiency and explore new designs, while at the same time reduce costly experimental trials.

* Corresponding author; e-mail: mmilos@masfak.ni.ac.rs

The finite element method (FEM) has become the preferred method in performing thermal analysis on many systems and processes in recent years [1]. There is a statement that thermal analysis is mostly performed using the finite element method, as this method has become a powerful tool for the numerical solutions of a wide range of engineering problems and dominates the methods of analysis [2]. With the advances in computer technology and computer aided design (CAD) systems, complex problems can be modeled relatively simply.

A FEA thermal analysis is a finite element analysis that looks at how heat affects certain materials and engineering designs. This heat can come in the form of an environmental load such as an ambient temperature of a certain degree affecting a model, or due to friction in a system, effectively converting it into thermal energy. It can also come from processes of conduction through two solids, convection between a liquid and a solid, or radiation such as in space. A thermal analysis is a great way to test a model before the model is built and real world tested in a thermal chamber. It can reduce the time to test a design by weeks, allowing for several redesigns and improvements to be made in the meantime.

Precise prediction of the maximum temperature is needed for the design of many systems [3], as well as braking systems [4], especially for both discs and linings. How to handle the high speed spinning of discs is the point of the heat/structure coupled analyses [5].

Transient thermal analyses determine temperatures and other thermal quantities that vary over time. The variation of temperature distribution over time is of interest in many applications such as cooling of electronic packages [6] or quenching analysis for heat treatment [7]. Also of interest are the temperature distribution results in thermal stresses that can cause failure [8]. In such cases, the temperatures from a transient thermal analysis are used as inputs to a structural analysis for thermal stress evaluations [9]. Heat generation controlling is a prerequisite for qualitative weld creation during the friction stir welding process, and it is important to have an adequate mathematical model that is capable of estimating heat generation with satisfying accuracy [10].

Thermal analysis is the primary stage in the study of braking systems, because the temperature determines the thermomechanical behavior of the structure. In the braking phase, kinetic energy transforms into thermal energy, resulting in intense heating of the railway wheel. This generates stresses and deformations, whose consequences are manifested by the appearance and the accentuation of cracks on treads of wheel, and eventually fractures of the whole wheel [11].

In recent years, many researches have been done on possibilities of predicting the thermal overload based on the characteristics of trains and rail-roads, especially on long-term braking on down-grade railroads on which trains run. Having concluded their research [12-15], the European Rail Research Institute ERRI proposed a valuation procedure, with the ultimate goal of making a decision on taking special measures to prevent the occurrence of thermal overload. This implies the application of the regulation, alternating brake or other measures, related to regime change and drive train formation. However, the proposed procedure, which involves calculating the coefficient for the particular estimation, does not provide an efficient and reliable use in all potential cases, particularly those relating to the long-term braking of the train at a very long fall with the changing slope. Therefore, the research for the improvement of the thermal overload assessment process continues. Preliminary works in this area have pointed out the problem of insufficient accuracy of the estimation coefficient. That was specifically expressed in conditions of running trains on Serbian railways with long fall parts (*e*. *g*. railway Belgrade-Bar) [16, 17].

Many research results have confirmed the dominant influence of thermal loads in regard to mechanical loads [12, 14, 18-20] and residual stresses induced by high thermal loads in block-braked solid wheel have been registered [21, 22]. Therefore, it is important to determine with high precision the temperature field of the braking system, as well as to emphasize that high thermal loads, in other words, overloads, of wheel very often occur as a result of long-term braking on down-grade railroads or unwanted locking of wheels. Those are the main goals of this paper which presents the results of a thermal analysis of a braking system of railway vehicles using analytical and numerical modeling of thermal effects during long-term braking for maintaining a constant speed on a down-grade railroad in order to analyze damages of solid wheels braked by blocks, especially on railway vehicles of national railway operator Serbian Railways.

Analytical modeling of thermal effects of a braking system of railway vehicles

To simulate a process of braking of railway vehicles it is necessary to define an analytical model of a thermal analysis that describes the heating transfer of the heat generated by friction at surfaces which are in contact, between a railway wheel and braking blocks, through the wheel and blocks, as well as heat outflow of the whole braking system due to cooling of the surrounding air. For those purposes, an analytical model for analyzing thermal effects in braking systems of passenger cars [23] was utilized and its adopted procedure is presented in this paper for a braking system of railway vehicles.

The thermal analysis of the braking system of railway vehicles requires a precise determination of the quantity of heat produced by friction, as well as the distribution of this energy between the railway wheel and the braking blocks. When the braking process occurs, blocks and railway wheel are in a sliding contact. The resulting force resists the movement so the train slows down or eventually stops. The friction between the wheel and blocks always opposes motion and the heat is generated due to conversion of the kinetic energy. However, the whole braking system is exposed to the enlarged air flow for high speed braking and the heat is dissipated.

The heat flux evacuated of surfaces in contact (between blocks and railway wheel) is equal to the power friction. The heat power generated per unit contact area at the radius *r* of the wheel can be calculated by the following equation:

$$q(r) = -f_f r\omega \tag{1}$$

where f_f is the friction force per unit contact area, and ω – the angular velocity of the railway wheel. In the following considerations, it is not the case of where the wheel rotates, but of the heat source.

The friction force per unit contact area can be calculated as:

$$f_f = \frac{\mu F_N}{A} \tag{2}$$

where μ is the friction coefficient, F_N – the normal braking force on one of the braking blocks, and *A* – the area of the contact surface between one braking block and the railway wheel.

The wheel and blocks dissipate the heat produced at the boundary between the braking blocks and the wheel by convection and radiation. The model also includes heat conduction through the blocks and the wheel by the transient heat transfer equation:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla(-k\nabla T) = Q - \rho C_p u \nabla T \tag{3}$$

where for materials of the wheel and the blocks ρ is the density, k represents the thermal conductivity, C_p is the specific heat capacity, u – the velocity field, and Q – the heating power per unit volume, which in this case is set to zero. The velocity field u involves all the points on the wheel with their local velocities of the heat transfer:

$$\vec{v}_d = \omega \vec{r} \tag{4}$$

where $\vec{r}$ is the position vector of the considered point.

At the contact surface between the wheel and the blocks, the braking process produces heat according to expression (1). The heat dissipation from the free surfaces of the wheel and blocks to the surrounding air is described by both convection and radiation:

$$q_{diss} = -h(T - T_{ref}) - \varepsilon\sigma(T^4 - T_{ref}^4) \tag{5}$$

In this equation, h equals the convective film coefficient, ε is the material's emissivity, σ – the Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}$), and T_{ref} – the temperature of the surrounding air.

To calculate the convective film coefficient as a function of the railway vehicle velocity v, the following formula should be used:

$$h = \frac{0.037k_a}{2r}\mathrm{Re}^{0.8}\mathrm{Pr}^{0.33} = \frac{0.037k_a}{2r}\left(\frac{2\rho_a r v}{\mu_{va}}\right)^{0.8}\left(\frac{C_{pa}\mu_{va}}{k_a}\right)^{0.33} \tag{6}$$

Here, material properties: thermal conductivity k_a, density ρ_a, viscosity μ_{va} and specific heat capacity C_{pa}, are given for the surrounding air.

Numerical modeling of thermal effects of a braking system of railway vehicles

As stated in the Introduction, high thermal loads of railway wheels very often occur as a result of a long-term braking for the maintenance of constant train velocity on down-grade railroads. For analyzing the process of braking, it is very useful to use FEM simulations based on the adopted and presented analytical model for defining heat sources at surfaces which are in contact with blocks, and to define the simultaneous heat inflow from friction (a part of heat transferred to the wheel rim) and heat outflow due to cooling at the segments of the surface, which are not in contact. In COMSOL Multiphysics the Heat Transfer Module (Heat Transfer in Solids) is used to carry out transient thermal analysis. The Module supports all fundamental mechanisms including conductive, convective and radiative heat transfer. Using the physics interfaces in this Module along with the inherent multiphysics capabilities of COMSOL Multiphysics, the transient thermal analysis was preformed, and the temperature fields of a railway wheel during long-term braking with different braking conditions were determined.

The thermal analysis was performed for braking a 444 class locomotive of the national railway operator Serbian Railways, that ran with three different velocities (20 km/h, 40 km/h and 60 km/h). The duration of the braking was t = 300 s for all cases. For each braking, there were two regimes, with low ($3.36 \cdot 10^5$ Pa) and high pressure ($7 \cdot 10^5$ Pa) in the braking cylinders. That made, in total, 6 different cases of braking that were analyzed. In the low pressure regime of braking, the normal braking force on one braking block was F_N = 20379 N and, with the high pressure, the normal braking force was F_N = 37162 N. These forces were introduced in the analysis throughout equations (1) and (2). The intermediate radius for the chosen locomotive wheel was r = 625 mm, the contact surface area between the braking block and the wheel was A = 19577 mm^2.

The coefficient of friction has significant effects on the form of the thermal field, as well as on temperature distribution. The proper definition of the coefficient of friction is very important for perception of temperature field qualities for analyzing thermal effects in braking systems at locomotives wheels. The value of the coefficient of friction depends on a number of tribological parameters such as speed of relative movement of parts in contact, the contact surface roughness, quality of materials of a tribo-pair, temperature of contact pars and so on [24, 25]. However, this paper did not consider tribological parameters of braking processes so the value $\mu = 0.115$ of the friction coefficient for materials of the block and the wheel was taken as the recommended value [26]. Moreover, the included computation did not take into consideration the dependence of wheel and block material characteristics on temperature changes. The numerical modeling of thermal effects was performed according to the following procedure in COMSOL Multiphysics.

Geometrical model

First, the 3-D model of the railway wheel and braking blocks (fig. 1) was created using the software package SolidWorks. The model was than imported in the COMSOL environment.

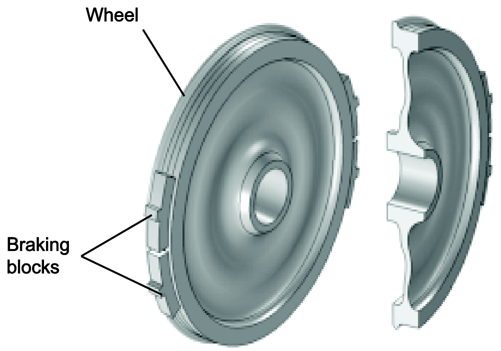

Figure 1. The solid model of the block-braked solid wheel assembly

Definition of materials

The material of the railway wheel is steel DIN 40Mn4 (AISI 1039, JIS S40C, Č3130) and of the braking blocks is gray cast iron P10. Table 1 summarizes the thermal properties of these materials; the density of air at a reference temperature of 300 K was calculated using the ideal gas law.

Table 1. Material properties

Property	Railway wheel	Braking block	Air
ρ [kgm^{-3}]	7850	7200	1.170
C_p [J kg^{-1}K^{-1}]	486	510	1100
k [W m^{-1}K$^{-1]}$	52	45	0.026
ε	0.28	0.31	–
μ_{va} [Pa·s]	–	–	1.8·10^{-5}

Meshing

In the finite element analysis the basic concept is to analyze the structure, which is an assemblage of discrete pieces called elements, which are connected, together at a finite number of points called nodes. A network of these elements is known as a mesh. For this analysis, automatic mesh generating capabilities were used in COMSOL rather than defining the nodes individually (fig. 2). The finite elements used for the meshing were Free Tetrahedral. The number of generated elements in the mesh was 68771.

Definition of the boundary conditions

After completion of the finite element model, it was necessary to apply constraints and loads to the model. The analyzed railway wheel with braking blocks was subjected to the following thermal loads:

- boundary heat source for the surface that was in contact between the wheel and one braking block (fig. 3), $q(r)$ (eq. 1),
- heat transfer by convection (heat flux) for surfaces of braking blocks and railway wheel that were not in contact (surrounded by air) (eq. 5),
- surface to ambient radiation for surfaces of braking blocks and railway wheel that were not in contact (eq. 5), and
- translational motion that made it possible to model rotational movement of a heat source by local translational velocities of heat transfer (eq. 4).

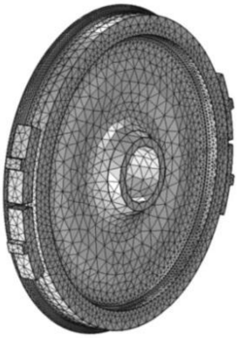

Figure 2. The meshed model of the block-braked solid wheel assembly

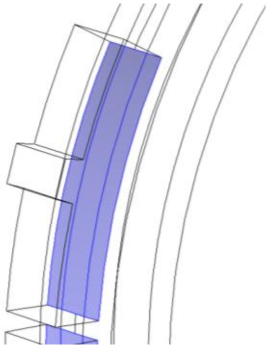

Figure 3. The contact surface between the wheel and one braking block

Solving

After verification of the model and boundary conditions, the calculation was started for the time of braking t = 300 s, in order to maintain a constant train velocity. The time dependent solver was used for solving. The number of degrees of freedom that was solved was 109453. The calculation time was approximately 3 minutes.

Results of thermal analysis of the braking system of the 444 class locomotive

The diagrams of the temperature distribution for the examined wheel of the 444 class locomotive of the national railway operator Serbian Railways at the moment t = 300 s of the braking process are shown in Figure 4 for the researched different braking regimes. The highest temperatures were reached at the contact surfaces wheel-blocks.

In order to determine the positions of areas with maximal temperatures, it was helpful to plot diagrams of temperature distribution versus time along with the wheel radius. The diagrams are displayed in fig. 5.

According to diagrams of the temperature distribution (figs. 4 and 5), tab. 2 is made in order to summarizethe values of maximal temperatures of the points at the wheel rim at the end of the simulation for all examined cases.

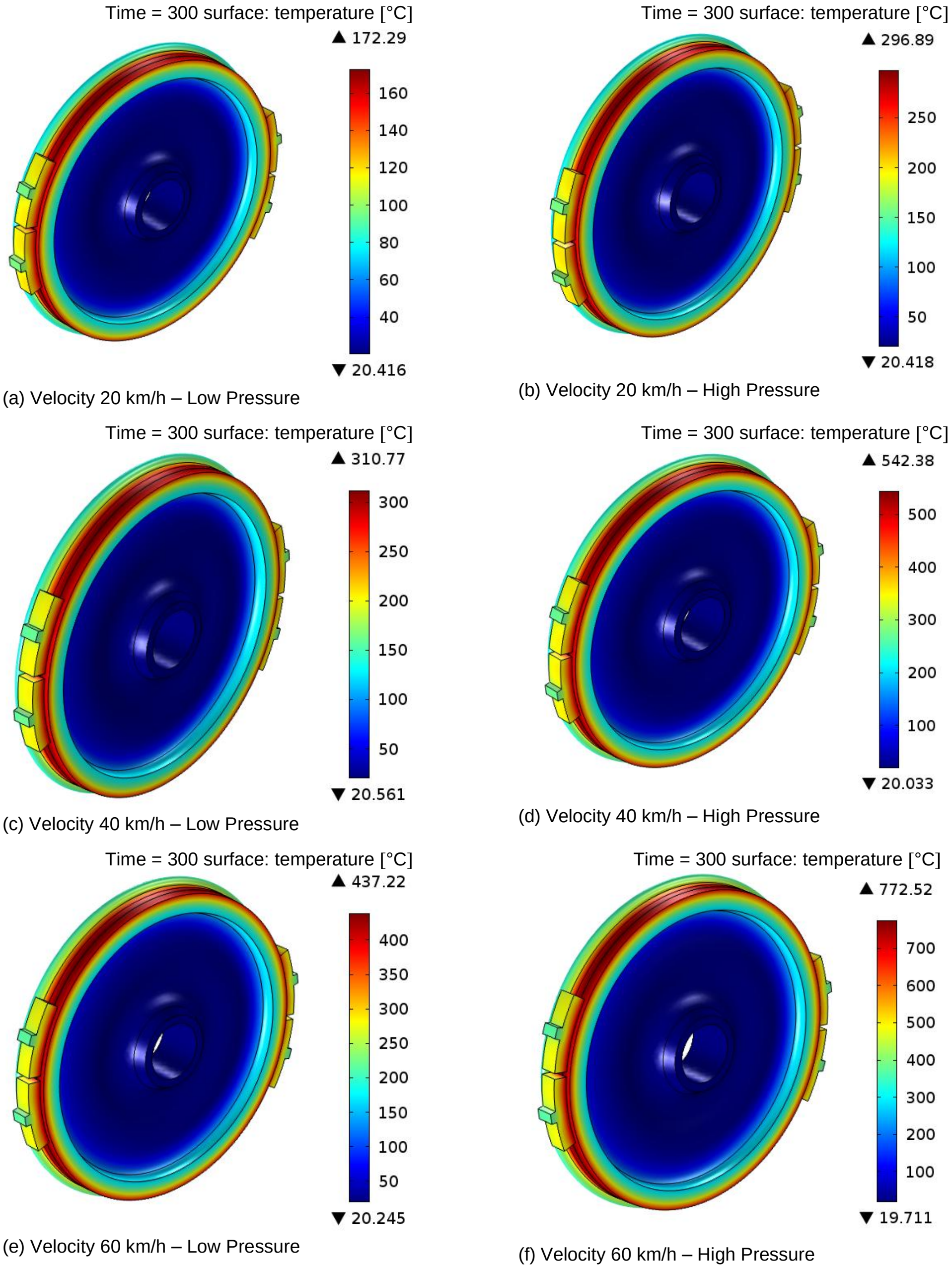

Figure 4. The temperature distribution at the wheel after *t* = 300 s

Table 2. Maximal temperatures at the wheel rim after *t* = 300 s

Braking regime	Low pressure			High pressure		
Locomotive velocity [kmh^{-1}]	20	40	60	20	40	60
Temperature [ºC]	172.29	310.77	437.22	296.89	542.38	772.52

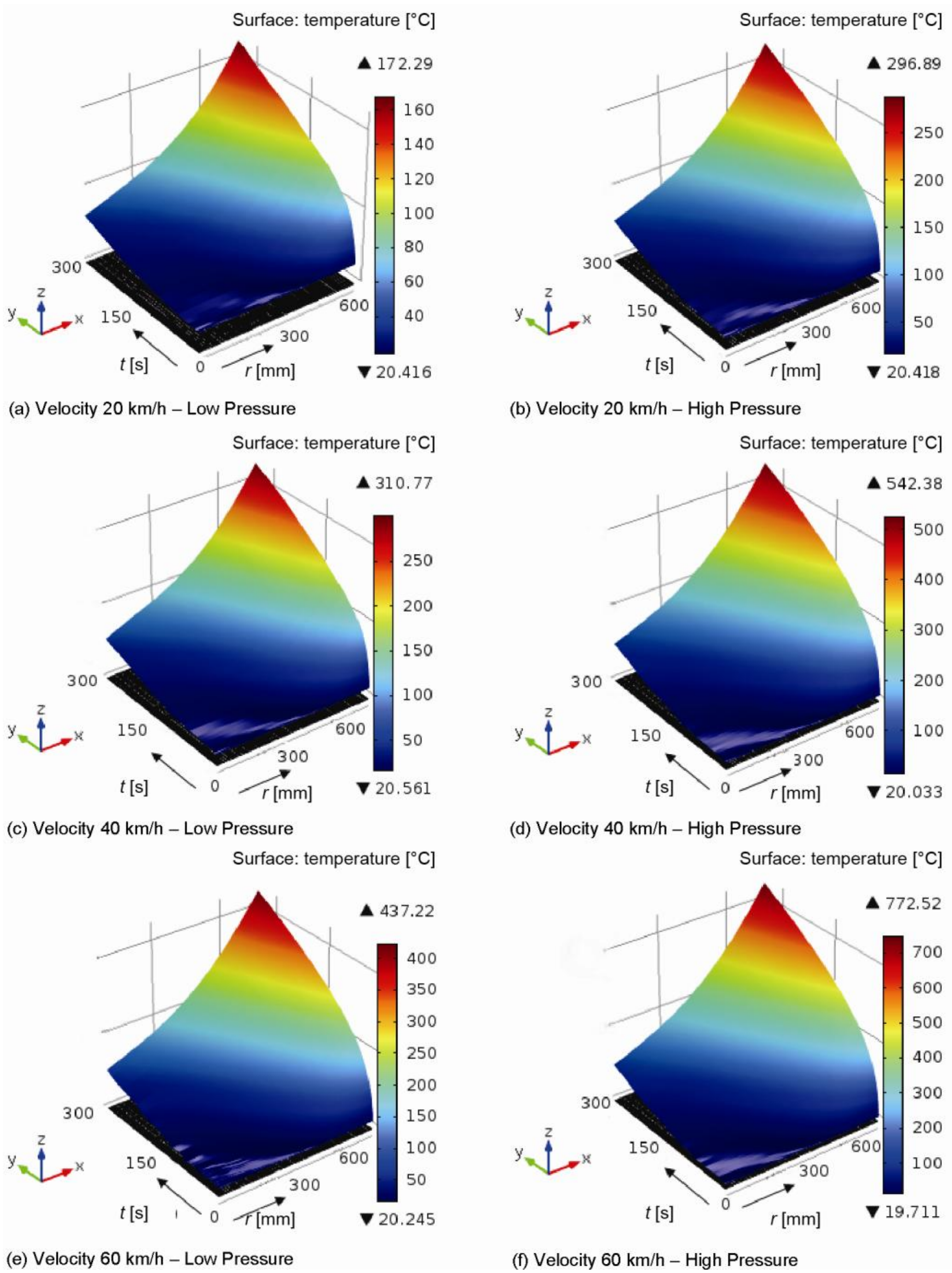

Figure 5. The temperature distribution at the wheel in function of time and wheel radius

On the basis of the obtained results it can be concluded that the ratio of maximum temperatures for low and high pressure braking regimes is approximately constant with the mean value of 1.74 (tab. 3). With this derived conclusion, if at a specific locomotive velocity at conditions of the low pressure braking regime the maximum wheel temperature is known, then at the same velocity, under the condition of the high pressure braking regime, the corresponding maximum temperature can be obtained by multiplying the low pressure maximal wheel temperature with the factor of 1.74.

Table 3. The ratio of maximum temperatures for low and high pressure braking regimes

Locomotive velocity [kmh^{-1}]	20	40	60
Ratio value $[-]$	$\frac{296.89}{172.29}=1.72$	$\frac{542.38}{310.77}=1.74$	$\frac{772.52}{437.22}=1.76$

Furthermore, the wheel rim is considered to be under transient heating and steady state cooling.

The intention of this research is based on the adaptation of a model for analyzing the heat generation in disc brakes of vehicles to the braking conditions of railway vehicles. The use of the adapted model is processed in detail in this paper on a very specific and concrete example of the thermal analysis of a block-braked solid railway wheel of a 444 class locomotive of the national railway operator Serbian Railways, using analytical and numerical modeling of thermal effects during long-term braking for maintaining a constant speed on a down-grade railroad. Obtained computational results of the temperature distribution are by their character very similar to the computational and measurement results published in the report ORE B 169/RP1 [27], and the calculation and experimental results of the research considering the analyzing of the wheel thermal load during down-grade running on the network line Belgrade-Podgorica [16]. Namely, depending on the position of the brake block in relation to the wheel rim, for equivalent data for the amount of generated heat power and heat transfer coefficients, comparable values for the data of the maximum temperatures at the wheel rim were obtained by analyzing different models of braking. Thus, the calculation for the thermal analysis of a long-term braking for maintaining a constant railway vehicle velocity of v = 55 km/h in the report ORE B 169/RP1 [27], where a wheel with different geometry was analyzed and in which the heat transfer was performed over the entire rim surface of the wheel, that means the entire surface at which the brake block slips, gave the value for the maximum temperature on the rim of the wheel of $T \approx 310$ °C, while in the national research [16], where the geometry of the wheel corresponds to the geometry of wheels that are used at national railway vehicles and in which the actual value of the contact surface of the wheel and the brake block was used, however, by using a two-dimensional surface analysis on a simplified model of the radial cross-section of the wheel with the adopted axisymmetric propagation of the heat, gave the value of $T \sim 350$ °C. These data are comparable with the value of the maximum temperature $T \approx 430$ °C which was reported in this paper obtained by using the thermal analysis of the volumetric three-dimensional model for a long-term braking for maintaining a constant railway vehicle velocity of v = 60 km/h. This can verify the methodology of the proposed calculations and usage of the applied software package based on finite element analysis in order to predict the thermal overload of railway vehicles wheels braked by blocks.

Conclusions

The existing models for the estimation of the amount of the heat generated during friction processes assume that the energy delivered to bodies in the frictional (or tribological) contact transforms into heat only due to the friction losses on contact surfaces. However, the real friction heat transformation appears under various and more complex conditions:

- bodies at the contact suffer elastic, plastic and/or elastoplastic deformations on contact surfaces as well as under the surface,
- during the contact, the roughness of the contact surfaces changes,
- main tribological processes: friction, wear and lubrication have mutual influence on each other, and
- mass transfer, adhesion, cohesion, vibration, sound, microstructure recristalization, chemical reactions, heating, *etc*. appear at the contact surfaces of bodies, and so on.

All mentioned processes consume some of the energy delivered to the moving body in contact and the rest of the energy transforms into heat and dissipates into the bodies in contact and the surrounding.

The recognition of dominant parameters that influence the heat generation process, as well as the estimation of the portion of energy that transforms into heat, is difficult and delicate since all parameters values change almost instantly, as well as the character of the process.

If it is possible to recognize and calculate changing of parameters, such as friction coefficient, contact pressure, thermomechanical properties of bodies in contact (yield strength, heat transfer coefficients *etc*.), temperature *etc*., during heat generation due to tribological contact between two bodies precisely enough, then they can be embedded into an analytical model for the estimation of the amount of the generated heat that will give satisfying mathematical modeling results. In this paper we made an effort to analyze a block-braked solid railway wheel of a 444 class locomotive of the national railway operator Serbian Railways, using analytical and numerical modeling of thermal effects during long-term braking for maintaining a constant speed on a down-grade railroad for different velocities and there breaking regimes, with low and high pressure in the braking installation. The intention was to make the contribution in preventing the fracture of solid wheels being braked by brake blocks caused by the thermal overloading because of the hypothesis that thermal loads are the main cause of crack occurrence on wheel rims of railway vehicles on the rail network of Serbian Railways. The presented approach is the basis for the following stress analysis of the appropriate stress states as a consequence of analyzed thermal loads in the simulated operation conditions. This approach could significantly decrease the probability of crack appearance caused by thermal loads. This research can also help to timely discover the conditions for the appearance of these cracks, and it represents the final part of the process of solving problems concerning the solid wheel fracture due to thermal loads.

Modeling of thermal effects of braking systems of railway vehicles (locomotives and wagons) is very important in the designing process of the braking assembly for defining materials, shape of a braking block, contact surfaces, and so on. In addition, modeling can effectively determine the limiting values for the regime of running of trains, which has so far been mostly left to manufacturers of brake equipment to determine by examining the possibility of providing maximum braking efficiency without any thermal analysis.

Nomenclature

Pr – Prandtl number, [–]
q – heat power generated per unit contact area, [Wm^{-2}]
q_{diss} – heat dissipation, [Wm^{-2}]
R_e – Reynolds number, [–]
r – wheel radius, [mm]
T – temperature, [K]
t – time, [s]
v_d – local velocity, [ms^{-1}]

References

[1] Saifullah, A. B. M., Masood, S. H., Finite Element Thermal Analysis of Conformal Cooling Channels in Injection Moulding, 5th Australasian Congress on Applied Mechanics, ACAM 2007, Brisbane, Australia, 2007, pp. 337-341

[2] Chandrupatla, T. R, Belegundu, A. D., Introduction to Finite Elements in Engineering, 3rd ed., Prentice-Hall, 2002

[3] Bhattacharyya, D. *et al*., Simulation of Temperature Distribution by Finite Element Analysis on Different Components of the EXAFS Beamline at INDUS-II Synchrotron Source, *Sadhana*, *30* (2005), 6, pp. 735-755

[4] Bakar Abu, Abd. R. *et al*., Thermal Analysis of a Disc Brake Model Considering a Real Brake Pad Surface and Wear, *Int. J. Vehicle Structures & Systems, 2* (2010), 1, pp. 20-27

[5] Thilak, V. M. M. *et al*., Transient Thermal and Structural Analysis of the Rotor Disc of Disc Brake, *International Journal of Scientific & Engineering Research*, *2* (2011), 8, pp. 33-36

[6] Wen, S., Guo-Quan Lu, Finite-Element Modeling of Thermal and Thermomechanical Behavior for Three-Dimensional Packaging of Power Electronics Modules, The Seventh Intersociety Conference ITHERM 2000, Las Vegas, Nev., USA, 2000, pp. 303-309

[7] Ferguson, B. L., Li, Z., Freborg, A. M., Modeling Heat Treatment of Steel Parts, *Computational Materials Science 34* (2005), 3, pp. 274-281

[8] Fujii, S. Saito, M., Transient Heat Transfer Analysis of High Speed Train Disc Brake Systems, 2011 SIMULIA Customer Conference, Barcelona, Spain, 2011, pp. 1-12

[9] Oder, G. *et al*., Thermal and Stress Analysis of Brake Discs in Railway Vehicles, *Advanced Engineering 3* (2009), 1, pp. 95-102

[10] Mijajlović, M. *et al.*, Mathematical Model for Analytical Estimation of Generated Heat During Friction Stir Welding. Part 1, *Journal of Balkan Tribological Association, 17* (2011), 2, pp. 179-191

[11] Belhocine, A., Bouchetara, M., Study of the Thermal Behaviour of Dry Contacts in the Brake Discs, *Mechanika, 17* (2011), 3, pp. 271-278

[12] ***, ERRI B 169/RP 4 Standardization of Coach Wheelsets, Standardization of a Block-Braked Solid Wheel (Rim Diameter 920 mm) for Coaches with a Maximum Speed of 160 km/h, Standard wheelsets for block brakes, Utrecht, The Netherlands, 1993

[13] ***, ERRI B 169/RP 5 Standardization of Coach Wheelsets, Methods of Monitoring Solid Wheelsets, Immediate Measures to Avoid Wheel Fractures (in French), Utrecht, The Netherlands, 1993

[14] ***, ERRI B 169/RP 6 Standardization of Coach Wheelsets, Methods of Monitoring Solid Wheelsets, Ultrasonic Method for the Non-Destructive Determination of Residual Stresses in Solid Wheel Rims (in French), Utrecht, The Netherlands, 1995

[15] ***, ERRI B 169/RP 8 Standardization of Coach Wheelsets, Determination of the Fracture Toughness of Solid Wheels Made of R7 Steel, Definition of a Test Method and an Acceptance Criterion (in French), Utrecht, The Netherlands, 1995

[16] Bečejac, Lj., Researching of the Possibilities to Predict the Thermal Overload of Railway Vehicles Braked by Blocks on Basis of Characteristics of the Train and Railtrack, M. Sc. thesis, Faculty of Mechanical Engineering, University of Nis, Nis, Serbia, 2003

[17] Milutinović, D., Radosavljević, A., Lučanin, V., Temperature and Stress State of the Block-Braked Solid Wheel in Operation on Yugoslav Railways, *FME Transaction, 31* (2003), pp. 15-20

[18] ***, ORE B 106/RP 12 Standardization of Coaches, Standardization of a Block-Braked Solid Wheel (Tread Diameter 920 mm) for Coaches with a Top Speed of 160 km/h, Basic Calculations, Utrecht, The Netherlands, 1989

[19] Jovanović, R., Milutinović, D., Modern Ways for Preventing the Damages Caused by the Railway Vehicle Solid Wheel Fractures (in Serbian), VI International Scientific Conference of Railway Experts – JUŽEL, Vrnjačka Banja, Serbia, 1999, pp. 117-124

[20] Milutinović, D., Tasić, M., Jovanović, R., Thermal Load as a Primary Cause for the Fracture of the Block-Braked Solid Wheel (in Serbian), *Železnice, 55* (1999), 11-12, pp. 712-716

[21] ***, UIC 510-2 Trailing Stock: Wheels and Wheelsets. Conditions Concerning the use of Wheels of Various Diameters, 3rd ed., 1998

[22] ***, UIC 812-3 Technical Specification for the Supply of Solid (Monoblock) Wheels in Rolled non-Alloy Steel for Tractive and Trailing Stock, 5th ed., 1984

[23] ***, COMSOL Multiphysics , http://www.comsol.com/showroom/gallery/102/

[24] Stamenković, D., *et al.*, Recommendations for the Estimation of the Strength of the Railway Wheel Set Press Fit Joint, *Proceedings*, Institution of Mechanical Engineers, Part F: *Journal of Rail and Rapid Transit*, *226* (2012) 1, pp. 48-61
[25] Mijajlović, M. *et al.*, About the Influence of Friction Coefficient on Heat Generation During Friction Stir Welding, *Proceedings,* 12th International Conference on Tribology SERBIATRIB '11, Kragujevac, Serbia, 2011
[26] Vainhal. V., *Brakes and Braking of Trains* (in Serbian), Bureau of Newspaper Publishing and Propaganda Activity of JŽ, Belgrade, 1982
[27] ***, ORE B 169/RP1 Thermal Limits of Wheels and Brake Blocks, Selection of Parameters for Testing Thermal Limits of Wheels and Brake Blocks (in French), Utrecht, The Netherlands, 1987

Paper submitted: May 3, 2012
Paper revised: July 9, 2012
Paper accepted: July 19, 2012