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RANS 3D CFD simulations to enhance the thermal prediction of tyre thermodynamic model: A hierarchical approach

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ABSTRACT

In this work, a combined numerical/experimental analysis is performed for an automotive tyre. A preliminary experimental activity is realized on examined tyre to measure the temperatures of its layers under various operating conditions. In a second stage, a 3D CFD model of tyre is developed in a commercial code and steady RANS simulations are performed in the full range of angular velocity with the aim to refine the prediction of convective thermal power and heat transfer coefficient. CFD simulation results are passed to a user-defined 3D thermodynamic model to furnish a detailed and reliable tyre thermal output with the advantage of a low computational time. Tyre thermodynamic model, enhanced by CFD-related thermal characteristics, demonstrates the capability to properly forecast the measured temperature of tyre layers in a wide range of investigated operating conditions. The proposed numerical approach represents a valuable tool supporting the optimization of tyre behavior and the development of advanced control rules for optimal tyre management.

1. Introduction

In the last years, an increasing interest is devoting to the optimal overall vehicle performance, starting from the optimization of tyre behavior under various operating conditions. To this aim, many research efforts have been developed to correctly understand and subsequently reproduce the tyre/road interaction, due to its great influence on vehicle dynamics [1–4]. Despite the huge progress in the sensing technology, the estimation of tyre parameters not directly acquirable, such as the thermal flows, could contribute to the development of proper "on-board" vehicle control logics, particularly useful for smart and autonomous driving vehicles. Basing on the above consideration, the numerical approach can represent a decisive factor to forecast the tyre thermal characteristics and to support the development of the optimal control logics, especially in transient conditions [5–7]. On a general point of view, a tyre thermal model should provide accurate and real-time outputs, taking into account system characteristics in detail. Of course, this still represents a challenging task. Indeed, a full tridimensional (3D) tyre structure has to be taken into account, as well as the proper definition of its composite nature [8,9]. This means that all geometrical characteristics and material properties are mandatory to adequately reproduce the highly non-linear behavior of tyre at varying the operating conditions, including forces, velocity, inflation pressure, etc. [10]. Although representing a hard task, the physical-based tyre modelling, enhanced on the thermal point of view, allows the thermal management to reach the optimal conditions and the maximum performance levels of tyre both for passenger vehicles and racing applications. In this way, the thermal energy transfer mechanism from brake to wheel rim and from the latter to the internal air and tyre compound can be adequately controlled during individual vehicle maneuvers.

In the light of the above discussed scenario, the accurate prediction of heat transfer for tyres represents a relevant topic, as already highlighted by a number of papers available in technical literature [11–20], also considering the widely demonstrated relationship between tyre performance and temperature [21–23]. This aspect assumes a remarkable relevance, especially in sports applications, to properly control the friction and viscoelastic effects on tyre performance. Different modelling approaches can be adopted to simulate the tyre thermal behavior, including simple mathematical correlations [11,12], 3D interconnected nodal models [13], and Finite element (FE) methods [14,15]. As an example, Kelly et al. [11] adopted an "isotropic brush" mechanical model for tyre and considered a simple mechanism for the prediction of tyre temperature variations. Also Sarniotti [12] proposed a semi-empirical method to reproduce the tyre temperature and incorporated the effects in a brush model.

The authors proposed in a previous work [13], a 3D nodal model for

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tyre structure showing the interesting potential to reproduce large motions and deformations with an acceptable computational effort. The proposed 3D model still presented the lack of advanced physical sub-models to refine the temperature prediction of different tyre layers. Tang and Wang [14,15] performed a numerical study employing a FE approach, coupled to a thermal model, based on Fourier equation, to evaluate the effects of inflation pressure and loading on temperature distribution of a rolling tyre under steady state conditions.

Of course, simple mathematical models appear desirable for their reduced computational cost; however, they still show some drawbacks in capturing thermal characteristics, due to the lack of information regarding system geometrical schematization and physical phenomena.

Conversely, 2D or 3D FE models present greater computational cost, mainly depending on the nodal or mesh resolution, while they furnish reliable outcomes for convective thermal flows at tyre walls. In addition, these models offer wider details, allowing for a better understanding of physical phenomena at varying the operating conditions. Similar features are showed by 3D nodal tyre model with the advantage to preserve the computational cost. In addition, these models if properly enhanced through the prediction of some input variables, especially the thermal ones, can represent an efficient numerical tool to be employed for "real-time" simulations aiming to the development of optimal tyre control strategies for improved vehicle performance.

In this paper, in a first stage, an experimental campaign is performed on tyre mounted on the test bench to acquire its characteristic temperatures over different operating conditions, including the variation in inflation pressure, vertical load and angular velocity.

Then, a full 3D CFD model for tyre is developed in a commercial code (ANSYS Fluent), considering the undeformed geometry configuration. The model is employed to compute tyre thermal characteristics, especially in terms of convective heat transfer, under steady state conditions and at varying its rotational speed. 3D-derived heat transfer coefficients of tyre sub-domains are utilized as input parameters in a "user-defined" 3D tyre thermodynamic model, through the development of a fitting curve interpolating the CFD findings. This procedure represents the novelty of the work and shows the main advantage of reliable predictions for tyre thermal performance with an acceptable computational effort. Tyre thermodynamic model is proved in simulating measured temperatures of tyre layers, showing the capability to achieve satisfactory agreements between numerical and experimental temperatures in a wide range of investigated conditions. The experimental validation of the here proposed methodology represents a relevant aspect which contributes to underline its robustness and validity.

This modelling feature opens the possibility to numerically explore tyre operating conditions differing from those here measured and also to perform a virtual physical-based optimization.

2. Experimental activity

The experimental activity on examined automotive tyre is performed on a "Flat-trac" test bench to acquire thermal data with the possibility to explore various working conditions, including variations in different parameters such as vertical loads, internal air pressure, angular velocity, slip ratio, slip/camber angles, etc. [24,25]. The Flat-trac tyre test bench includes a hydraulically operated tyre support, a wide-range loading system, a controlled brake device, a complete sensor system, and a data acquisition and control system which continuously monitors the experimental variables. In the present study, tests are carried out to acquire a proper dataset to be employed for the validation of enhanced thermodynamic model. To this aim, tests are realized at a constant vehicle velocity of 100 km/h along time evolution (Table 1), considering three levels for both internal air pressure (2, 2.5 and 3 bar) and vertical load (800, 1500 and 3000 N). Tyre was equipped with different sensors to measure temperatures and to control the internal air pressure during the experiments. In particular, the temperature of inner liner is acquired at different positions using a wireless 8 channels sensor (8 laser beams). TPMS sensor was positioned on tyre valve body and used to measure both pressure and temperature of inner air. A thermal imaging camera was adopted to measure the temperature of contact patch. Furthermore, an infrared sensor was employed to acquire the groove temperature. All sensors were connected to a dedicated data acquisition system (Analog/Digital CAN Bus).

Table 1
Analyzed operating conditions for tyre at constant vehicle speed of 100 km/h.

Parameter									
Time (s)	1500	3000	4000	5500	7000	8000	9500	11000	12000
Pressure (bar)	3,0	2,5	2,0	3,0	2,5	2,0	3,0	2,5	2,0
Load (N)	800	800	800	1500	1500	1500	3000	3000	3000

3. CFD model

The grid for CFD analyses has been generated starting from a CAD model of a tyre for automotive applications. Main features of considered tyre are listed in Table 2.

A hydrid mesh is realized for tyre domain in a commercial meshing tool, taking into account proper refinements at walls. In particular, the standard meshing tool available within the ANSYS Fluent is employed. The hybrid mesh counts a total number of 4 million cells. Regular tetrahedron elements are employed due to their simplicity and capability to better fit to complex geometry. Mesh represents a proper selection based on a preliminary grid dependency analysis. As known, a convergence analysis is performed with the aim to highlight a substantial convergence of numerical outcomes at varying the mesh dimension. This analysis was carried out by generating and testing three different grids characterized by a decreasing total cell number: ~13, 4 and 2 million cells. Convergence study demonstrated that heat transfer coefficients and thermal powers of tyre reached the same values for cases at 4 and 13 million cells.

Therefore, the adopted grid (4 million cells in Table 3) represents a compromise between the accuracy of predictions and computational effort. Mesh quality and stability is verified to guarantee reliable 3D numerical simulations; to this aim, some mesh characteristics are controlled, including the aspect ratio, skewness and dimensionless wall distance y+. Fig. 1 reports a detail of hybrid mesh, also depicting a zoom at wall boundary to highlight the relative mesh refinement. In addition, Table 3 shows a comprehensive list of characteristics of the adopted mesh and the selected tolerances for mesh parameters during the convergence analysis.

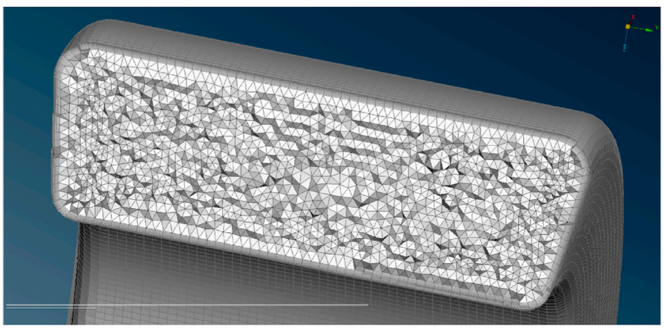
The adequate resolution of boundary layer is proved by wall y+; a value below one, as in the case of generated mesh, ensures a reliable resolution of flow field close to the walls. This choice represents a best practice in the case of laminar-to-turbulent transition and special

Table 2
Tyre characteristics.

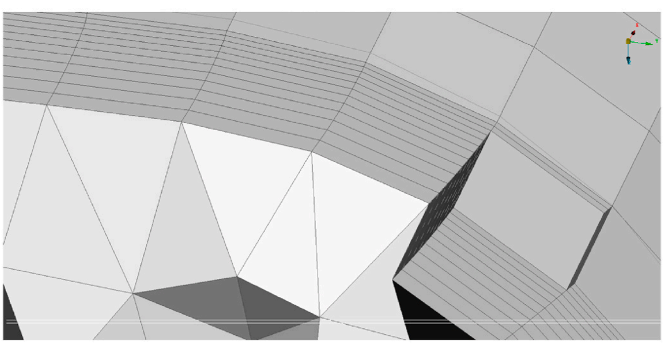
Model	Automotive
Inner liner radius and width	320/310 mm
Rim radius and width	220/279 mm
Inner liner area	0.664 m^2
Rim area	0.410 m^2
Sidewall area	0.108 m^2

Table 3
Mesh details.

	Hybrid Mesh	Tolerance for convergence study
Total cell number	4 million	2 ÷ 13 million
Cell Type	Tetrahedron	
Meshing Method	Semi-automatic	
Inflation	Code Controlled	
Number of boundary layers	10	5 ÷ 10
Growth rate	1.15	1.2
Average aspect ratio	~2.5	1 ÷ 5
Skewness	0.4	0.25 ÷ 0.5
Maximum Wall y+	$\sim 5{\cdot}10^{-1}$	<1



(a)



(b)

Fig. 1. Adopted hybrid mesh: global overview (a), details at wall boundary (b).

accuracy demands for heat transfer calculations, as discussed in literature papers and CFD scientific community [26,27]. In a previous authors' work, reporting a quite similar CFD study, the quality of employed grid close to walls was ensured with a wall y + well below unity (max y + equal to $4.4{\cdot}10^{-1}$) [28].

Concerning the 3D model setup, RANS simulations are realized using the Fluent solver of ANSYS. Considering the undeformed geometry of tyre the incompressible solver is selected with the pressure-velocity coupling formulation. Turbulence is reproduced by the K-ω SST model and a second order numerical scheme is employed both for the mean flow and turbulence fields. Tuning constants of adopted turbulence model are kept unchanged with respect to the recommended values by the code [29].

The air inside the tyre domain is modelled as incompressible ideal gas, and this approximation is quite reasonable for the case study, considering that the Mach number is well below 0.3. The latter level represents the maximum threshold for the incompressible fluid hypothesis corresponding to a fluid density variation of 5%. The initial air operating pressure is set at 2 bar. Concerning the boundary condition at walls, fixed temperatures are defined at each wall surface and different values are assigned to inner liner, rim and side-wall surfaces (Table 4), based on authors' knowledge. They are typical average levels for an automotive tyre.

It is worth to emphasize that the selected constant set of wall temperatures represents a "first-attempt" choice. Of course, a more rigorous analysis requires the modification of the set of wall temperatures according to the operating conditions. For instance, the variability of wall temperatures with tyre operations can be captured by measurements with infrared sensors. This drawback could affect the prediction of heat transfer coefficients and the agreements with the experimental data.

A moving wall boundary condition is considered to simulate tyre rotation around its own axis. Further information about 3D model setup can be found in a previous authors' paper [28]. The overall adopted assumptions for CFD analyses (undeformed tyre geometry, steady operation and constant average wall temperatures) represent a basic level in the case of a tyre simulation. This approach has been selected because it shows the advantage of a very simple modelling which furnishes quite reasonable outcomes and reduced error predictions, especially when low tyre deformations and not extended variations in the operating conditions occur.

Anyway, the employed assumptions can be considered as a starting point to be further refined for more accurate CFD investigations.

3.1. Description of CFD analyses

CFD analyses are carried out with main aim to derive the convective heat transfer coefficients of inner liner and rim in steady-state conditions by varying the tyre angular velocity. The investigated angular velocities cover a wide range of values up to the maximum allowable level of 187.5 rad/s for the considered tyre. Five discrete velocities are taken into account for the 3D simulations, as depicted in Table 5.

At each investigated angular velocity, the numerical convergence of thermal variables and related convective coefficients is verified. The consistency of 3D simulations is also proved considering the exchanged thermal powers by the tyre sub-domains. As expected, under steady state operations the net thermal power of tyre domain substantially reaches the null value at varying the angular velocity. Once verified the reliability of 3D CFD model in reproducing thermal characteristics of tyre in steady conditions, the convective heat transfer coefficients (related to ambient air) are computed by 3D simulations only for inner liner and rim because of their relevance in the heat exchange of tyre. The latter represent a fundament prerequisite to estimate the temperature of tyre walls through a refined 3D thermodynamic model, discussed in the following. Computed CFD-related heat transfer coefficients are fitted within MATLAB code to establish fitting curves. In this way, if the thermodynamic tyre model runs outside or among the CFD simulated conditions the individual heat transfer coefficient is reproduced by the corresponding fitting curve.

4. 3D thermodynamic model of tyre

Tyre thermodynamic model here adopted has been developed by authors and deeply discussed in previous papers [13,28,30]. It is based on the application of Fourier diffusion equation to the 3D heterogeneous domain of the wheel. This equation is generalized per each node of the entire wheel, considering the characteristics of various materials, according to the position in the 3D domain. In this way, a system of 1st differential equations in the typical matrix form (1) is solved:

Table 4
Temperatures at tyre wall surfaces.

Temperature	(°C)
Inner liner	90
Rim	50
Sidewalls	70

Table 5
CFD simulations for various tyre angular velocities.

Case Number	Angular velocity (rad/s)
1	37.5
2	75.0
3	112.5
4	150.0
5	187.5

$$\begin{Bmatrix} \frac{\Delta T_1}{\Delta t} \\ \frac{\Delta T_2}{\Delta t} \\ \vdots \\ \frac{\Delta T_n}{\Delta t} \end{Bmatrix} = \begin{Bmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{Bmatrix} + \begin{bmatrix} a_{1,1} & \cdots & a_{1,n} \\ \vdots & \ddots & \vdots \\ a_{n,1} & \cdots & a_{n,n} \end{bmatrix} \begin{Bmatrix} T_1 \\ T_2 \\ \vdots \\ T_n \end{Bmatrix} \tag{1}$$

A scheme of the employed thermodynamic model for the wheel is depicted in Fig. 2. Based on this model representation, heat generations and all possible transfer mechanisms (conduction, convection and radiation) are taken into account for the wheel.

A detailed list of considered thermal processes in the developed model is reported in the following:

- Heat generations, related to tangential interaction at tyre/road interface (Friction), cyclic deformation of tyre during rolling and tyre structure deformation for tangential loads (SEL, Strain Energy Loss);
- Heat conduction involving the different materials within the tyre structure, also including the contact patch zone between rubber compound and road texture;
- Heat convection terms: the first one related to interaction of tyre with the external environment; the second one concerns the interaction of inner air with the surfaces of inner liner, rim and sidewalls;

$$\frac{\Delta T_{(InAir)}}{\Delta t} = \frac{1}{\rho \cdot c_v V}\left[h_{Rim}(V)A_{Rim,InnAir}(T_{Rim} - T_{InAir}) + h_{Innerliner}(V)A_{InLiner,InnAir}(T_{InLiner} - T_{InAir})\right] \tag{2}$$

- Additional convective and radiative fluxes (heating or cooling sources) from brakes or exhaust gases, mainly affecting the rim;

A particular attention is paid to the modelling of the conductive

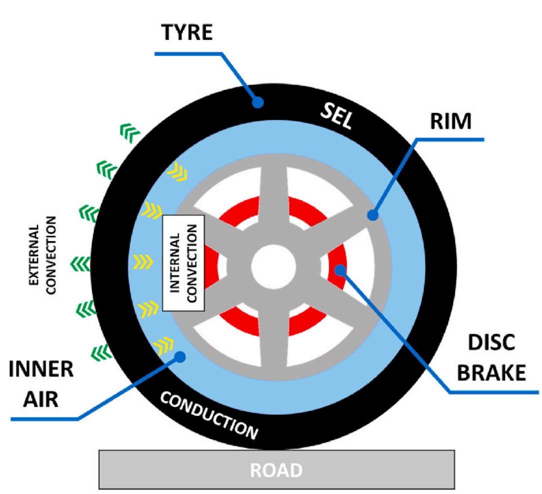


Fig. 2. Scheme of the thermal exchanges considered in the model for wheel, including tyre, inner air, rim and brake disc.

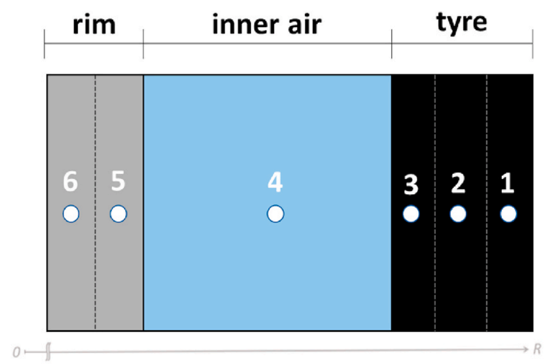


Fig. 3. Radial thermal flux for wheel: a simple sketch.

mechanism within the tyre. It has to be underlined that the composite nature of tyre layers (rubber, steel belts, plies, etc.) is schematized in a fully 3D configuration, considering the dependency of thermal properties of each material on temperature level. Main purpose of present research work is the enhanced prediction of heat exchanges involving the inner air. Therefore, the modelling of the radial thermal flux in the wheel assumes a relevant role. Radial thermal flux is here treated basing on the representation proposed in Fig. 3, where six nodes are considered. They schematize the thermal fluxes from the external rim to the tyre surface in contact with road. Detailed explanations per each node of schematized radial thermal flux are reported in the following Table 6.

As already discussed, tyre thermodynamic model is defined through a system of differential equation (1), requiring certain input parameters. As an example, equation (2) is written for the case of inner air. It clearly highlights the presence of unknown variables named h_{Rim} and $h_{InnerLiner}$, representing the convective heat transfer coefficients for rim and inner liner surfaces, respectively:

Actually, a simple integration of the CFD and the 3D thermodynamic models has been taken into account. It consists in the so-called "one-way" exchange data mechanism between models, where the computed convective heat transfer coefficients by CFD model are passed to the thermodynamic one, without the need for iterations between models. This simple procedure of integrated models represents the main novelty of present study and in this way the 3D thermodynamic model gains an

Table 6
Nodes in radial schematization of thermal flux for tyre.

Node	Schematized tyre component	Thermal interactions or function
1	External surface of rubber compound (tread)	External convective flux and thermal exchanges regarding tyre/road interaction
2	Rubber compound layer (belt)	Description of tyre grip and stiffness dependencies towards temperature and pressure effects
3	Equivalent carcass structure (carcass)	Thermodynamic description of inner tyre layers
4	Internal Air	Convective thermal flows with inner liner and rim surfaces
5	Metal alloy rim layer	Convective thermal exchange with internal air
6	External layer of rim alloy	External convective and radiative mechanisms with brakes, diffusers or heating/ cooling devices

improved reliability.

Once the integration between models is performed, the presented tyre thermodynamic model requires an average calculation time of 0.0004–0.0005 s on the Xeon simulator machine (150 nodes in the case of a passenger tyre) for each time step. Therefore, considering that the typical frequency employed within simulator automotive environments is 1 kHz the developed tyre model can be adopted both in real-time and off-line configurations.

5. Results and discussion

An essential characteristic of a 3D CFD model is represented by the prediction of flow fields inside the considered system at varying the boundary conditions. This aspect assumes a remarkably relevance in the case of tyre to guarantee an adequate reproduction of the actual thermal behavior. In the light of above considerations, an example of basic 3D CFD outcome is plotted in Fig. 4 referring to a constant tyre angular velocity of 187.5 rad/s. Consistently with the physical expectations, the flow field inside the rotating tyre (Fig. 4) shows an increasing gas velocity along the radial direction, resulting from the imposed rotation. Conversely, no substantial gas velocity variations along the axial direction are observed. Similar results are obtained for the other analyzed tyre angular velocities, but they are not shown here for brevity.

Once verified the reliability of computed flow fields inside tyre under steady rotating conditions, a thermal analysis is performed deriving the computed thermal power per each tyre sub-domain (Table 7).

Table 7 confirms that the exchanged thermal powers by tyre sidewalls are negligible with respect to the ones related to inner liner and rim. The adopted boundary temperatures (average constant values) do not exert a remarkable effect on the level of thermal power exchanged by the sidewalls.

In addition, the net thermal power substantially reaches the null value, underlining the model capability in reproducing the expected thermal equilibrium condition under the steady operation.

3D CFD model is employed to derive the convective heat transfer coefficients both for inner liner and rim (Fig. 5), being these tyre subdomains mostly interested in the heat transfer. As expected, Fig. 5 shows an increasing trend of computed heat transfer coefficients for rim and inner liner with tyre angular velocity. The increase in the angular velocity involves an enhanced convective heat transfer at walls, due to the greater turbulence value along the radial direction.

3D-derived heat transfer coefficients represent preliminary numerical data to be integrated in the thermodynamic model for a refined simulation of tyre temperature evolution at varying its operating conditions. The comparison of numerical temperatures provided by thermodynamic model against the measured ones for tyre surface and inner liner layer are shown in Fig. 6.

As depicted in Fig. 6a, nine characteristic points are selected along the temporal evolution of experiments on "Flat-trac" test bench. These points are properly differentiated by operating conditions: all possible combinations including three constant vertical loads and three internal air pressure are explored. In particular, an increasing load trend is observed along the temporal evolution of performed tests on tyre. It is the case to underline that the reference vertical load condition is the one at 1500 N; this last corresponds to a pure rolling condition and the wheel radius is equal to the case of the un-deformed configuration. Therefore, the load condition at 1500 N is a reference to evaluate the capability of developed thermodynamic tyre model enhanced by 3D CFD heat transfer coefficients. A certain attention is devoted to the prediction of inner liner temperature for its relevance on thermal effects within tyre structure. In addition, the experimental inner liner temperature represents the average temperature value among the measured ones at eight different positions. Referring to the tyre temperatures, Fig. 6b and c report the numerical/experimental comparisons for inner liner and external tyre surfaces in the measured characteristic points of Fig. 6a. Two different numerical temperatures are computed with thermodynamic model: the first one by employing the analytical formulation for the convective heat transfer coefficients, available in the literature [30] (called "Old-Corr."); the second one by using the convective heat transfer coefficients evaluated by 3D CFD model (called "3D CFD"). As can be noted in Fig. 6b, for the examined vehicle velocity (100 km/h)

Table 7
Computed thermal powers for tyre sub-domains through RANS simulation at different angular velocities.

Angular velocity, rad/s	Inner liner power, W	Rim power, W	Sidewall_1 Power, W	Sidewall_2 Power, W	Net Power, W
37.5	63.44	−63.30	−0.07	−0.07	0
75.0	109.88	−111.14	0.63	0.63	0
112.5	157.18	−159.21	1.015	1.015	0
150.0	208.63	−211.87	1.625	1.625	0.01
187.5	260.49	−262.22	0.89	0.89	0.05

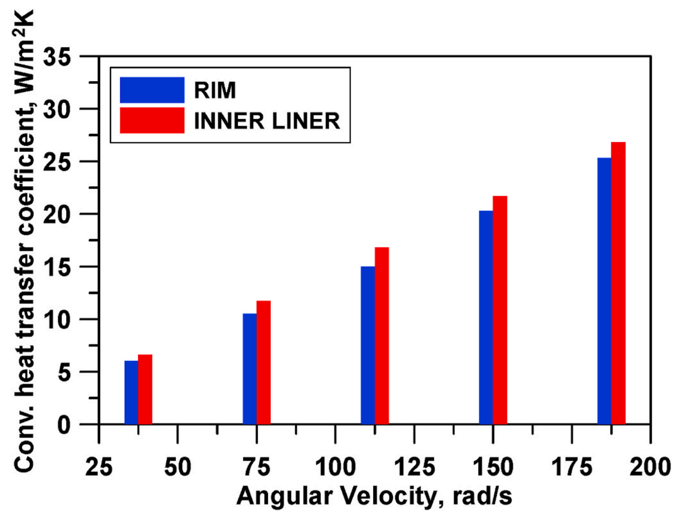


Fig. 5. 3D numerical convective heat transfer coefficients for Rim and Inner liner at varying the tyre rotational speed.

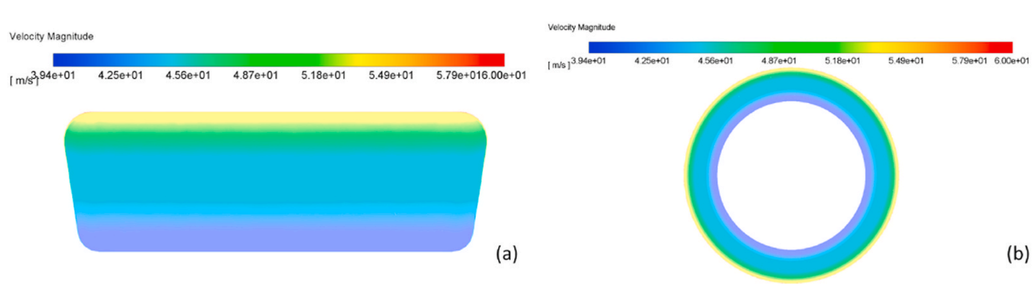


Fig. 4. Velocity distributions in cross (a) and longitudinal (b) sections for RANS simulation at angular velocity of 187.5 rad/s.

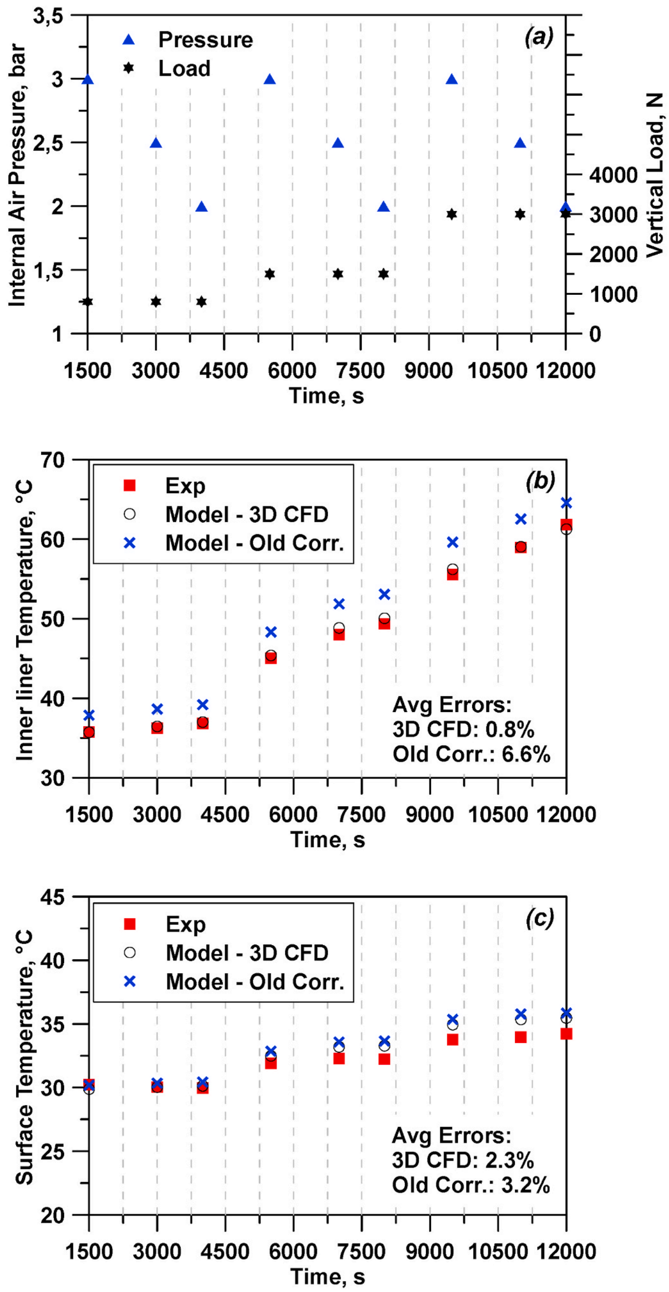


Fig. 6. Tyre operating conditions at vehicle velocity of 100 km/h (a); numerical/experimental comparisons of inner liner temperature (b) and surface temperature (c).

and tested conditions (Fig. 6a), a not negligible improvement in the numerical/experimental agreement for the inner liner temperature is realized when the CFD-related convective heat transfer coefficients are adopted. Indeed, the proposed CFD-enhanced thermodynamic model is capable of accurately predicting the measured evolution of inner liner temperature according to the tyre operating condition with a very low mean absolute percent error (~0.8% in Fig. 6b). In addition, an acceptable accuracy is also found for the reproduction of tyre surface temperature by the here presented CFD-enhanced thermodynamic model, reaching a mean absolute percent error slightly higher than 2.0% (Fig. 6c). For both computed temperatures (inner air and surface), CFD-enhanced thermodynamic model improves the predictions with respect to the previous model version, based on the analytical correlations for the convective heat transfer coefficients (see the mean absolute percent errors in Fig. 6b and c).

The discussed results demonstrate that the proper combination of a 3D CFD model and of a tyre thermodynamic one allows to provide fast and reliable thermal predictions of wheel layers under various operating conditions. Therefore, the numerical procedure is compatible with the real-time application in automotive simulator environments.

6. Conclusions

This work presents a hierarchical integration of a 3D CFD model with a 3D thermodynamic model for an automotive tyre. Computed convective heat transfer coefficients by 3D CFD model are passed to a thermodynamic model aiming to a fast and accurate simulation of tyre thermal behavior, especially in terms of tyre layers' temperatures. Convective heat transfer coefficients are estimated by 3D CFD model in steady state conditions for various tyre rotational speeds. CFD outcomes underline the negligible impact of sidewalls if compared to inner liner and rim surfaces in terms of exchanged thermal powers. This evidence involves the substantial employment of convective heat transfer coefficients related to the inner liner and rim as input variables for 3D thermodynamic model. The numerical outcomes of tyre structure model are compared to the measured data acquired by a dedicated flat trac test bench. A satisfactory agreement is reached between numerical and experimental tyre temperatures over the considered operating conditions and an improved prediction of inner liner temperature is realized, mainly thanks to the computed convective heat transfer coefficients by 3D CFD model. Summarizing, the proposed numerical methodology shows the capability to refine the thermal predictions of an automotive tyre, providing the basics for the subsequent numerical optimization studies. For the sake of completeness, it is worth noting that, to achieve the remarkable benefit of the methodology, an initial effort has to be paid to build the CFD analyses and to the relative computational costs, delegating the evaluation of the advantage in applying this methodology to a case-by-case assessment.

The future challenge for the development of this activity is the implementation of an automated numerical procedure integrating the CFD model the 3D thermodynamic. This means that the models will exchange the related data in real time during the entire simulation, enhancing the predictivity under transient conditions.

In addition, the authors will investigate the opportunity to employ a 2D CFD model to save the computational time, while preserving the reliability of numerical findings with respect to the 3D model. Finally, once adequately refined, the procedure can be adopted to perform robust and reliable optimizations aiming to identify optimal tyre performance at varying the operating condition.

Author contribution

Luigi Teodosio: Conceptualization, Methodology, Investigation, Formal analysis, Writing - Original Draft, Writing - Review & Editing; **Francesco Timpone**: Resources, Funding acquisition; **Guido Napolitano dell'Annunziata**: Validation, Visualization, Writing - Review & Editing. **Andrea Genovese:** Conceptualization, Methodology, Supervision, Writing - Original Draft, Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] M. Tanelli, M. Corno, S. Saveresi, Modelling, Simulation and Control of Two-Wheeled Vehicles, John Wiley & Sons, 2014.
[2] A. Sakhnevych, V.M. Arricale, M. Bruschetta, A. Censi, E. Mion, E. Picotti, E. Frazzoli, Investigation on the model-based control performance in vehicle safety

critical scenarios with varying tyre limits, Sensors 21 (16) (2021) 5372, https://doi.org/10.3390/s21165372.
[3] R.H. Smith, Analyzing Friction in the Design of Rubber Products and Their Paired Surfaces, CRC Press, Boca Raton, FL, USA, 2008.
[4] L. Gargallo, D. Radic, Physicochemical Behavior and Supramolecular Organization of Polymers, Springer Science & Business Media: Berlin/Heidelberg, Germany, 2009, pp. 43–162.
[5] L. Xiong, Z. Yu, Y. Wang, et al., Vehicle dynamics control of four in-wheel motor drive electric vehicle using gain scheduling based on tyre cornering stiffness estimation, Veh. Syst. Dyn. 50 (2012) 831–846.
[6] W.F. Milliken, D.L. Milliken, Race Car Vehicle Dynamics, vol. 400, Society of Automotive Engineers, Warrendale, PA, 1995.
[7] E. Villano, B. Lenzo, A. Sakhnevych, Cross-combined UKF for vehicle sideslip angle estimation with a modified Dugoff tire model: design and experimental results, Meccanica (2021), https://doi.org/10.1007/s11012-021-01403-6.
[8] B. Lorenz, B. Persson, G. Fortunato, et al., Rubber friction for tire tread compound on road surfaces, J. Phys. Condens. Matter 25 (2013), 095007.
[9] V.L. Popov, Contact Mechanics and Friction, Springer, Berlin, 2010.
[10] G. Kmavros, H. Rahnejat, P.D. King, Investigation of steady-state tyre force and moment generation under combined longitudinal and lateral slip conditions, in: Proceedings of the 18th IAVSD Symposium Held in Kanagawa, Japan, 24, 2004, pp. 351–360, 30 August, 2003.
[11] D.P. Kelly, R.S. Sharp, 'Time optimal control of the race car: influence of a thermodynamic tyre model', Vehicle System Dynamics, International Journal of Vehicle Mechanics and Mobility 50 (4) (2012) 641–662, https://doi.org/10.1080/00423114.2011.622406.
[12] A. Sorniotti, Tire Thermal Model for Enhanced Vehicle Dynamics Simulation, SAE International Technical Paper, 2009, 2009-01-0441, doi: 104171/2009-01-0441.
[13] F. Farroni, A. Sakhnevych, F. Timpone, A three-dimensional multibody tire model for research comfort and handling analysis as a structural framework for a multi-physical integrated system, Proc. Inst. Mech. Eng. - Part D J. Automob. Eng. 233 (1) (2019) 136–146, https://doi.org/10.1177/0954407018799006.
[14] T. Tang, et al., Numerical Evaluation of the temperature field of steady-state rolling tires, Appl. Math. Model. 38 (2014) 1622–1637, https://doi.org/10.1016/j.apm.2013.08.033.
[15] Wang, Z. Finite element analysis of mechanical and temperature field for a rolling tire. In Proceedings of the IEEE 2010 International Conference on Measuring Technology and Mechatronics Automation, Changsha, China, 13–14 March 2010; IEEE: Piscataway, NJ, USA.
[16] C. Allouis, F. Farroni, A. Sakhnevych, F. Timpone, Tire thermal characterization: test procedure and model parameters evaluation, Proceedings of the World Congress on engineering 2 (2016).
[17] F. Calabrese, M. Baecker, C. Galbally, A. Gallrein, A detailed thermo-mechanical tire model for advanced handling applications, SAE International Journal of Passenger Cars-Mechanical Systems 8 (2015) 501–511.
[18] M. Pearson, O. Blanco-Hague, R. Pawlowski, TameTire: introduction to the model, Tire Sci. Technol. 44 (2) (2016) 102–119.
[19] L. Romano, A. Sakhnevych, S. Strano, et al., A novel brush-model with flexible carcass for transient interactions, Meccanica 54 (2019) 1663–1679, https://doi.org/10.1007/s11012-019-01040-0.
[20] M. Gipser, FTire-the tire simulation model for all applications related to vehicle dynamics, Veh. Syst. Dyn. 45 (S1) (2007) 139–151.
[21] R.S. Sharp, P. Gruber, E. Fina, Circuit racing, track texture, temperature and rubber friction, Veh. Syst. Dyn. 54 (4) (2016) 510–525.
[22] G. Mavros, A thermo-frictional tyre model including the effect of flash temperature, Veh. Syst. Dyn. 57 (5) (2019) 721–751.
[23] Jorge Sergers, Analysis techniques for racecar data acquisition. Analysis Techniques for Racecar Data Acquisition, SAE, 2014, pp. i–xviii.
[24] J.A. Cabrera, A. Ortız, A. Simon, et al., A versatile flat track tire testing machine, Veh. Syst. Dyn. 40 (2003) 271–284, https://doi.org/10.1076/vesd.40.2.271.16542.
[25] M.G. Pottinger, Flat-trac II(R) machine, the state-of the- art in tire force and moment measurement, Tire Sci. Technol. 20 (1992) 132–153, https://doi.org/10.2346/1.2139513.
[26] T. Ahmad, S. L. Plee, and J. P. Myers. Fluent User's Guide.
[27] M. Ahmadvand, A.F. Najafi, Shahidinejad, An experimental study and CFD analysis towards heat transfer and fluid flow characteristics of decaying swirl pipe flow generated by axial vanes, Meccanica 45 (2010) 111–129, https://doi.org/10.1007/s11012-009-9228-9.
[28] L. Teodosio, G. Alferi, A. Genovese, F. Farroni, B. Mele, F. Timpone, A. Sakhnevych, A numerical methodology for thermos-fluid dynamic modelling of tyre inner chamber: towards real time applications, Meccanica 56 (2021) 549–567, https://doi.org/10.1007/s11012-021-01310-w.
[29] ANSYS Fluent User's Guide R-17, 2, 2016.
[30] F. Farroni, M. Russo, A. Sakhnevych, F. Timpone, TRT EVO: advances in real-time thermodynamic tire modeling for vehicle dynamics simulations, Proc. Inst. Mech. Eng. - Part D J. Automob. Eng. 233 (2019) 121–135, https://doi.org/10.1177/0954407018808992.

Glossary

Notations

A: Area
c_v: Specific heat at constant volume
h: Heat transfer coefficient
$\dot{Q}$: Heat transfer power
t: Time
T: Temperature
V: Volume

Greeks

ρ: density

Acronyms

2D/3D: Two/Three dimensional
CAD: Computed Aided Design
CFD: Computational Fluid Dynamics
DX: Right side
FE: Finite Element
RANS: Reynolds Averaged Navier Stokes
SEL: Strain Energy Loss
SST: Shear Stress Transport
SX: Left side
TPMS: Tyre pressure monitoring system