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Finite Element Analysis for Estimating the Effect of Various Working Conditions on the Temperature Gradients Created Inside a Rolling Tire

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ABSTRACT

Periodic deformation of a tire during its rolling motion causes energy dissipation and heat generation due to hysteretic nature of the rubber. Because of rubber low thermal conductivity, the tire temperature increases and leaves unwelcomed effects on safe service life and safety of vehicles. In this study a numerical simulation based on finite element method is used for evaluating the effect of various working conditions on temperature field of a rolling tire. In each case, the maximum created temperature is checked to be less than critical level. Compared with related published studies, the obtained results show a very good consistency and validity.

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1. INTRODUCTION

It is noted that periodic deformations of a rolling tire result in energy dissipation and heat generation due to hysteresis property. Owing to low diffusivity of the rubber, as the main parts of tire structure, temperature locally rises in the tire structure [1]. Thermal effects are regarded as the most important factors in maintaining and optimal operation of pneumatic tires. The fatigue strength of rubber compounds drops with increase in temperature especially at a temperature of 90-120°C [2]. Furthermore, the adherence coefficient of the rubber and consequently the interaction of tire with road is strongly affected by the warming. So, evaluating the effect of different operating conditions on tire temperature distribution is very necessary for safe service life and optimum fuel consumption of vehicles.

Some sophisticated systems with modern temperature and pressure monitoring sensors are used for experimental measurements of the tires thermal aspects [3]. The results clearly indicate a complex relationship between the influential parameters and created heat inside the tire structure. Furthermore, the mechanical behavior of rubber compounds are highly temperature dependent [4]. However, experimental investigations are costly and time consuming methods.

In recent years, the numerical simulations have diminished the dominance of empirical methods in many engineering applications [5, 6, 7]. With the rising capacity of personal computers, the finite element-method (FEM) has turned out to be a robust tool for the analyses concerned with the interaction of rolling tire and the pavement surfaces [8, 9].

Assuming that the inelastic energy of deformation process is completely converted into volumetric heat, several steady-state thermal analyses are conducted for evaluating the effect of various operating conditions on temperature distribution of rolling tires. All the numerical methods used for thermal analysis of the tires have in common the fact that the time histories of

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strains and stress must be approximated to calculate the hysteretic loss and generated heat inside the domain. By fitting Fourier or polynomial series on the strain and the stress of nodes, obtained from a 3D finite element model, Wang evaluated the heat generation for thermal analysis of a rolling tire [10]. In recent investigations, using the transient dynamic algorithms for rolling process, a combination of motion and stress analyses are obtained for the nonlinear stress-strain curves and thermal effects [1, 4, 11].

However, including the rolling effect in simulation requires long CPU time; furthermore the obtained results for strains have a considerable oscillation which affects the accuracy of the analysis. In this study, by adding the centrifugal forces to the static interaction of tire with the road, an efficient method is proposed for estimating the strain energy stored inside the tire body. Compared with investigations based on dynamic rolling analysis, the results of proposed method for temperature gradients have a considerable consistency and accuracy.

2. TIRE CONSTRUCTION

Today, common radial tires used in vehicles are made as composite layers of different materials such as nylon, steel cable and rubber. So, two main categories of components can be found for a pneumatic tire structure: 1) the carcass and wear resistant blocks of tread, as two main rubber parts, withstand internal-external loads and provide necessary traction at leading and trailing edges of tire, respectively. 2) Several layers of circumferential belts which are laid to stiffen the treads and strengthen the carcass or the tire body and prevent excessive deformation of the rubber (Figure 1).

3. THEORETICAL BASIS OF THE ANALYSIS

According to various mechanisms, such as viscosity, friction, hysteresis and etc., some of supplied energy of tire is dissipated into heat and contributes to increase in tire temperature [12, 13]. However it is noted that hysteresis, which is defined as the ratio of loss to total strain energy, accounts for 90 to 95% of dissipations [14]. The experimental analysis made by Lin and Hwang demonstrated that the hysteresis ratio H can be considered to be 0.1 for a variety of operating temperatures [14]. So, in any related numerical prediction the main issue is the evaluation of total stored energy within the tire body.

The work done by the external forces is stored in the body as strain energy which its amount per unit volume can be calculated by the following generalized equation:

$$w_{tot} = \int \sigma_{ij} d\tau_{ij} \tag{1}$$

where w_{tot}, is the density of stored energy, σ_{ij} and ε_{ij} are components of stress and strain tensors.

Based on non-linear Money-Rivlin material model, local stresses and strains caused by interaction of the tire with road can be obtained by the following constitutional relation [15, 16]:

$$\sigma = 2\left(\lambda - \frac{1}{\lambda^2}\right)\left(C_{01} + \frac{C_{10}}{\lambda}\right) \tag{2}$$

where $\lambda = 1 + \varepsilon$ is the extension ratio, C_{01} and C_{10} are temperarure-dependent constants which have been experimentally determined for a variety of working temperatures [17]. As result, the mechanical behavior of tire is affected by temperature [18]. However, in this work, the temperature variation is not considered for evaluating the strain energy. The rate of generated heat inside a rolling tire with linear velocity V_L can be found from the following relation:

$$Q_V = W_{loss} \times f = H \times W_{tot} \times \frac{V_L}{2\pi R} \tag{3}$$

where Q_V is the volumetric heat generation rate in each revolution of tire motion; V_L is the speed and R is valid rolling radius of the tire. Using the following general partial differential equation governing the heat conduction of a material, the created gradient of temperature inside the rolling tire can be evaluated:

$$-\nabla\left(k\nabla T\right) = Q_V \tag{4}$$

where k is the thermal conductivity coefficient for the tire.

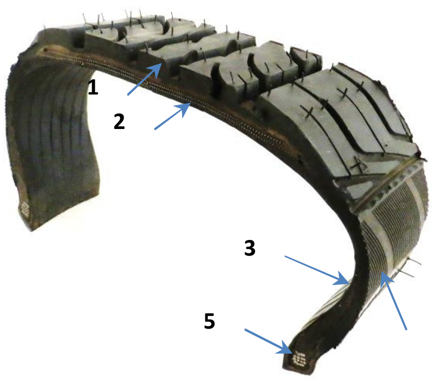


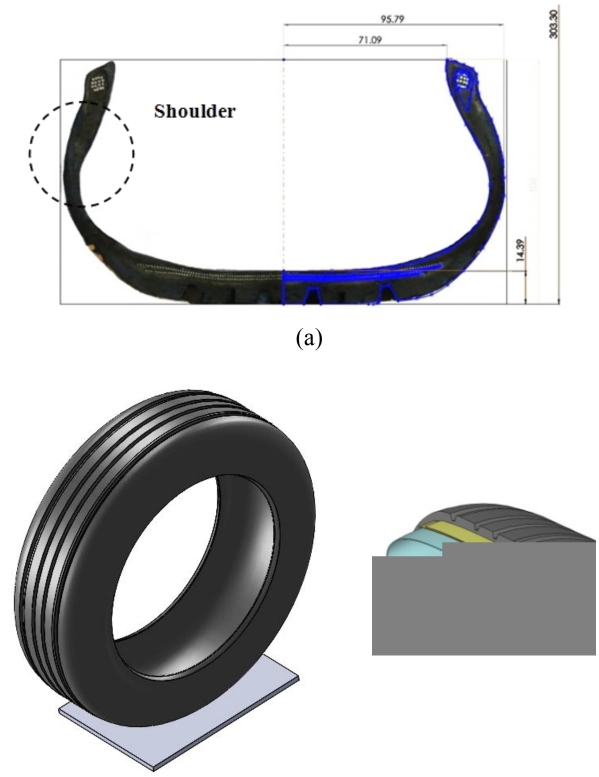
Figure 1. Structure of a common radial-ply tire (185/60R15)

4. RESULTS AND DISCUSSIONS

4. 1. Mechanical Analysis In this work, as first step for evaluating the thermal effects, use of a 3D finite element model the interaction of 185/60R15 steel belted radial tire with a rigid road surface is analyzed for obtaining the strain energy loss and resultant heat generation rate. Using Solidworks Premium, an exact model of tire cross section is created according to the geometrical size of the considered tire (shown in Figure 1) and then rotated by 360° to construct a 3D finite element model of the tire.

Four shallow circumferential notches are grooved on the tread as shown in Figure 2. In order to facilitate the calculations, the tire is assumed to be composed of carcass ply, belt layers, tread and bead. The mechanical behavior of rubber parts consisted mainly of treads is described by Mooney-Rivlin material model. While other parts of the tire, namely carcass ply and bead are considered to be linear and elastic materials. The thermal and mechanical parameters used in numerical simulations are given in Table 1. Using 60621 nodes and 33369 solid elements, the aspect ratio of generated mesh is about 1.5 which is a reasonable value for an accurate numerical analysis. For imposing boundary conditions, inflation pressure, axle load and contact conditions are applied to the tire. In the bead region, all the nodes in contact with the rim are considered to be fixed. Figure 2 (c) shows the tire finite element model for simulation of tire/road interaction. It should be noted that for a rolling tire the centrifugal force should also be added to the analysis of tire/road static contact. Variation of the total stored strain energy with the inflation pressure and loading, are illustrated in Figurs 3 and 4. It is evident from the results that the amount of strain energy increases with increasing normal load. For the same axle load, the total strain energy is observed to decrease with increasing inflation pressure which can be attributed to increased amounts of deformations on lower inflation pressure.

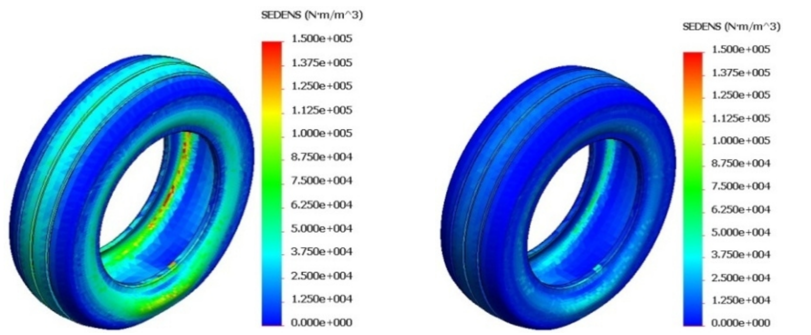
On the other hand, the maximum strain energy occurs at the tire/road interaction surface as a direct consequence of large deformations. The results of the study for strain energy are in a good agreement with the results of transient dynamic analysis employed in several published works [1, 19, 20].



(a)

(b) (c)

Figure 2. (a) Cross section of tire constructed according to the actual size of radial tire 185/60R15, (b) 3-D model of the tire and (c) imposition of boundary conditions for radial tire components modeled in Solidworks Premium.



(a) (b) (c)

Figure 3. The strain energy density for $5\,kN$ axel load and three inflation pressures: $a)\,P_i = 25\,psi$, $b)\,P_i = 35\,psi$ and $c)\,P_i = 45\,psi$.

TABLE 1. Material properties used in tire FE model [4].

	Tread			Belt	Carcass	Air
Temperature, $^{\circ}C$	**0**	**20**	**40**			
Mooney-Rivlin constants (Mpa)						
C_{01}	8.061	2.0477	0.550966	-	-	-
C_{10}	1.806	1.1859	0.00373778	-	-	-
Density, ρ $\left({kg}/{m^3}\right)$	1400	1140	1100	7644	1390	-
Modulus of elasticity, E (Gpa)	-			55	0.794	-
Poisson ratio, υ	-			0.3	0.45	-
Thermal conductivity, $\mu\left({W}/{m^2\,^{\circ}C}\right)$	0.293			60.5	0.293	0.055
Hysteresis constant, H	0.1			-	-	-

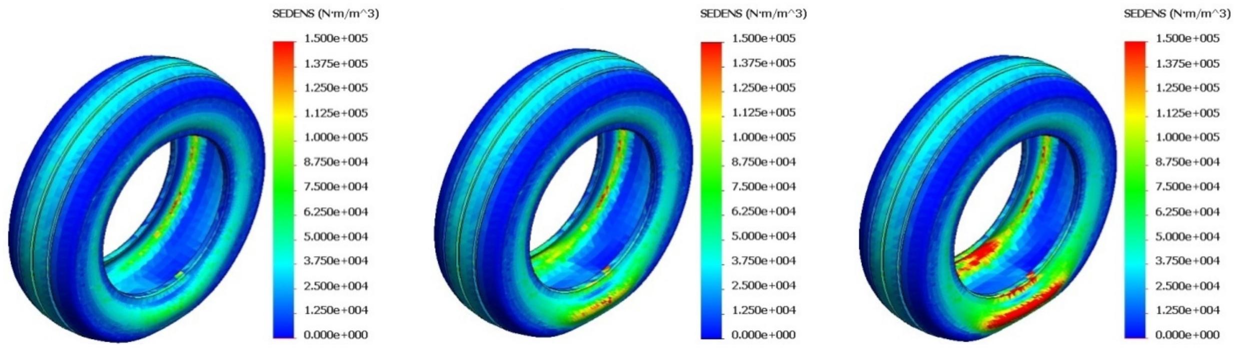


Figure 4. Variations of strain energy density for different values of axle load: $a)3\,kN$, $b)4\,kN$ and $c)5\,kN$.

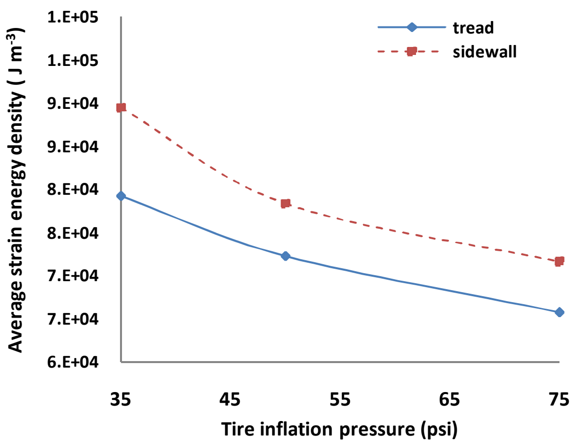


Figure 5. Variation of total average strain energy density with the inflation pressure

It is noted that some of strain energy stored in the rubber parts including tread and sidewall, contributes to operating temperature [21, 22]. Variations of the strain energy stored in tread and sidewall with inflation pressure are shown in Figure 5.

Due to more endured deformations, the average strain energy density of the sidewall is larger than those of the tread. These observations closely match the trends of the published results [19].

4. 2. Thermal Analysis As the first step for the thermal investigation, it is assumed that the whole tire is made by the rubber and the thermal properties such as conductivity and specific heat have minimal variations within operating conditions and can be considered as constant values. There is thermal conduction across the rubber and body-ply layers and convective/radiated heat exchanges on domain boundaries exposed to the surrounding:

$$q_n = \sigma\varepsilon\left(T - T_0\right) + h_c\left(T - T_0\right) \quad (5)$$

where σ and ε are Stefan-Bultzman and emissivity constants, respectively.

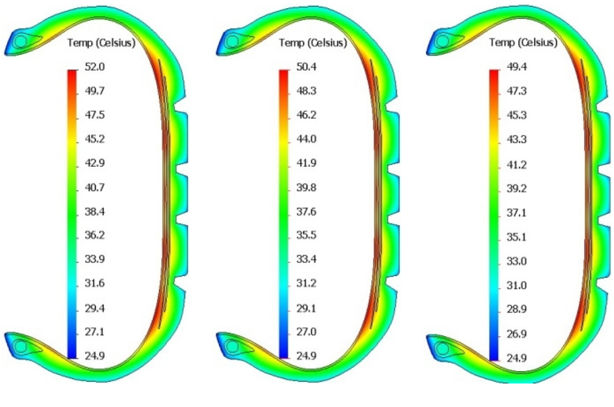
The flow of air with velocity of v around the outer surfaces of the tire causes forced heat transfer convection which its coefficient h_c can be found through the following empirical relation [12]:

$$h_c = 5.9 + 3.7v \tag{6}$$

The airflow over the treaded surface has a single value that can be easily obtained, but the relative velocity around the sidewall of rolling tire is a function of linear distance measured form the hub center. So, the average velocity on this surface is substituted in Equation (6). The convection coefficient at the inner surface is taken to be $5.9 \frac{W}{m^2 \, {}^\circ C}$ due to negligible relative velocity of the inside air [23, 24]. According to empirical observations, the temperature of inflated air volume is about $15^\circ C$ more than ambient temperature [19]. For three different values of inflation pressures, temperature gradients within tire domain are represented in Figure 6. The ambient temperature and the translational velocity of rolling tire are selected as $25^\circ C$ and $80 \, km/h$, respectively. An axis-symmetric trend can be observed for all the cases. Furthermore the low temperature field occurs at the bead region owing to conduction between the tire and rim.

Neglecting the frictional effects, the maximum temperature occurs in domain of lower inflated tire due to more deformations and strain energy stored. Variation of maximum tire temperature with inflation pressure is shown in Figure 7. It can be easily found that rolling a high pressured tire with stiffer mechanical behavior leads to creation of lower thermal gradient inside the tire. The above results are noted to be very similar to the simulations performed by many researchers [1, 10, 23]. For a variety of ambient temperatures, the maximum obtained values for the belt edge temperature are depicted in Figure 8. It can be observed that working on a warmer conditions will cause more intense temperature gradient for the tire which is proved by the results of experimental analysis [4, 14]. This extreme increase in temperature has bad effects on fatigue strength of the rubber and as result; tiny cracks are found in the side walls of the tire after a while of working.

For better understanding of the temperature gradients across the tire cross-section, the temperature distributions along three paths of A, B and C are shown in Figure 9. The tire is considered to be loaded with $3kN$ and inflation pressure of $35 \, psi$. It is clear that the hysteretic effect of rolling tire does not produce high temperature zones on the parts exposed to the air flow; i.e. the thread blocks and outer surfaces of the tire while the belts become the hottest regions due to low thermal conductivity of the rubber. Gradients of temperature for three different velocities are illustrated in Figure 10. Despite more convective heat transfer coefficient at higher speeds, it is obvious that any increase in tire velocity leads to smaller period of one revolution and consequently increase in the amount of heat generation rate. So, the maximum temperature found to be raised with increase in tire velocity.



(a) (b) (c)

Figure 6. The effect of inflation pressure on tire temperature field: (a) 25 psi, (b) 35 psi and (c) 45 psi.

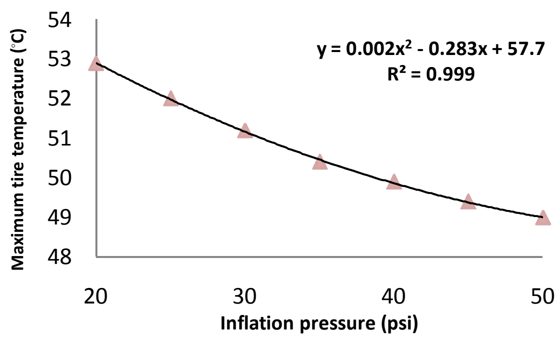


Figure 7. Variation of maximum tire temperature with the inflation pressure.

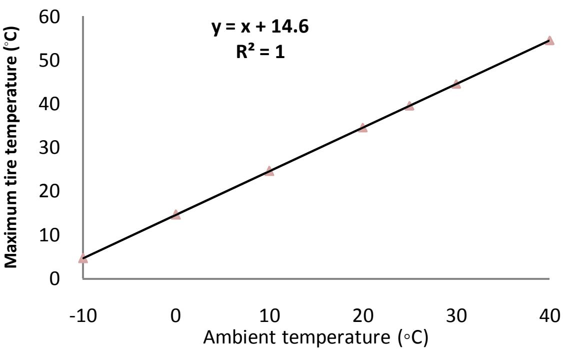


Figure 8. Variation of maximum tire temperature with ambient temperature.

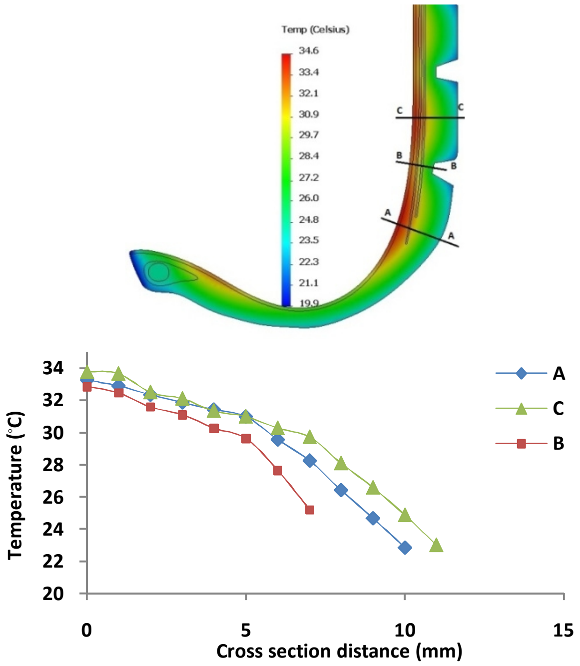
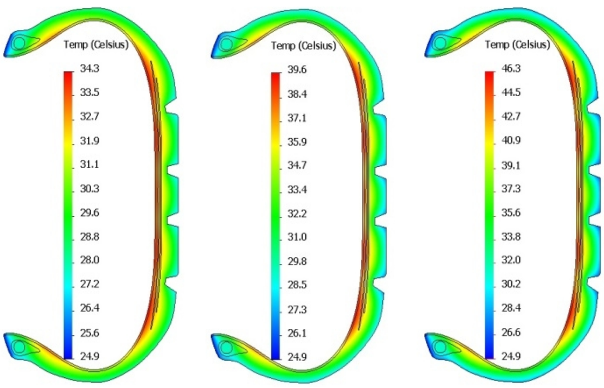


Figure 9. Variation of temperature from internal surface of the tire to the treads.



(a) (b) (c)

Figure 10. The effect of velocity on tire temperature field: (a) 40 , (b) 80 and (c) 120 km/h .

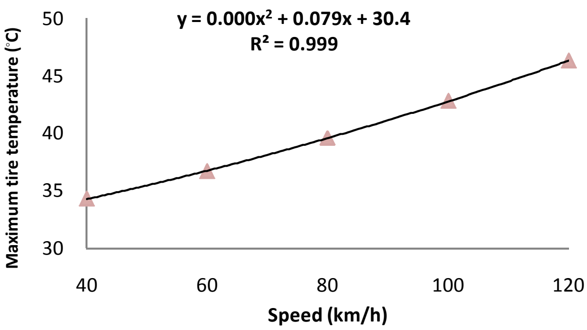
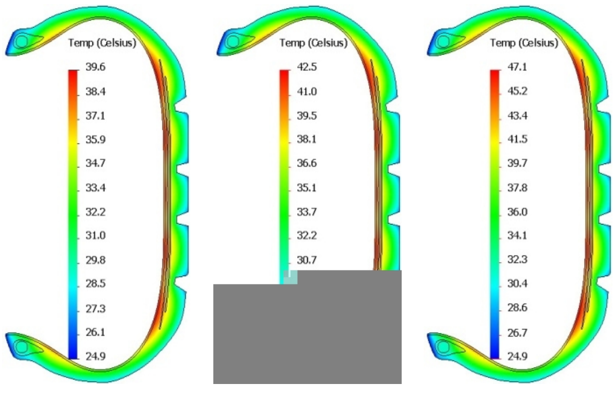


Figure 11. Variation of maximum tire temperature with the velocity.



(a) (b) (c)

Figure 12. The effect of axle load on tire temperature field: (a) $3\,kN$, (b) $4\,kN$ and (c) $5\,kN$.

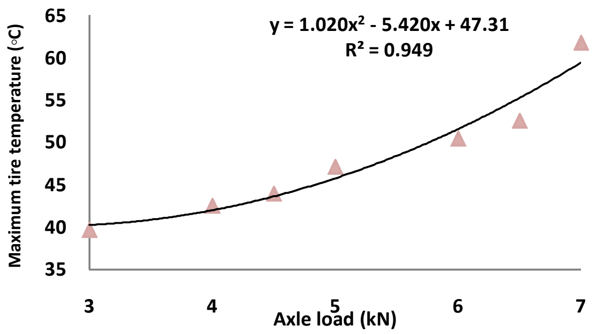


Figure 13. Variation of maximum tire temperature with the axle load.

As shown in Figure 11, the maximum generated temperature created inside the tire has a linear variation with the velocity. The trend is found to be very similar to the results of experimental analyses [10, 14, 25].

Figure 12 shows the contour plot of temperature distribution of the tire calculated at various axle loadings F= 3, 4 and $5\,kN$, respectively. When the loading is increased, higher amount of deformation and strain energy storage occur at the sidewall and tread and as a direct consequence, severe temperature gradient is created inside the tire. Variation of maximum tire temperature with the axle loading is illustrated in Figure 13. An approximate increase of $10\,^{\circ}C$ can be found for the temperature from 3 to $6\,kN$.

5. CONCLUSION

In this study, an efficient numerical scheme is presented for evaluating the contribution of different working conditions to operating temperature of radial tire 185/60R15. The results of mechanical analysis are used to calculate the hysteretic loss and heat generation rate. Through an uncoupled thermal analysis, the temperature gradient created inside a rolling tire is evaluated as the goal of the research. According to the results, an axi-symmetric distribution of temperature can be observed for all the cases. Higher temperature regions are located in the shoulder and around the belt due to low diffusivity of the rubber. The results show that the ambient temperature and axle loading are the most effective parameters in increasing the tire temperature. It is found from the results that for all cases the maximum temperature of the tire is far below the critical level. Compared with related investigations, the results of proposed method have a considerable consistency and accuracy.

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چکیده

به علت پدیده هیستریتیک، تغییر شکل های متوالی ناشی از دوران تایر، باعث اتلاف انرژی جنبشی و تولید گرما در ساختار آن می شود.. به علت رسانایی ضعیف لاستیک که عمده ترین بخش ساختار تایر است، دمای بخش هایی از تایر به شدت بالا می رود که ابن افزایش دما تأثیرات مخربی بر حد دوام لاستیک در برابر شکست خستگی و در نتیجه عمر مفید آن بر جا می گذارد.. به همین علت این میزان می بایست در شرایط مختلف کارکرد تایر بررسی شود. در این تحقیق یک شبیه سازی عددی بر پایه المان محدود برای ارزیابی تأثیر شرایط کاری متفاوت بر دمای تایر در حال دوران ارائه می گردد. در این تحلیل هندسه نسبتاً پیچیده و مواد مختلف سازنده ساختار آن به خوبی مدل شده اند. مقایسه نتایج بدست آمده از این تحقیق، هماهنگی خیلی خوبی با تحقیقات منتشر شده در این زمینه دارد.

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