

Application of Fluid Dynamics in the Formula One car: Exploring automobile air drag force and model design principles

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Abstract. Formula one racing is one of the best sporting events in the world, in addition to the driver's driving skills, the performance of the vehicle also plays an important role in this race. The application of fluid mechanics and aerodynamics in vehicles has greatly improved vehicle performance, maneuverability and stability, it can reduce the effect of air drag force on the vehicle and convert the air drag force into a force that is beneficial to the vehicle. To achieve this, it must be started with the design of the vehicle itself. This article will start from the basic application theory of fluid mechanics and aerodynamics in vehicles, and the composition of aerodynamics components, make a model based on the 2018 Formula one car as a reference, and then use CFD (Computational Fluid Dynamics) software Ansys workbench to conduct simulation verification and analysis. Looking to the future from now on and drawing conclusions.

Keywords: Formula one car, fluid mechanics, design of vehicle.

1. Introduction

The utilization of fluid dynamics in Formula One racing has become a focal point in enhancing automobile performance. As a sport where both driver skill and vehicle efficiency are paramount, the minimization of air drag and optimization of aerodynamic forces are crucial. This research delves into the fundamental principles of air drag and fluid mechanics, exploring how these forces impact vehicle design and performance. The resistance created by air drag, defined by various factors such as air density, object velocity, drag coefficient, and object windward area, poses significant challenges in high-speed racing environments [1, 2].

Current advancements in fluid mechanics have introduced a distinction between laminar and turbulent flows, significantly affecting vehicle aerodynamics [3]. The application of these principles is evident in the sophisticated design of aerodynamic components such as splitters, ducts, diffusers, and spoilers, which are integral to managing airflow and minimizing drag [4]. However, challenges remain in balancing downforce and lift to prevent high-speed instabilities. The integration of advanced Computational Fluid Dynamics (CFD) tools like Ansys Workbench for simulation and analysis is pivotal in refining these designs and enhancing vehicle stability and speed under varying racing conditions [5].

This paper constructs a model based on the 2018 Formula One car to systematically explore and verify the application of fluid mechanics in automobile design. Through CFD simulations, the study investigates how different aerodynamic designs influence air flow, drag, and vehicle performance. Key design elements such as streamlined shapes and aerodynamic adjustments are analyzed for their impact on reducing drag and increasing downforce, critical for high-speed maneuverability and stability. The findings aim to contribute to the ongoing development of more efficient and competitive racing vehicles, adhering to FIA regulations and anticipating future trends in hybrid and electric motor integration.

2. Background Theory of Fluid Mechanics and Air Drag Force

2.1. Definition of Air Drag Force and Influencing Factors

Air drag force (F_d) is the resistance that air exerts on an object when it is moving through the air, due to the viscous and inertial effects of air [3].

It can define as.

$$F_d = \frac{1}{2} \rho v^2 C_d A \quad (1)$$

Where, the ρ is density of air, the v is the velocity of the object to the air, the C_d is the drag force coefficient, the A is windward area of the object [4].

According to the definition, it can be known that the factors affecting air drag force are air density, the velocity of the object relative the air, the drag coefficient, and the area of the object facing the wind. And they are proportional to the size of drag force [5]. In addition, for vehicles the surface roughness and the design of shape also have a certain impact on the size of the air drag force.

2.2. Principles of Fluid Mechanics

There are two types of fluid flows: Laminar Flow and Turbulent Flow.

Where, the laminar flow moves in parallel layers with little mixing or interlacing between the layers, with the flowing molecules sliding along regular and parallel paths without significant lateral mixing or disturbance [6]. Turbulent flow is the opposite of it, turbulence is an irregular flow state with a large number of irregular eddies and waves, and the layers are mixed with each other, its characteristics are the flow lines are disorganized, with significant speed and pressure fluctuations and there are significant energy losses and high friction [7].

The way to determine the flow pattern is Reynolds Number (Re).

It can define as.

$$Re = \frac{\rho VL}{\mu} \quad (2)$$

Where, V is the velocity of the flow, L is the length scales of the flow, ρ and μ are the fluid density and fluid viscosity respectively.

Generally, when $re > 4000$ the flow is turbulent flow $Re < 2000$ the flow is laminar flow, but when $2000 < Re < 4000$ the flow is transitional flow [8]. Transitional flow is the transition process from laminar to turbulent, the flow begins to become irregular, but it is not yet completely turbulent. There may be some turbulent areas.

During the movement of vehicle, due to the viscosity of the fluid, the fluid flowing between the vehicle surfaces will produce a thin flow area, this area called the boundary layer. At the beginning of the vehicle movement, the front of the vehicle is laminar flow, but as the fluid flows along the surface of the vehicle, the velocity gradient, pressure distribution and viscosity effect of the fluid in the boundary layer will slowly change. When the critical condition is reached, the laminar flow in the boundary layer will become unstable and turn into turbulent flow.

2.3. Application of Aerodynamics in Automobile Design

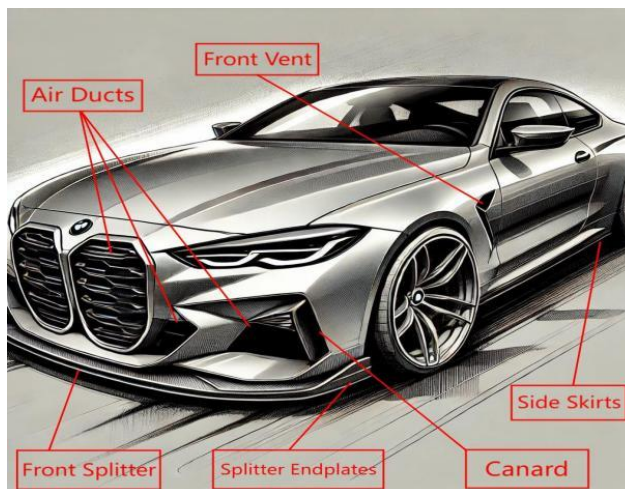


Figure 1. Vehicle front aerodynamics devices (Photo credit: Original).

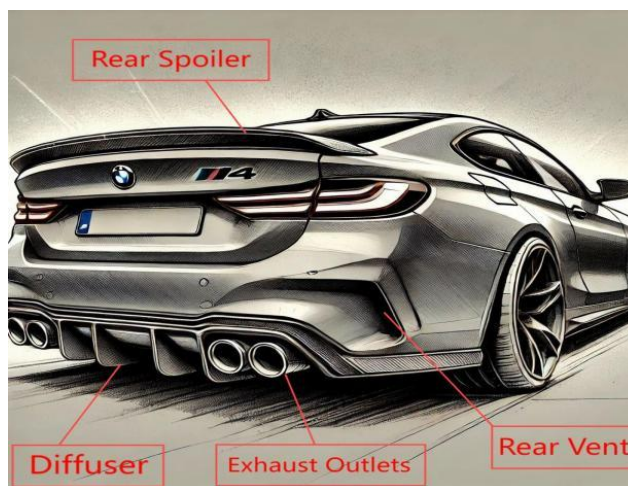


Figure 2. Vehicle backside aerodynamics devices (Photo credit: Original).

Aerodynamics application in vehicles is mainly achieved by aerodynamics components, listed in the Fig.1 and 2 are the common aerodynamic components, they are the front splitter, air ducts, canard, diffuser and vents, as well as spoilers and side skirts [9]. In addition to these, some high-performance vehicles will also be equipped with rear wings, vortex generators and aerodynamic body kits even the active aerodynamic systems. The active aerodynamic system refers to the spoiler and rear wing that automatically adjusts to the vehicle's movement in terms of angle and lift, these functions and design goals are to optimize air flow, reduce the impact of drag force, lift force and vortex on movement, and make the vehicle stable and efficient [10].

3. Design of Aerodynamics in Formula One Car

3.1. Formula One Car'S Aerodynamics Design Goals

The design of aerodynamics can be roughly divided into four aspects: Drag force reduction, Downforce increase, Balancing drag force and downforce, and Air flow management.

On long straights or high-speed tracks, reducing air drag force can effectively increase vehicle speeds, when the car goes around the bend, it is necessary to increase downforce to make the vehicle stick to the track, which helps to improve grip and stability, and avoid the centrifugal force generated during high-speed cornering to make car lose control. As downforce increases, air drag force also increases, it is important to find a balance between these two forces to avoid compromising speed

performance. Meanwhile, when driving at high speeds in race, both internal and external parts of the car will generate high temperatures due to friction and energy loss from work, which requires good air flow management, so that the air flow through the car can not only dissipate heat inside the car, such as the engine or braking system, but also minimize the impact of air drag and vortices on the vehicle.

3.2. The Main Aerodynamics Design Elements

Formula One car has a streamlined design. Streamlined design allows the fluid to flow through the vehicle more smoothly. At the same time, a larger proportion of laminar flow is formed on the surface of the vehicle, which reduces energy loss. In addition, from the perspective of fluid mechanics, the fluid has the characteristic of flowing along the streamline direction, which can greatly reduce the impact of drag force. As show in the fig.3.



Figure 3. Mercedes-Benz Formula One racing car streamlined side view (Photo credit: Original).

In fluid mechanics, according to the Bernoulli's principle: where the flow rate is high, the pressure is low, and where the flow rate is low, the pressure is high. For Formula One car, due to the streamlined body, the flow rate of the flow on the top of the body is accelerated, and the air flow rate at the bottom is relatively slow, which will form an upward pressure difference, thereby generating lift to reduce grip and stability. At this time, an upward-curved streamlined rear wing is used to generate a downward pressure difference to balance the lift. As show in the fig.4.

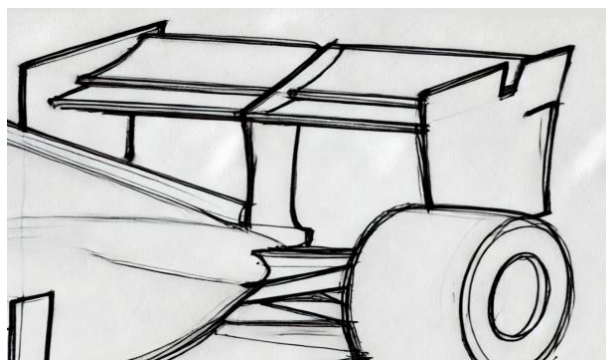


Figure 4. Formula One car's rear wing (Photo credit: Original).

Another iconic design of Formula One car is front wing, it has the same function as the rear wing, which is to provide downforce to balance lift, but it also has another important function of diverting airflow. According to the FIA (Fédération internationale de l'Automobile) regulations, the front wing of Formula One car is composed of a specified number of airfoils arranged in an up-and-down combination at a specific angle of attack, with gaps between the airfoils and end plates at both ends. Therefore, the fluid can be diverted for use in cooling system and other aerodynamics components of car body, it is an important part of the airflow management. As show in the fig.5.

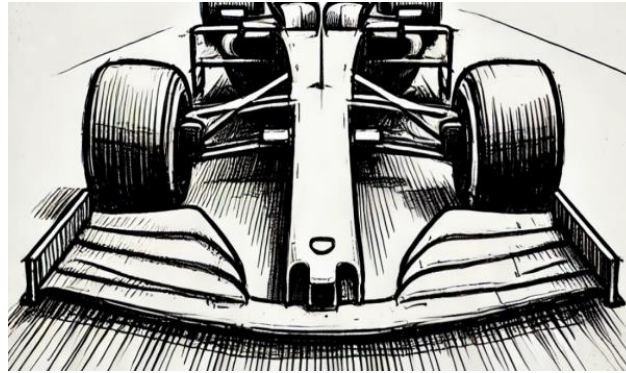


Figure 5. Formula One car's front wing (Photo credit: Original).

4. CFD Simulation Data Verification and Analysis

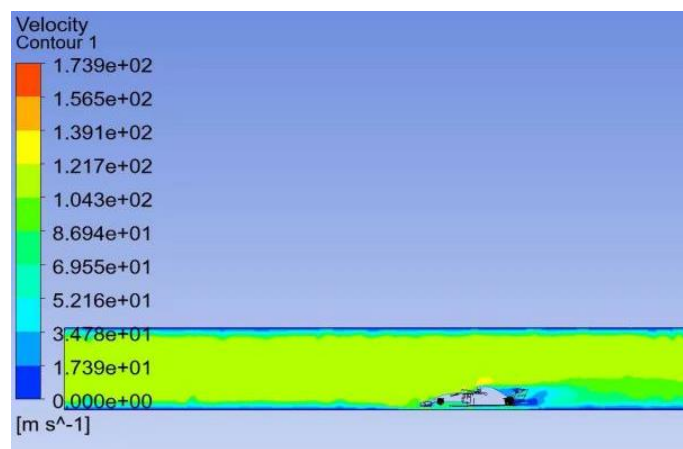


Figure 6. Flow velocity contour (Photo credit: Original).

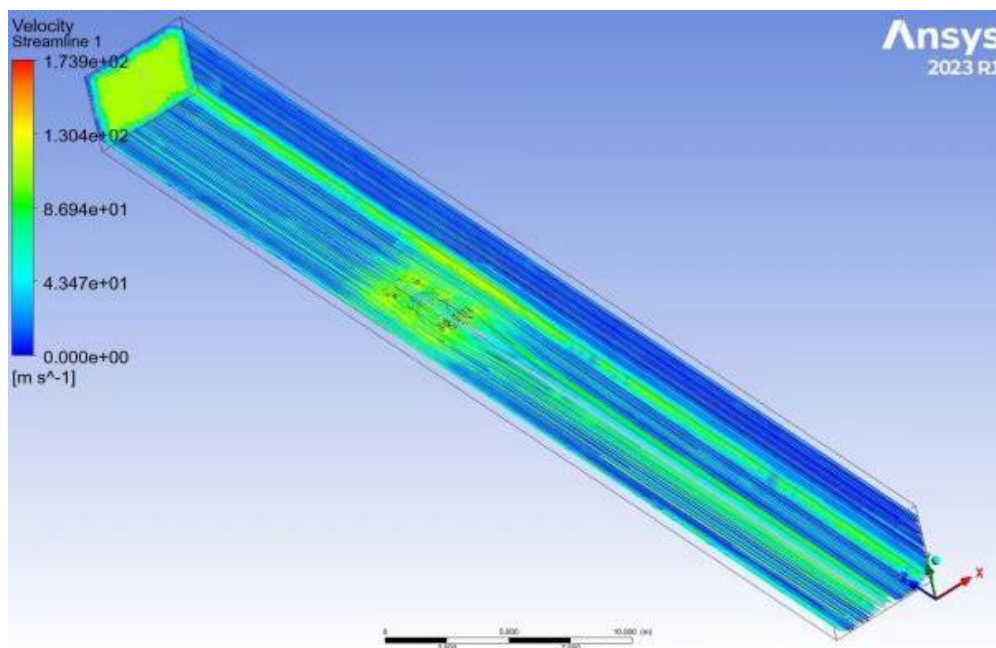


Figure 7. Flow velocity streamline (Photo credit: Original).

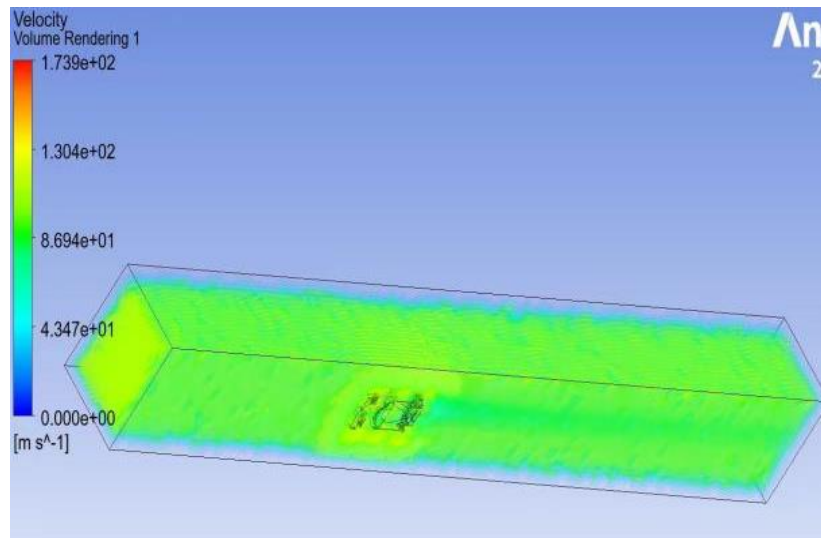


Figure 8. Flow velocity volume rendering (Photo credit: Original).

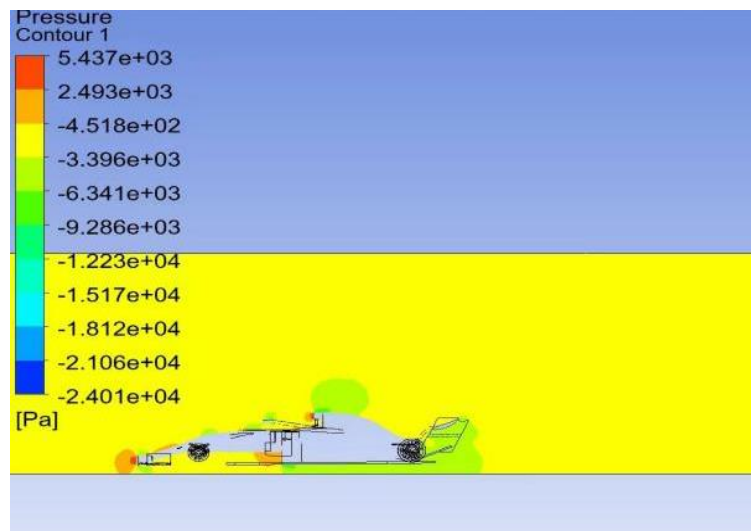


Figure 9. The pressure on the vehicle (Photo credit: Original).

As shown in the fig.6 to fig. 8. According to the analysis of the experimental results, due to the front wing and streamlined design, significant acceleration is generated at the bottom of the car and the top of the car body, local turbulence or separation may occur on the sides and roof. From the perspective of pressure distribution, the overall downforce can balance the lift generated.

5. Challenges and Future Development Trends

The current aerodynamics challenges are mainly to balance downforce and lift. Under the premise of following the FIA regulations, it needs to test better wing shape, size and arrangement. With the development of electricity, new energy vehicles and hybrid models have gradually become mainstream, Formula One car is no exception. In 2014, electric motors were added to become hybrid models. Electric motors have improved its power system to certain extent. At present, the proportion of motors in Formula One cars is not very large, but the new regulations introduced by the FIA in 2026 stipulate that the proportion of internal combustion engines and electric motors must reach 50% each. This means that there will be more devices on the vehicle, and the vehicle design also needs to accommodate more devices while ensuring and further optimizing the current aerodynamic design and application.

6. Conclusion

This study has advanced our understanding of fluid dynamics and aerodynamics in Formula One racing by applying computational simulations to analyze the effects of air drag forces on vehicle design. Through the meticulous integration of CFD tools, this research has highlighted the pivotal role of aerodynamic components in enhancing vehicle performance, stability, and fuel efficiency under various racing conditions. By focusing on the interaction between air flow and vehicle dynamics, the research has underscored the importance of streamlined designs and innovative aerodynamic adjustments that significantly reduce drag while increasing downforce, essential for high-speed maneuverability and stability.

The scope of research in Formula One aerodynamics is set to expand with the advent of hybrid and electric vehicle technologies. As regulations evolve to mandate a balanced integration of electric motors and internal combustion engines by 2026, future studies will need to address the aerodynamic challenges posed by the addition of new components and systems. This will involve rethinking vehicle architecture to accommodate these changes while continuing to optimize aerodynamic performance. The ongoing development and refinement of CFD simulation techniques will be crucial in facilitating these advancements, ensuring that Formula One vehicles not only meet regulatory standards but also push the boundaries of what is aerodynamically possible in high-speed automotive racing.

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