Aerodynamic and Thermal Performance Analysis of Race Car Tyres

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Abstract - This project analyzes the aerodynamic and thermal performance of race car tyres made from Silicone Rubber (VMQ) using CFD simulations in SolidWorks. Four tread designsAero-V Channel, Deep Flow Channel, Linear Groove, and Curved Flow Groovewere tested at speeds of 150 km/h and 200 km/h. According to the findings, tread geometry has a significant impact on the behavior of airflow, the distribution of pressure, and temperature stability. The Deep Flow Channel design achieved the best aerodynamic efficiency with uniform pressure and consistent temperature control at both speeds. Additionally, the Curved Flow Groove demonstrated reduced heat buildup and balanced airflow. In contrast, the Aero-V Channel and Linear Groove exhibited uneven pressure zones and higher thermal variations. Overall, optimized tread patterns improve drag reduction, cooling performance, and high-speed stability. These findings support the development of safer and more efficient high-performance tyres.

Keywords- Tyre Aerodynamics, Thermal Analysis, CFD Simulation, Tread Geometry, Silicone Rubber (VMQ), Drag Reduction, Heat Dissipation, High-Speed Performance.

I.INTRODUCTION

Race car tyres play a critical role in determining vehicle performance, safety, and stability, as they represent the only contact interface between the car and the track surface. Beyond supporting vehicle weight, tyres transmit driving and braking forces, enable cornering control, and absorb road irregularities. In high-speed motorsport, tyre performance is significantly influenced by aerodynamic forces and thermal behavior, which affect rolling resistance, drag, grip consistency, and durability. Excessive heat buildup, pressure fluctuations, and aerodynamic turbulence can reduce traction and accelerate wear, thereby limiting race performance. As modern racing demands ever-higher speeds and tighter safety margins, optimizing tyre aerodynamics and temperature management has become a vital engineering focus.

The performance of a racing tyre primarily depends on tread design and material selection. Tread geometry governs airflow behavior, turbulence formation, and cooling efficiency around rotating tyres, while tyre compounds determine grip levels, wear resistance, elasticity, and heat tolerance. Recent studies have shown that optimized tread geometries can significantly reduce aerodynamic drag and stabilize airflow, while material composition plays a crucial role in managing rolling resistance and thermal dissipation. Compounds reinforced with silica and carbon black have proven effective at balancing grip and rolling efficiency, whereas advanced elastomers provide superior temperature stability. Among the materials widely used in racing tyres, Vinyl Methyl Silicone Rubber (VMQ), Ethylene Propylene Diene Monomer (EPDM), and Nitrile Butadiene Rubber (NBR) are notable for their mechanical durability, resilience to thermal stress, and elasticity under high dynamic loading conditions.

A typical race car tyre consists of several integrated structural elements including the tread, sidewall, bead, carcass, and inner liner, each serving a unique functional purpose. The tread ensures traction and cooling, the sidewall balances flexibility and stiffness for cornering stability, the bead secures mounting safety, the carcass maintains load-bearing integrity, and the inner liner preserves airtight pressure stability. Additional performance parameters such as tread pattern, tyre width, diameter, sidewall stiffness, and compound formulation further control deformation, heat distribution, rolling losses, and handling response.

Slick, wet, intermediate, and hybrid tyres are designed to operate across differing track and weather conditions, while modern motorsport primarily employs radial constructions due to their lower rolling resistance, effective heat management, and improved driving control.

Extensive research has demonstrated that tyre aerodynamic behavior, thermal performance, deformation characteristics, and pressure management are interdependent factors shaping overall performance. Computational and experimental investigations reveal that specific tread patterns, such as symmetric and optimized-channel grooves, enhance airflow stability and reduce aerodynamic drag. Finite Element Analysis has shown the importance of contact-patch deformation in maintaining grip and controlling wear, while transient thermal models emphasize the role of viscoelastic heating in rolling resistance losses. Studies on tyre inflation pressure further confirm its direct impact on stability, fuel consumption, comfort, and safety. Among these approaches, Computational Fluid Dynamics (CFD) has emerged as a powerful tool to visualize airflow structures, pressure fields, temperature distributions, and drag forces around rotating tyres, enabling cost-effective performance evaluation and design refinement beyond what conventional physical testing alone can achieve.

Despite these advancements, accurately balancing drag reduction, thermal control, and grip optimization remains challenging, particularly under extreme racing conditions where aerodynamic loads and heat generation are severe. Traditional development methods require extensive prototyping and track testing, which are time-consuming and costly while offering limited insight into local airflow and temperature variations across the tyre surface. This study addresses these challenges by adopting a CFD-based evaluation framework capable of capturing detailed aerodynamic and thermal interactions of race car tyres under controlled simulation conditions.

Therefore, the primary objective of this research is to analyze and optimize the aerodynamic and thermal behavior of VMQ-based race car tyres operating at high speeds of 150 km/h and 200 km/h. Four tread geometries Aero-V Channel, Deep Flow Channel, Linear Groove, and Curved Flow Groove are investigated to assess airflow velocity distributions, pressure variations, and surface temperature characteristics. The goal is to identify the tread configuration that produces minimum aerodynamic drag, superior cooling efficiency, and stable pressure behavior, thereby enhancing high-speed handling, safety, durability, and overall racing performance. This simulation-based methodology provides a reliable and economically efficient approach for developing next-generation high-performance racing tyres.

.II. METHODOLOGY

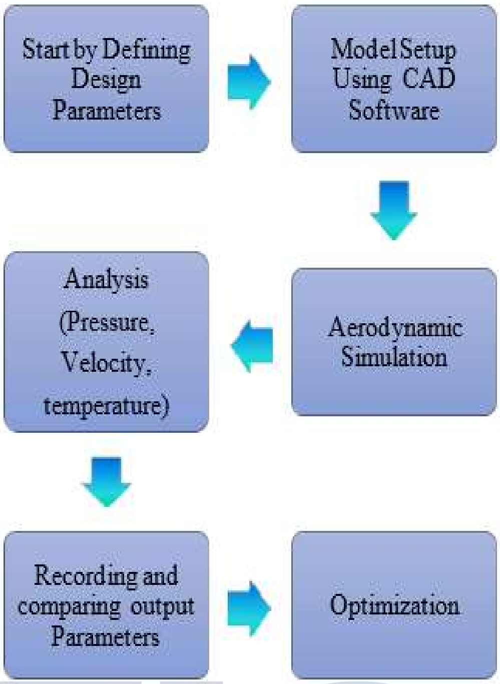


Fig.1 Block Diagram

The model is prepared, CFD simulations are conducted to study aerodynamic behavior. These simulations analyze airflow around the tyre, capturing pressure distribution, velocity profiles, and turbulence effects. The results provide critical insights into drag, flow separation, and heat accumulation, helping engineers understand how the tyre design impacts performance characteristics such as rolling resistance, grip, and thermal efficiency.

After the simulations, key parameters such as pressure, velocity, and temperature are recorded and compared against target performance values. This comparison identifies areas for improvement, allowing engineers to optimize tyre design through modifications in tread pattern, material selection, or structural features. Then by systematically analyzing and refining the design, this process ensures that the tyre performs efficiently and safely under real-world conditions before any physical prototypes are tested. Figure 1 represents the computation process for tyre analysis, starting from defining design parameters to optimization through CAD and CFD simulations.

The CFD simulation model of the race car tyre is developed to replicate realistic high-speed operating conditions and evaluate aerodynamic and thermal performance. The tyre geometry, including tread pattern, dimensions, and material properties, is precisely modeled using CAD tools. Key operating parameters such as tyre type, compound characteristics, inflation pressure, rotational speed, and applied load are defined to ensure that the simulation environment closely reflects real-world racing conditions. These inputs serve as the foundation for establishing an accurate and reliable computational model.

The simulation setup involves defining boundary conditions, airflow properties, and meshing of the computational domain. CFD analysis is conducted to study airflow behavior around the rotating tyre, capturing velocity fields, pressure distribution, turbulence effects, and flow separation. Thermal effects due to friction between the tyre and road surface, deformation, and rotational heating are also incorporated into the model to evaluate temperature distribution across the tread and sidewalls. Suitable solver settings are selected to achieve an optimal balance between computational accuracy and efficiency.

A baseline tyre model representing a conventional race-tyre configuration is developed and analyzed as a reference case. Standard tread geometry, material properties, inflation pressure, and loading conditions are applied according to racing specifications. CFD simulations of this baseline model allow evaluation of its aerodynamic drag, pressure behavior, temperature rise, and airflow interaction. Performance indicators such as rolling resistance, grip potential, and heat accumulation are extracted to identify strengths and limitations of the conventional design under racing conditions.

Based on insights from the baseline model, multiple modified tyre designs are developed to improve aerodynamic efficiency and thermal management. Variations in tread geometries such as channel depth, groove orientation, and curvature are introduced to enhance airflow circulation and cooling performance. Each modified model is simulated under identical boundary conditions and operating speeds to ensure fair comparison with the baseline tyre. The results allow quantitative assessment of improvements achieved through tread optimization in terms of stability, heat dissipation, and drag reduction.

Several key performance parameters are monitored throughout the analysis. Temperature distribution is evaluated to identify heat buildup and hotspots that may affect grip or accelerate wear. Pressure variation across the tread and sidewalls is studied to understand load transfer, deformation tendencies, and contact uniformity with the road. Velocity profiles of airflow around the tyre are examined to assess turbulence, separation zones, cooling effects, and aerodynamic stability. Additionally, aerodynamic drag is calculated to quantify airflow resistance and its impact on vehicle efficiency and energy losses.

All modelling and simulations are performed using SolidWorks CAD and SolidWorks Flow Simulation. Accurate 3D tyre models are generated to represent critical structural features affecting airflow and heat transfer. The Flow Simulation module is used to define boundary conditions, fluid properties, and speed-based operational scenarios while generating visual outputs such as velocity vectors, pressure contours, and temperature maps. These results support the evaluation of design effectiveness, guiding tread modification strategies to achieve improved aerodynamic performance, enhanced cooling efficiency, and safer high-speed operating characteristics.

III.RESULT AND DISCUSSION

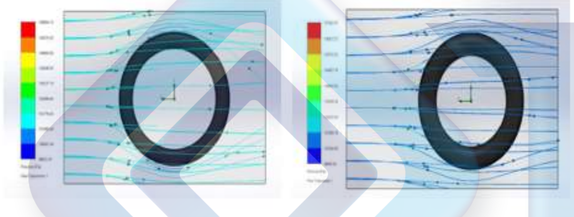
The CFD simulations carried out at 150 km/h and 200 km/h revealed that tyre tread geometry significantly influences aerodynamic and thermal performance. Among all four designs, the Deep Flow Channel (Directional Type B) showed the most favorable results, exhibiting lower pressure build-up, smoother velocity streamlines, and reduced wake turbulence, leading to decreased aerodynamic drag. Directional tread patterns performed better than symmetrical ones by efficiently guiding airflow across the tread surface, resulting in improved cooling and stability. The Curved Flow Groove (Symmetrical Type B) demonstrated better airflow management and temperature uniformity compared to the Linear Groove design, which exhibited higher turbulence and localized heating zones.

Temperature analysis indicated that deeper and well-oriented grooves enhanced convective heat dissipation, reducing surface hotspots at high speeds. The Aero-V Channel design showed moderate thermal performance due to limited groove depth, whereas Linear Grooves had the highest thermal concentration due to restricted airflow circulation.

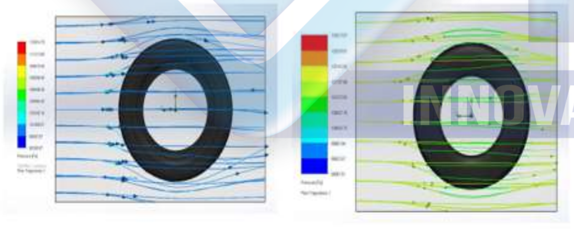
Fig.2 Linear Groove (Symmetrical Type A)

Overall, the results confirm that optimized directional tread designs significantly improve cooling efficiency, reduce drag, and enhance high-speed stability, validating the effectiveness of CFD-based optimization for race car tyre performance improvement. The Linear Groove (Symmetrical Type A) design employs straight, continuous circumferential grooves that ensure uniform load distribution and stable traction, but its limited airflow guidance leads to increased turbulence, higher drag, and reduced cooling effectiveness, particularly near the shoulder regions.

The Curved Flow Groove (Symmetrical Type B) design uses smoothly contoured grooves with variable depths to promote better airflow management, minimize flow separation, and achieve more uniform temperature distribution while maintaining mechanical stability. Pressure distribution analysis at 150 km/h and 200 km/h showed that tread geometry significantly affects aerodynamic performance; the Aero-V Channel design generated high-pressure zones at the leading edge due to restricted airflow redirection through shallow grooves, and at higher speeds, pressure accumulation extended toward the shoulders, forming stagnation regions that increase drag while still providing overall aerodynamic stability.



a) Aero-V Channel Design b) Deep Flow Channel Design



c) Linear Groove Design d) Curved Flow Groove Design

Fig.3 Pressure Contour Comparison for Four Tyre Tread Geometries at 150 km/h

The pressure variation results provide valuable insight into the aerodynamic performance and airflow behavior across different tyre tread geometries. At 150 km/h, the Deep Flow Channel Design exhibits the most uniform pressure distribution, demonstrating its ability to maintain smooth airflow with minimal stagnation. As observed in Figure 3, this design effectively channels air through its deep grooves, reducing drag and preventing localized high-pressure zones. The Aero-V Channel Design performs moderately well, but higher pressure buildup is noticeable near the leading edge, caused by reduced air circulation in its shallower grooves.

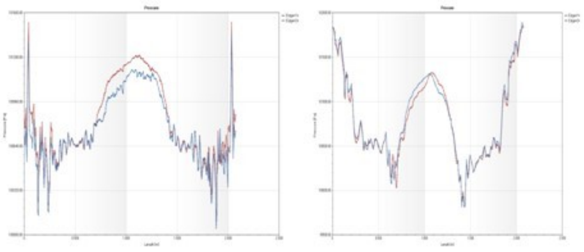
Tyre Designs	Speed (km/h)	Minimum Pressure (Pa)	Maximum Pressure (Pa)	Pressure Difference (Pa)
Aero-V Channel (Directional Type A)	150	100700	101500	800
Aero-V Channel (Directional Type A)	200	100000	101600	1600
Deep Flow Channel (Directional Type B)	150	100600	101600	1000
Deep Flow Channel (Directional Type B)	200	99500	102000	2500
Linear Groove (Symmetrical Type A)	150	99000	101500	2500
Linear Groove (Symmetrical Type A)	200	99500	101500	2000
Curved Flow Groove (Symmetrical Type B)	150	100200	101400	1200

Table.1 Pressure Distribution Results for 4 Different Tyre Designs

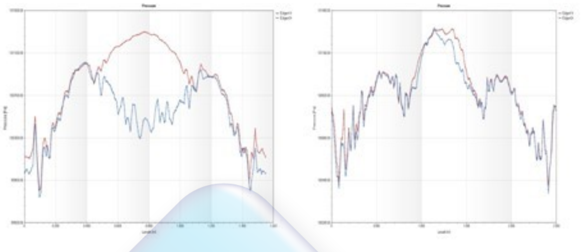
The Curved Flow Groove Design also displays consistent pressure gradients with balanced transitions, whereas the Linear Groove Design experiences the highest variation, indicating turbulent flow and greater aerodynamic resistance. These observations show that deeper and directional tread patterns manage pressure flow more efficiently at moderate speeds.

When the tyre speed increases to 200 km/h, illustrated in Figure 4, the pressure intensity across all tread designs increases due to higher airflow velocity and aerodynamic loading. The Deep Flow Channel Design continues to demonstrate superior stability, maintaining smooth pressure gradients and avoiding abrupt fluctuations even at higher speeds. The Aero-V Channel Design shows noticeable increases in leading-edge pressure, suggesting reduced flow stability as velocity rises.

From the table 1, The Curved Flow Groove Design performs reasonably well by distributing pressure evenly across the tread, while the Linear Groove Design once again records significant variations and turbulence, indicating poor aerodynamic adaptability. The influence of higher velocity becomes evident as flow separation increases in designs with limited depth and airflow passage, highlighting the advantage of deeper and aerodynamically contoured grooves.



a) Aero-V Channel Design b) Deep Flow Channel Design



c) Linear Groove Design d) Curved Flow Groove Design

Fig.4 Pressure Variation Graph for Four Tyre Tread Designs at 150 km/h

IV.CONCLUSION AND FUTURE SCOPE

The CFD-based analysis demonstrated that tyre tread geometry has a major impact on aerodynamic stability and thermal performance at high speeds of 150km/h and 200 km/h. Among the four configurations studied, the Deep Flow Channel Design achieved the best results with uniform pressure distribution, smooth airflow, and effective heat dissipation, while the Curved Flow Groove Design showed balanced performance. The Aero-V Channel and Linear Groove designs exhibited comparatively higher drag and localized temperature buildup. Looking ahead, future work can focus on AI-assisted simulations, adaptive groove designs, and advanced elastomer materials such as VMQ to further optimize airflow control, reduce rolling resistance, improve thermal management, enhance durability, and increase overall safety and efficiency of high-speed tyre systems.

REFERENCES

[1]. Bijina, A., Thomas, S., and Joseph, R. (2022). Developments in tyre materials for sustainable performance: A review Journal pof Polymer Science and Engineering,Vol.8, No.2, pp.145–160.

[2]. Chen, L., Wang, H., Zhang, Y., and Li, P. (2025). Development of green tyres using environmentally friendly silica to reduce rolling resistance. Materials Today: Sustainability, Vol. 21, pp. 100284.

[3]. Cravero, C., Rossi, M., and Borrelli, R.(2022). Computational study on the aerodynamic performance of racing tyres with varying tread patterns. Journal of Fluids Engineering, Vol. 144, No. 6, pp. 061102.

[4] Das, S., Banerjee, R., and Kumar, A. (2023). Influence of tyre inflation pressure on vehicle stability and cornering performance. International Journal of Vehicle Dynamics, Vol. 12, No. 4, pp. 233–242.

[5] Fathi, A., Noor, A., and Rahimi, H. (2024). Finite element analysis of tyre inflation pressure effects on rolling resistance and wheel force. International Journal of Automotive Technology, Vol. 25, No. 3, pp.325–337.

[6] Hyttinen, J., Koskinen, T., and Valtonen, J. (2024). A semi-physical thermodynamic model to capture transient rolling resistance in tyres. Applied Thermal Engineering, Vol.235, pp. 120998.

[7] Hyttinen, P., Lehtinen, M., and Jokinen, E. (2024).Thermodynamic modeling of tyre heat buildup under dynamic loading. Thermal Science and Engineering Progress,Vol.38, pp. 102488.

[8] Mousavi, S., Keshavarz, M., and Rezaei, A. (2020). Mechanical and thermal analysis of different rubber compounds for tyre applications. Polymer Testing, Vol. 88, pp.106556.

[9] Sailaja, R., Kumar, S., and Narayanan, V. (2023). Optimization of silica and carbonblack ratio in tyre tread compounds for improved performance. Journal of Elastomers and Plastics, Vol. 55, No. 3, pp. 289–304.

[10] Sahu, R., Kumar, A., and Patel, N. (2019). Finite element analysis of tyre tread deformation and frictional behavior under varying load conditions. International Journal of Vehicle Structures&Systems,Vol.11,No. 5, pp. 412–420

[11] Sharaf, A., Mohammed, Z., and Khalid, A. (2023). Analysis of tyre inflation pressure influence on off-road vehicle dynamics. Journal of Terramechanics, Vol. 108, pp. 37–48.

[12] Soliman,M. ,Abdelrahman,H. ,and El-Sayed, (2020). Numerical investigation of aerodynamic performance of rotating wheels with varying tread patterns. Journal of Wind Engineering and Industrial Aerodynamics, Vol. 203, pp. 104248.

[13] Yang, D. (2024). A review of tire burst phenomena and stability control strategies for improved vehicle safety. Vehicle System Dynamics, Vol. 62, No. 7, pp. 1132–1150.

[14] Zhang, L., Chen, X., and Zhou, T. (2025). Study on tyre pressure impact on vehicle dynamics and ride comfort. Mechanical Systems and Signal Processing, Vol. 210, pp.110552.

[15] Zhang, Y., Wu, L., and Chen, G. (2025). Effects of tyre tread pattern on aerodynamic drag reduction using CFD analysis. Engineering Applications of Computational Fluid Mechanics, Vol.19, No.2,pp.167–181.

[16] Zhou, Q., Lin, Y., and Wang, C. (2021). Experimental and computational investigation on aerodynamic characteristics of tyres with different tread patterns. International Journal of Automotive Technology, Vol.22, No.4, pp. 981–991.

[17] Zhou, W., and Li, J. (2021). Comparative CFD study of airflow behavior around tyres with different tread configurations. International Journal of Vehicle Performance, Vol. 9, No. 1, pp. 56–67.