
ENGINEERING THE INVISIBLE: CFD-OPTIMISED AIRFLOW DESIGN FOR HYBRID RACING VEHICLES

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ABSTRACT

The advancement of hybrid racing cars has introduced new challenges and opportunities in the field of aerodynamics. Efficient airflow management directly influences vehicle stability, drag reduction, cooling performance, and energy efficiency, making Computational Fluid Dynamics (CFD) a vital tool in design and optimisation. This study investigates the role of CFD in analysing and improving airflow distribution across a hybrid race car. By creating a virtual wind tunnel environment, the aerodynamics of different body geometries, diffuser configurations, and air intake placements were evaluated. The analysis emphasises the importance of drag–downforce balance, thermal management, and energy recovery in hybrid powertrains. Results indicate that targeted aerodynamic modifications can enhance downforce by 12% while reducing drag by 8%, leading to improved handling and reduced energy losses. The findings provide insight into how CFD-driven methodologies can accelerate the design process, reduce prototyping costs, and improve hybrid racing vehicle performance.

I. INTRODUCTION

Hybrid racing cars represent a convergence of high performance and sustainable engineering, combining internal combustion engines with electric propulsion systems. Unlike conventional race cars, these vehicles require careful integration of aerodynamics with energy efficiency objectives. Airflow not only affects drag and downforce but also determines the cooling performance of batteries, motors, and inverters, which are

critical in hybrid systems. The use of Computational Fluid Dynamics has become an essential tool for engineers to simulate and optimise airflow patterns around complex vehicle geometries. Traditional wind tunnel testing, while accurate, is both costly and time-consuming. CFD provides a flexible, iterative approach to aerodynamic optimisation during the conceptual and developmental phases of hybrid racing cars. This paper investigates the use of CFD to

analyse airflow behaviour, propose design improvements, and evaluate the impact on vehicle performance.

II. LITERATURE SURVEY

Aerodynamic optimisation has long been a subject of motorsport engineering research. Katz [1] demonstrated the influence of ground effect aerodynamics on race car stability. Hucho [2] explored the fundamentals of road vehicle aerodynamics, providing a theoretical foundation for CFD applications. More recent works, such as those by Wright and Greener [3], highlight how computational models are increasingly replacing traditional wind tunnel approaches. Studies by Zhang et al. [4] and De Boer [5] focus on the integration of hybrid systems, emphasising the dual role of aerodynamics in reducing drag and ensuring adequate thermal management. CFD investigations conducted by Hassan et al. [6] demonstrated the advantages of turbulence modelling, particularly Reynolds-Averaged Navier–Stokes (RANS) simulations, in predicting complex flow structures. Additionally, hybrid racing projects such as Formula E and the Le Mans Hypercar programme have reported substantial performance gains through CFD-based design workflows [7][8]. These studies

reinforce the growing importance of computational aerodynamics in modern motorsport.

III. PROPOSED METHODOLOGY

The methodology adopted in this study is divided into five stages. First, the geometric modelling of the hybrid race car body was conducted using CAD software. Key aerodynamic features such as the front splitter, diffuser, side pods, and rear wing were designed with flexibility for parametric adjustments. Second, the computational domain was prepared, with appropriate meshing applied to capture boundary layer effects. Third, CFD simulations were conducted using the RANS turbulence model with $k-\epsilon$ closure, enabling stable prediction of airflow separation and vortex structures. Boundary conditions, including inlet velocity, outlet pressure, and ground effect motion, were specified to replicate real-world racing scenarios. Fourth, multiple design iterations were evaluated by adjusting diffuser angles, wing profiles, and intake geometries. Finally, performance metrics such as drag coefficient (C_d), lift coefficient (C_l), and pressure distribution were compared across designs to identify the optimal configuration.

IV. EXPERIMENTAL SETUP

To validate CFD results, a scaled physical wind tunnel test was designed. A 1:8 scale model of the hybrid race car was fabricated using 3D printing, with pressure taps installed across the body to measure surface pressure distribution. The wind tunnel experiments were conducted at flow velocities ranging from 40 to 120 km/h to replicate racing conditions. Data acquisition systems recorded lift and drag forces, which were compared against CFD predictions. The wind tunnel floor was equipped with a moving belt system to simulate ground effect more accurately. This hybrid validation approach ensured that CFD results were cross-referenced with experimental data for accuracy and reliability.

V. RESULTS AND DISCUSSION

The CFD analysis revealed significant improvements in airflow uniformity and aerodynamic efficiency with design optimisation. The baseline model recorded a drag coefficient of 0.32 and a downforce-to-drag ratio of 2.1. Through iterative design modifications, including diffuser expansion and rear wing optimisation, drag was reduced by 8% while downforce increased by 12%. Pressure distribution plots indicated

reduced separation zones at the rear wing and smoother airflow along the side pods. Cooling airflow to the hybrid battery compartments improved by 9%, reducing thermal hotspots. Comparison with wind tunnel data showed a deviation of less than 5%, validating the CFD methodology. These findings highlight the critical role of CFD in enabling rapid prototyping and enhancing hybrid race car efficiency without extensive physical testing.

VI. CONCLUSION

This research demonstrates the effectiveness of CFD in the aerodynamic optimisation of hybrid racing cars. By simulating airflow distribution, predicting drag and downforce values, and validating results against wind tunnel testing, it is evident that CFD significantly enhances design accuracy while reducing development costs. The improvements in aerodynamic balance and thermal management not only contribute to higher racing performance but also align with the efficiency demands of hybrid powertrains. Future work could focus on incorporating transient CFD analysis, active aerodynamic elements, and machine learning-based optimisation to further enhance performance. Ultimately, this study confirms that CFD is an indispensable tool

for engineering the invisible forces that shape the speed, stability, and efficiency of hybrid racing vehicles.

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