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XV SCIENTIFIC-EXPERT CONFERENCE ON RAILWAYS RAILCON '12

MODELING THERMAL EFFECTS OF THE BRAKING PROCESS AT BLOCK-BRAKED RAILWAY VEHICLES

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Abstract *– The modeling of thermal effects has become increasingly important in product design in different transport means, road vehicles, airplanes, railway vehicles, and so forth. Moreover, 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 is prevailing 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. In that way induced thermal loads determine thermomechanical behavior of the structure of railway wheels. In cases of thermal overloads, the generation of stresses and deformations are occurred 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 determines a dare research task. Therefore, the thermal analysis of a block-braked solid railway wheel of a locomotive of the type 444 of the national railway operator Serbian Railways using analytical and numerical modeling of thermal effects during braking until the locomotive stops, is processed in detail in this paper.*

Keywords - railway, braking, block-braked solid wheel, thermal load, friction generated heat.

1. INTRODUCTION

Thermal analysis is involved in almost every kind of physical processes and can be the limiting factor for many processes. 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 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 reducing costly experimental trials. The finite element method (FEM) has become the preferred method in performing thermal analysis on a many systems and processes in recent years [1]. A FEA thermal analysis is a finite element analysis that looks at how heat affects certain materials and engineering designs. Thermal analysis and precise prediction of the maximum temperature is needed for the design of many systems, for example braking systems [2], especially for both discs and linings, where how to handle the high speed spinning of discs is the point of the heat/structure coupled analyses [3]. The thermal analysis is a primordial stage in the study of the braking systems, because the temperature determines 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 wheels and finally fractures of wheels [4].

Many researches results confirmed dominant influence of thermal loads in regard to mechanical loads [5] and residual stresses induced by high

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thermal loads in block-braked solid wheel were registered [6]. Therefore, it is important to determine with high precision the temperature field of the braking system, as well as to emphasis that high thermal loads, in other words overloads, of wheel can occur as a result of long braking. Those are the main goals of this paper which presents results of a thermal analysis of a braking system of railway vehicles using analytical and numerical modeling of thermal effects during braking, until locomotive stops, in order to analyze damages of solid wheel braked by blocks, especially on railway vehicles of national railway operator Serbian Railways.

2. ANALYTICAL MODELING OF THERMAL EFFECTS OF THE BRAKING PROCESS AT BLOCK-BRAKED 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 that purposes an analytical model for analyzing thermal effects in braking systems of passenger cars [7] 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 and 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 and 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:

$$q(r,t) = -f_f \cdot r \cdot \omega(t) = -f_f \cdot r \cdot (\omega_0 + \alpha \cdot t) \tag{1}$$

where f_f is the friction force per unit contact area, ω is the angular velocity, ω_0 is the initial angular velocity, α is angular acceleration of the railway wheel and t is braking time. In the following considerations, it is not the case where the wheel rotates, but the heat source.

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

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

where μ is the friction coefficient, F_N is the normal braking force on one of the braking blocks, and A is 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:

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

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 is the velocity field and Q is 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:

$$\vec{v}_d = \omega(t) \cdot \vec{r} \tag{4}$$

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 the 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:

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

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

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

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

3. NUMERICAL MODELING OF THERMAL EFFECTS OF THE BRAKING PROCESS AT BLOCK-BRAKED RAILWAY VEHICLES

High thermal loads at railway wheels very often occur as a result of a long braking. 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 braking, until locomotive stops were determined, with different braking conditions.

The thermal analysis was performed for braking a locomotive of the type 444 of the national railway operator Serbian Railways, that ran with initial velocity of 120km/h. Two different cases of braking were analyzed, with low ($3.36 \cdot 10^5$ Pa) and high ($7 \cdot 10^5$ Pa) pressures in the braking installation. In the low pressure regime of braking, the normal braking force on one braking block was F_N =20379N, with duration t=35s of the braking until the locomotive stops. In the case of high pressure regime of braking, the normal braking force was F_N =37162N, with duration t=19s of the braking until the locomotive stops. Braking forces were introduced in the analysis throughout equations (1) and (2). The intermediate radius for the chosen locomotive wheel was r=625mm, the contact surface area between the braking block and the wheel was A=19577mm^2, and the friction coefficient for materials of the block and the wheel was μ=0.115.

Fig.1. shows the meshed 3D model of the railway wheel and braking blocks. In the meshing process this assembly was devided in 68771 finite elements.

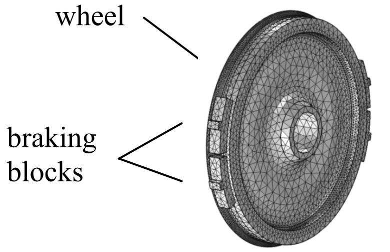

Fig.1. The meshed model of the block-braked solid wheel assembly

The material of the railway wheel is steel DIN 40Mn4 (AISI 1039, JIS S40C, Č3130) and 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 [kg/m3]	7850	7200	1.170
C_p [J/(kg·K)]	486	510	1100
k [W/(m·K)]	52	45	0.026
ε	0.28	0.31	-
μ_{va} [Pa·s]	-	-	1.8·10-5

4. RESULTS OF THERMAL ANALYSIS OF THE BRAKING PROCESS OF THE 444 LOCOMOTIVE

During the braking process, as the velocity of the locomotive decreases, the generated heat due to the friction between surfaces in contact decreases as well (1). At a time the generated heat becomes smaller than the dissipated heat from the free surfaces. For this analysis, at the moment t=17.8s, for the low pressure regime of braking, and t=11.8s, for the high pressure regime in the braking installation maximum temperatures were reached. After these times, as the braking process continue, the temperature starts to decrease and the wheel starts to cool down. The diagrams of the temperature distribution at the moment with maximal temperatures reached, for the examined wheel of the locomotive of the type 444 of the national railway operator Serbian Railways, are shown in Fig.2.

In order to determine positions of areas with maximal temperatures it is helpful to plot diagrams of temperature distribution versus time along with the wheel radius. These diagrams are displayed in Figure 3 for the low pressure regime of braking and for the high pressure regime in the braking installation.

According to the diagrams of the temperature distribution (Fig. 2 and 3) Table 2 is made in order to summarize, for examined cases, the values of the maximal temperatures at the points at the wheel rim at the moment when temperature reached the maximal values for the braking process of a locomotive of the type 444 of the national railway operator Serbian Railways from the initial velocity of v = 120 km/h until the locomotive stops.

Table 2. The maximal temperatures at the wheel rim

Braking regime	Low pressure	High pressure
Time of braking t [s]	17.8	11.8
Temperature [°C]	170.73	220.64

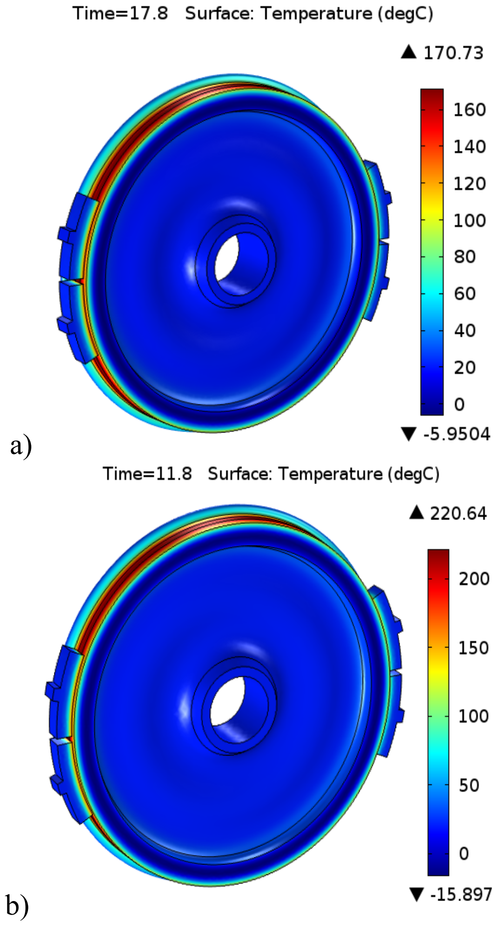

Fig.2. The temperature distribution at the wheel at: a) t=17.8s (low press.); b) t=11.8s (high press.)

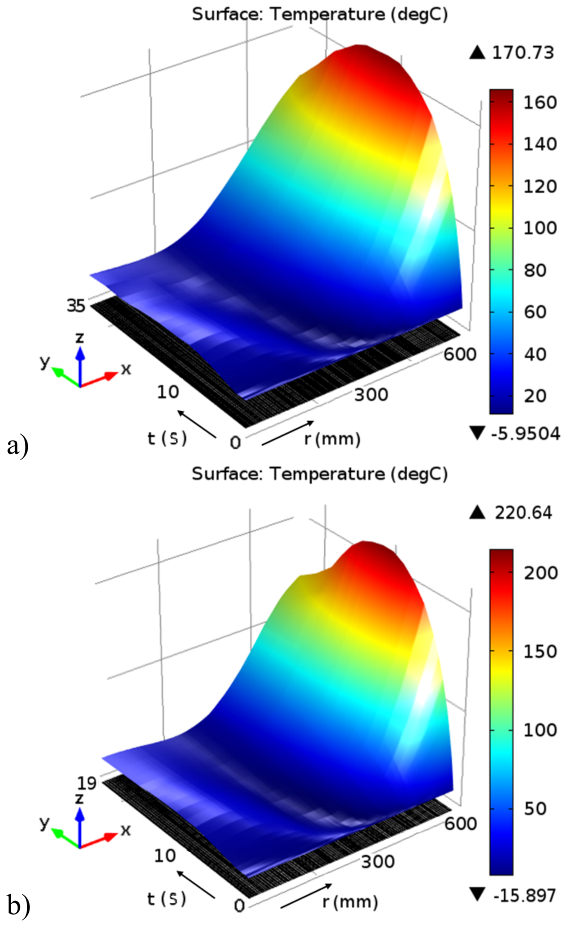

Fig.3. The temperature distribution at the wheel in function of time and wheel radius a) low pressure; b) high pressure

5. CONCLUSIONS

In this paper we made an effort to analyze a block-braked solid railway wheel of a locomotive of the type 444 of the national railway operator Serbian Railways using analytical and numerical modeling of thermal effects during braking, until locomotive stops, for two breaking regimes, with low and high pressure in the braking installation. The intention was to make the contribution in preventing the fracture of the solid wheels being braked by brake blocks caused by the thermal overloading because of the hypothesis that thermal loads are the main cause of cracks occurrence on wheel rim of railway vehicles on the rail network of Serbian Railways.

The presented modeling thermal effects of the braking process at block-braked railway vehicles is the base for the following stress analysis of the appropriate stress states as consequence of analyzed thermal loads in the simulated operation conditions. That approach could significantly decrease the probability of appearing of cracks caused by the thermal loads. This research can also help to discover on time the conditions for appearing these cracks and represents the final part of the process of solving problems concerning the solid wheel fracture due to thermal loads.

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