Evaluating the Effect of Operating Conditions on Temperature Variation Rate of Inner Walls and Inside Inflated Air of Pneumatic Tires

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Abstract: For rolling pneumatic tires, the thermal induced effects are mainly resulted from the visco-elastic behaviour of rubber parts and dissipation of stores strain energy during the cyclic deformations. It is noted that the operating conditions crucially contribute to the rubber hysteresis effect and temperature development in a rolling tire. In the current study, an elaborated 3D FE model is worked up for simulating the certain inflation pressure, loading and velocity conditions for a specified radial tire. Special emphasis is given to transient temperature distribution of interior walls and tire cavities as critical zones. Compared with the experimental tests, the current study gives satisfactory results for the time rate of change in the temperature of tire walls and inside inflated air.

Keywords: Finite Element Method, Interior Temperature, Rolling Tire, Transient Thermal Analysis

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1 INTRODUCTION

The rolling pneumatic tire endures alternatively compression and expansion during its rolling motion and because of the hysteresis property of rubber, energy dissipation takes place and temperature develops in the tire [1]. It is noted that the rubber has low thermal diffusivity. So, dangerously high local temperatures are created inside the tire domain [2]. Under such conditions, the tire/ground contact area increases, the created stress and deformation fields inside the tire body as well as adhesion of the tire with the road are badly affected [3], [4]. Furthermore, high temperatures can strongly accelerate chemical alternation processes which lead to deteriorating the rubber network structure [5]. On the other hand, a significant number of vehicles operate with tire pressures below the manufacturer's specification and with higher vertical loads. Thus, for a variety of operating conditions and mechanical properties the interior temperature distribution of the rolling tire should be analyzed.

However, it is noted that evaluating the dissipated mechanical energy, which is directly converted into heat, is a highly challenging task. The rubber shows non-linear elastic and inelastic with large deformations when subjected to external loads; while steel belts exhibit completely different material properties in the anisotropic structure of the tire [1], [5]. Furthermore, the contact to the road and the rim demands a contact formulation. Another problem is that the viscoelastic material property of rubber is temperature dependent moduli [6].

Due to the complexity of the problem and limitation in analytical approaches, the experimental methods required to determine the tire temperature field. For this purpose, some sophisticated systems with modern temperature and pressure monitoring components are used for evaluating of tires under dynamic conditions. Among them, Kostial et al. developed a robust wireless system for measuring both inner and outer temperatures of rolling tires [7]. However, tire related experimentations are usually noted to be extremely expensive and time consuming and are restricted to manufacturers, with relatively few studies in the open literature. Furthermore, just the temperatures at certain points in the tire body have been measured in these works [8], [9].

By the finite element analysis for the design process of tires, more details and parameters about the mechanical and thermal performance of rolling pneumatic tires can be easily considered. Meanwhile, some limitations of experimental methods can also be omitted. In recent years owing researchers have done a lot of works to predict the temperature distribution developed inside the rolling tires.

Lin and Hwang [10] conducted dynamic mechanical testing for evaluating the relationship between the hysteresis and total stored strain energy and used the results for numerical investigation of the temperature distribution in a smooth tread bias tire. In the work performed by Zepeng [11] the strain and stress of the nodes were fit by Fourier series and are used to calculate the heat generation rate. The work presented by Sokolov [2] considers internal friction and internal heat generation relative to be the mechanical energy losses. Konde et al. used temperature- dependent friction coefficient for thermo-mechanical analysis of aircraft tires [12]. Behnke and Kaliske [5] also evaluated the energy loss from the material and friction in the tire/road contact zone. Narashima et al. proposed an approach a technique for including the tread patterns into the analysis [13]. Wang et al. published a parametric study for steady state temperature distribution of rolling tires by using a modular simulation approach [14]. Tang et al. investigated the effect of body-ply stiffness and loading on the hysteresis energy loss of rubber [15]. Srirangam et al. used an innovative pavement interaction modal to iteratively determine the effect of tire operating temperatures on hysteretic friction on the tire/road interaction surface [1].

In this work a transient thermal analysis based on the results of the interaction of rolling tire with the rigid road is used for evaluating the effects of inflation pressure and axle load on temperature distribution of a 185/60R15 radial tire and for several considered regions of the tire, the local increase rate of temperatures is well determined via numerical analysis. The results of the mechanical analysis performed by the authors [16] are used for evaluating the thermal investigation of the same tire. The novel aspect of the present work is including the thermal effects of air filled volume as another thermal boundary condition to the internal surfaces of the carcass. So, besides the tire body, a comprehensive evaluation may also be performed for temperature gradient of inside air. The accuracy of the analysis is verified via comparison with experimental measurements of Haung et al. [17] for the same tire. A great consistency of the results proves the validity of the simulation procedure.

2 MATERIALS AND METHODS

Appropriate modelling the complicated structure of the pneumatic tire is a crucial step for a reliable numerical investigation. However, the tire is a complicated combination of rubber compounds and steel belts [12] and no data about the tire cross section geometry or inner plies are usually available from manufacturers. So, in the current study the tire has been cut using a water jet "Fig. 1". This method gives a 2D section of the tire with all its features. A 3D model is then developed by revolving this 2D cross section. As shown in "Fig. 2", the main rubber parts in tire structures are shoulder, sidewall and tread. For reinforcement, several belt layers and steel cords are laid to stiffen the tire body and provide better tread wear. The pressure of inside inflated air is held by bead bundles.

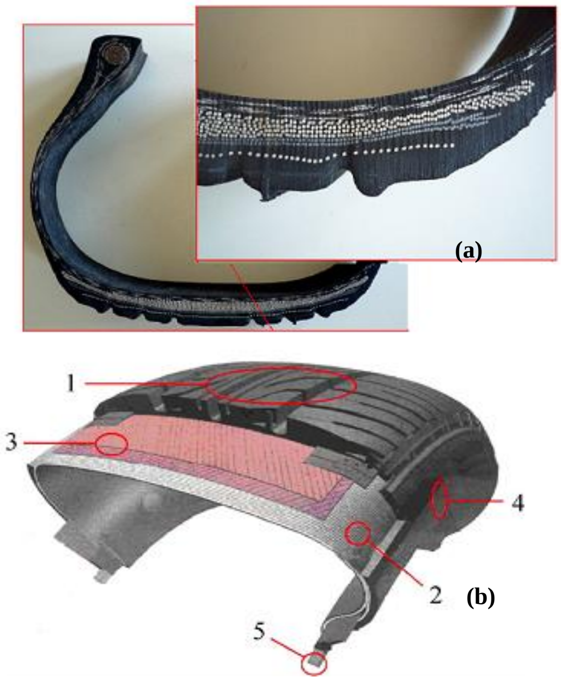

Fig. 1 (a): A: Water jet cutting and layout of the composite structure and (B): Structure of a radial-ply tire [21]: 1−Tread; 2−shoulder; 3−Belt layers; 4−Sidewall; 5−Bead.

Fig. 2 The rotary drum for experimental measurement of tire temperature.

The rubber which is the main structural part of a pneumatic tire shows a highly nonlinear stress-strain relationship. So instead of ordinary linear methods, the models based on stored mechanical energy provides more useful means for measuring the response of the tires to the external loading [18]. The Mooney-Rivlin model is one of the most commonly used models for describing the mechanical behavior of rubber structures. According to this model, the nonlinear stress- strain relationship which is obtained based on the strain energy function, can be expressed as [19]:

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

Where C_{10} and C_{01} are material constants and λ is expansion ratio. According to the experimental investigations [20], various rubber parts of the tire such as sidewall, shoulder and tread exhibit different mechanical behavior. In this work the reinforcing belt and steel plies elements are modeled as linear elastic materials. The Mooney-Rivlin constants and elastic properties of reinforcements are provided in "table 1". Compared with the mechanical constants of rubber parts, it can be easily observed that the reinforcing elements have considerable moduli.

Table 1 Mooney-Rivlin material constants of rubber and elastic properties of the reinforcing materials [20]

Rubber Material	C_{10}	C_{01}	Modulus in tension	Modulus in compression
sidewall	171.8 kPa	830.3 kPa	-	-
Undertread	140.4 kPa	427 kPa	-	-
Tread	806.1 kPa	1.805 MPa	-	-
Reinforcing material				
Belt ply	-	-	3.97 GPa	198.5 MPa
Steel ply	-	-	200 GPa	100 GPa

During a cyclic loading and unloading condition, the rubber parts also show considerable visco-elastic behavior known as hysteresis. According to the experimental data, for a vast range of vehicles speed, 90-95% of dissipations stem from hysteresis effect of the rubber and other additional heat source terms like friction or external heat flux are not considered [10]. As result, the recovered energy from deformations of each cycle is less than the required energy to create another cycle [22].

Through a mechanical analysis, the total stored strain energy density which is energy per unit volume is calculated for a rolling tire subjected to different inflation pressures and axial loadings. This value is multiplied by the hysteresis to find the lost strain energy density:

$$U_{loss} = H.U_{total} \tag{2}$$

This lost energy is assumed to completely contribute to internal heat generation in this study [13]. A 3D thermal analysis can then be used to study the temperature evolution in the tire. Knowing the rotation rate of the tire, the heat generation rate can be calculated from the following equation.

$$\dot{q}_V = U_{loss} \times \frac{V_L}{2\pi R_t} \tag{3}$$

Where V_L is the speed and R_t is the effective radius of the rolling tire. The general governing equation of heat transfer in polar coordinates, is expressed as:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \theta}\left(kr\frac{\partial T}{\partial \theta}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}_V=\rho C\frac{\partial T}{\partial t} \tag{4}$$

Where T is temperature, k is thermal conductivity and $\dot{q}_v$ is the heat generation per unit volume resulted from internal hysteresis. Solving this equation one can easily found the time variation of the temperature inside the tire domain. The transient temperature distribution of inside air can then be evaluated using the results of the analysis. Furthermore, assuming the compressed air as an ideal gas, the increase rate in inflation pressure can be easily found via this investigation. For showing the accuracy of the obtained results, the experimental measurements of Huang et al. [18] for the interior temperature of the same tire are used for validation. In their scheme, the tire is put on a rotary drum and a fan with adjustable blowing speed is used for simulating the convective heat transfer during the test.

This paper mainly focuses on the temperature of inflated inside air. The positions where the sensors are installed in the tire are shown in “Fig. 7”. Several other points are also considered on the tire tread, tire shoulder and the sidewall for evaluating the temperature distribution over the tire surfaces. In the system, the thermistors of the MF52 type with measuring range -20 ºC to 500 ºC and accuracy of ±2 ºC are chosen as temperature sensors due to their small size and economic cost. As shown in fig.5, all thermistors are linked to a communicative system for transmission of data from the interior of the tire to the external environment.

3 RESULTS AND DISCUSSIONS

In the current study, the size of the standard passenger tire 185/60R15 is used for the simulation. The results of a mechanical analysis conducted by the authors for the same tire [16], is used to calculate the strain energy density and energy dissipation in the tire. A 3D thermal analysis can then be performed for evaluating the temperature evolution in the tire body.

The mechanical model of the tire is created using Solidworks Home Premium. Owing to the complexities of the tire structure, the accuracy of numerical analysis deteriorates when 3D tire model is meshed automatically. So, different components of tire structures are meshed separately to overcome this difficulty.

For the spatial case where the tire velocity is 60 km/hr, the temperature gradient of the tire is depicted in “Fig. 3”. The axle load and inflation pressure are considered to be 200 kpa and 2 kN respectively. It can be observed that the shoulder experiences higher temperatures rather than other parts of the tire. This can be explained by the fact that the tire shoulder as the thickest part of the tire has greatest deformations during running time of the tire. So, the shoulder produces more hysteric heat.

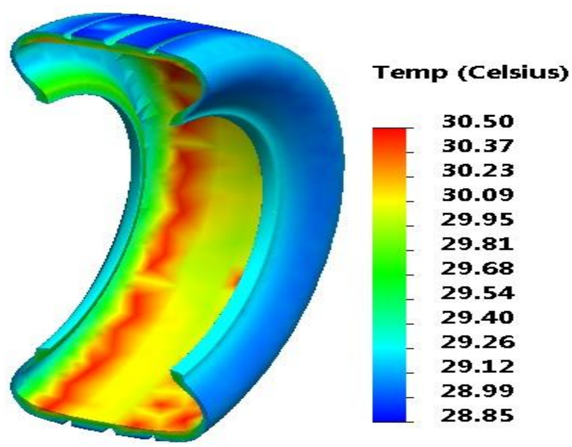

Fig. 3 The temperature gradient of the tire for running velocity of 60 km/hr.

The sidewall is the thinnest part of the tire and less amount of heat is generated in this region. On the other hand, the sidewall has the direct contact with the metallic rim. As a result, great heat transfer occurs in this region and the sidewall is noted to be the coolest part of the tire.

The tread has a periodical contact with the road surface which leads to considerable heat exchange over the thread surface. So, the temperature of the tread and the area around it are much lower than the shoulder. It can be concluded that the tire shoulder has more possibility to be damaged and more attention should be paid to designing. For 30 minutes, the variations in temperature of several points across the tire cross-section are depicted in “Fig. 4”. The locations of considered points are given in “Fig. 5”.

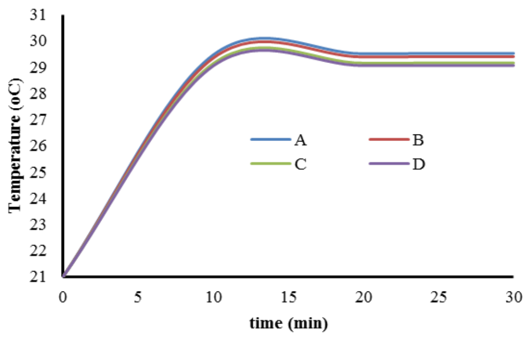

Fig. 4 The time rate of change in temperature of several points across the tire cross-section.

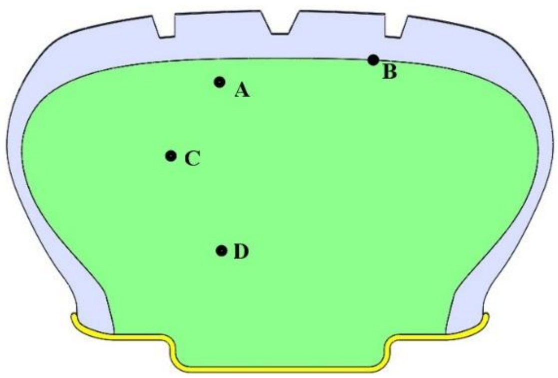

Fig. 5 The location of considered points across the tire cross-section.

It is evident that in the early stages of the analysis, the temperature gradient has a very fast increase rate. After about 15 minutes from the start, the tire arrives at the steady state when all generated heat inside the tire is transferred into ambient air and the road and there would be no considerable increase in temperature.

The gradient temperature of inside air for the same conditions is shown in "Fig. 6".

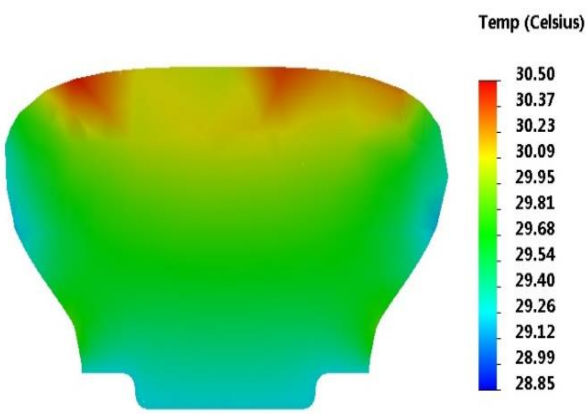

Fig. 6 The temperature gradient of inside air for running velocity of 60 km/hr, inflation pressure 200 kpa and axle load 2 kN.

As can be seen and just like the gradient of the tire, the inside air also has an ax symmetrical distribution of thermal effects. According to the results, the inside air has higher temperature near the inner surfaces of shoulder and tread which are noted to be hotter walls. Compared with the points located on external surfaces, the points located on inner side of the tire and inside air have relatively higher temperatures due to poor thermal convection inside the tire; while more effective thermal convection takes place for external surfaces.

As schematically shown in "Fig. 7", four thermistors are installed in the tire cavity for measuring the temperature of inside air. Variations of temperature for four distinct points inside the tire are given in "Fig. 8" for first 1500 sec of rolling motion. For estimating the accuracy and acceptability of the results, they are compared with the experimental data obtained from the sensors attached to the same rolling tire with the same working condition.

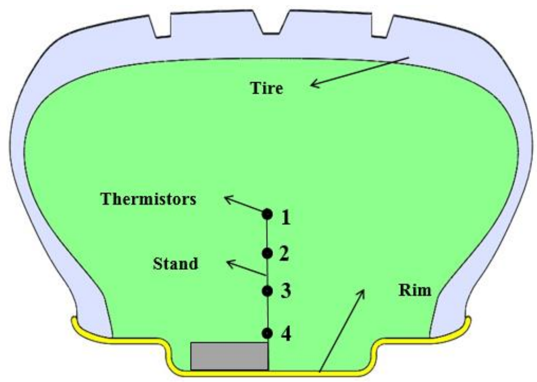

Fig. 7 The location of four considered points inside the tire cavity.

A great agreement can be easily observed which proves the accuracy of the numerical investigation. However as can be seen, the numerical results have a slight error in the prediction of steady state temperature. But prediction transient part of heat transfers for each specified point is performed with a sufficient accuracy. This is due to the fact that for both transient and steady state steps of heat transfer, the same thermal conditions are supposed in this study.

"Fig. 9" shows the thermal gradient of the tire when the speed is 40 km/hr, 60 km/hr, 80 km/hr and 100 km/hr respectively. The ambient temperature and axial load are set to be 21ºC and 316 kg respectively and for all considered speeds, the tire pressure is 240 kpa. According to previous studies [16] the increasing velocity has a negligible effect on the amount of dissipated energy. However, the results show that the tire surface increase with speed. This can be explained by the fact that in higher speeds the frequency of the tire deformation increases and resultantly the hysteretic heating would increase.

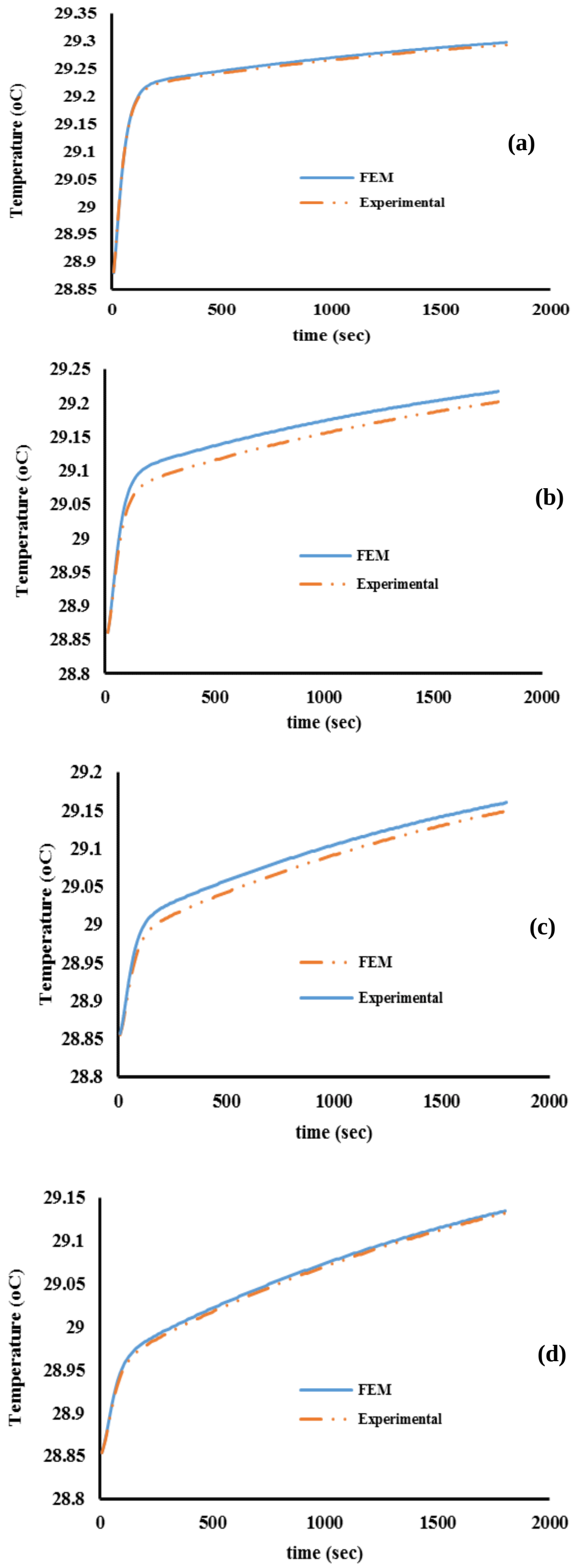

Fig. 8 Comparing the experimental and numerical results for four distinct points inside the tire inflated air: (a): for thermistor 1, (b): for thermistor 2, (c): for thermistor 3 and (d): for thermistor 4.

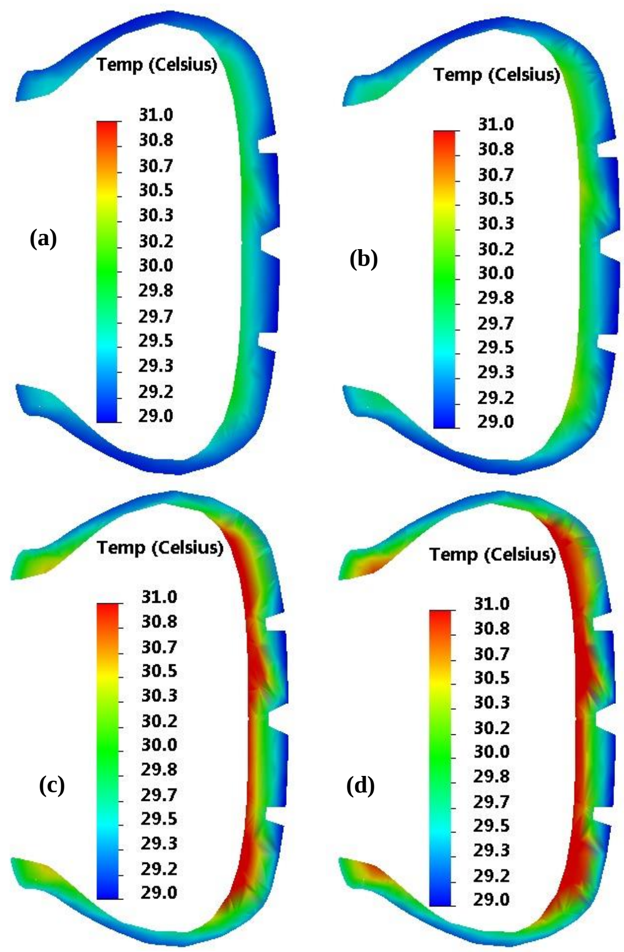

Fig. 9 Gradient of tire temperature for various speeds: (a): 40 km/hr, (b): 60 km/hr, (c): 80 km/hr and (d): 100 km/hr.

Thus, the tire temperature would increase with increasing speed. It can also be noted that the tread temperature is higher than that of the sidewall. For five inflation pressures, the tire gradients of temperature are shown in “Fig. 10”. It is evident that for 100 kPa inflation pressure, the most severe condition occurs for the tire because of huge cyclic deformations in shoulder and tread regions. In other words, a tire with lower internal pressure endures higher deflection and deformation for given applied loads and more strain energy is stored inside it. So, the convenient value of inflation pressure can guaranty the safe service life of the tire. The effect of axle load on the gradient temperature of the tire is given in “Fig. 11”. The lower parts of the tire are greatly affected by increasing axle loads.

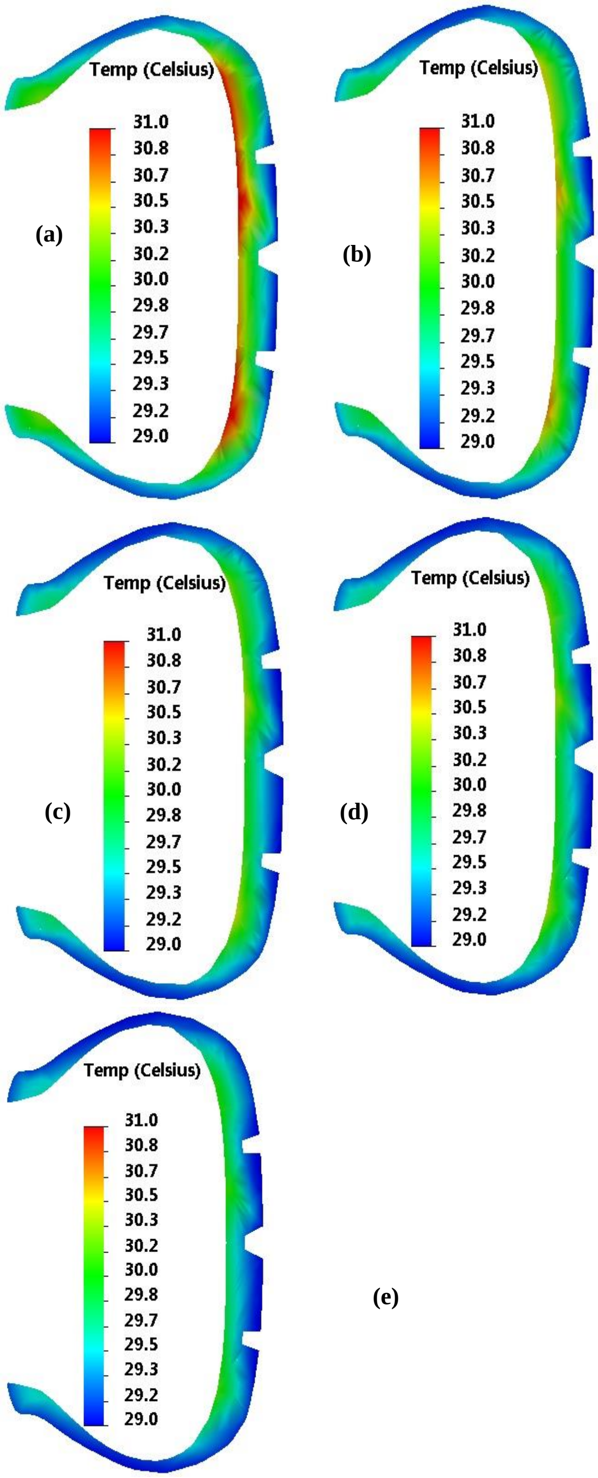

Fig. 10 Gradient of tire temperature for various inflation pressures: (a): 100 kPa, (b): 150 kPa, (c): 200 kPa, (d): 250 kPa and (e): 300 kPa.

In these regions, both stress and strains are very high [16] and huge hysteretic heating is generated. It is noted that the shoulder and tread regions have thicker layers of rubber than other parts of the tire. For shoulder and tread regions, which are made of a poor conductivity substance, the high generated heat causes severe thermal conditions. It can be easily noted that increasing axle loads leads to the higher amount of heat generation temperatures.

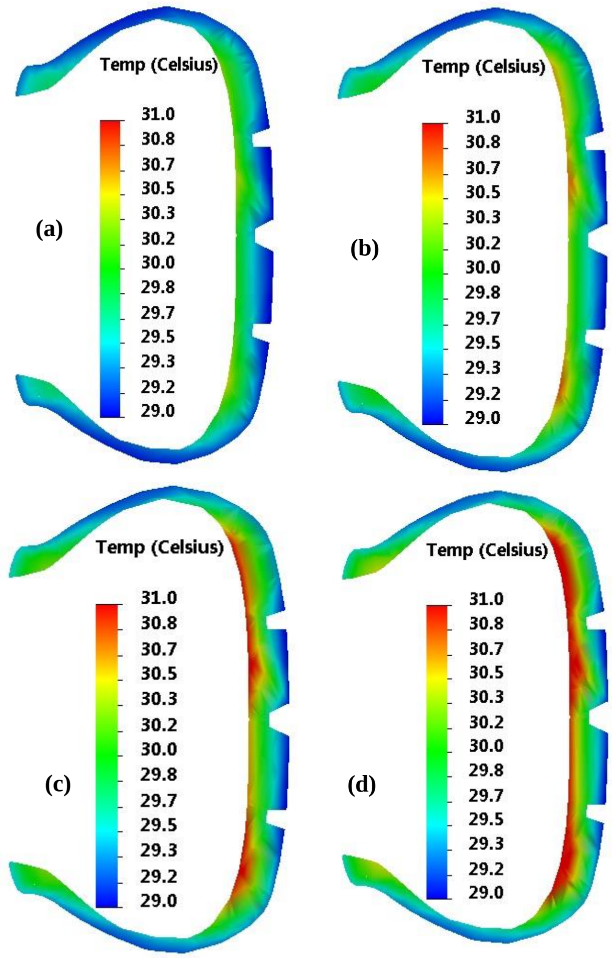

Fig. 11 Gradient of tire temperature for various axle loads: (a): 2 kN, (b): 2.5 kN, (c): 3kN and (d): 3.5kN.

For different operating conditions, the variation of the average temperature of inside inflated air and the maximum temperature induced in the tire are given in Figures 12-14. According to the results, for the most critical cases, i.e. high rolling speeds, huge axle loads and low inflation pressures, the average inflation pressure has a negligible increase compared with what happens to the tire. It is noted that for the worst condition, the air temperature is increased just by 3.33%. However, the working conditions have intense effects on the tire structure. It is noted that when the axle load increases from 2 kN to 3.5 kN, the peak temperature of the tire is about 8.62% more than the air average temperature, while, the increase in air temperature does not exceed 0.5ºC. By decreasing the inflation pressure from 250 kPa to 100kPa, the tire peak temperature would be 6.7% more than the average temperature of the air.

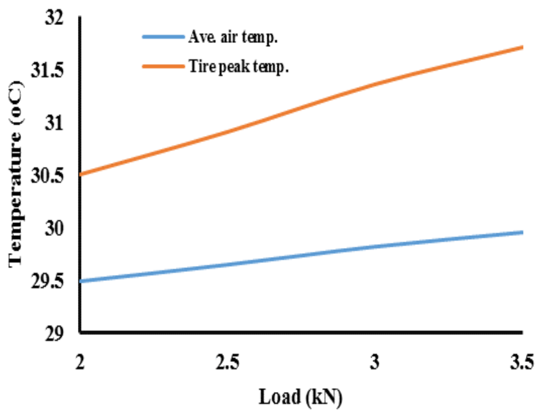

Fig. 12 The average temperature of the air and maximum temperature of the tire for different axle loads.

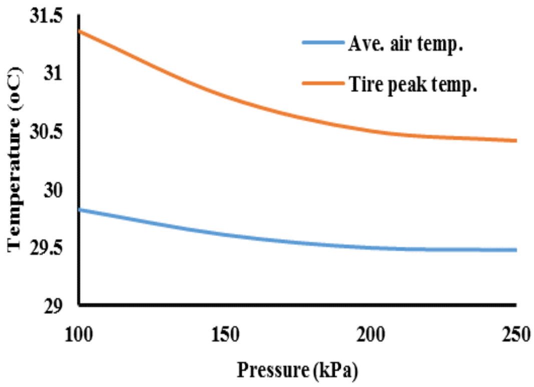

Fig. 13 The average temperature of the air and maximum temperature of the tire for various inflation pressures.

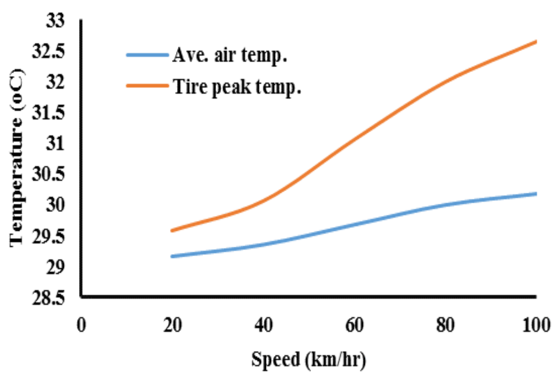

Fig. 14 The average temperature of the air and maximum temperature of the tire for various rolling speeds.

As result, the axle load has a more effective role in increasing the tire temperature. However, the most serious parameter in temperature variation of a rolling tire is the speed. According to the results, when the tire speed increases from 20 km/hr to 100 km/hr, the peak temperature of the tire will increase by 13.87%. The trend of results shows that the temperature gradient of the tire would be even more intensified for higher rolling speeds.

4 CONCLUSIONS

In the current study, a 3D FE model of the 185/60R15 radial tire has been developed for the determination of the transient variation of temperature under combined effects of loading, velocity and inflation pressures. For all considered cases, it has been found that the inner side of shoulder and belt region experiences the peak temperatures and the sidewall would be the coolest part of the tire.
The results show that the speed is the most effective parameter in increasing the tire temperature. It is noted that the heat generation rate resulted from dissipated strain energy, is directly dependent on the frequency of the cyclic deformations of a rolling tire. When the speed is set to 100 km/hr, the peak temperature of the tire is found to be about 11.86% more than the average temperature of inside inflated air.
The tire axle load has a significant effect on both tire peak temperature and thermal distribution for inside air. According to the results, by 1.4 kN increase in the tire velocity, the peak temperature of the tire and the average temperature of inside air will increase by 6 % and 1.7% respectively. So, the axle load mainly affects the tire rather than the inner air.
The inflation pressure also found to have an impressive effect on the distribution of temperature. The high temperature area will considerably decrease as the inflation pressure of inside air increases. The results of the experimental measurements are used to show the consistency and accuracy of the current study. The comparison shows that the proposed method predicts the temperature of several points inside the tire air-filled volume with relative error less than 3%.

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