DESIGN MODIFICATION AND AERODYNAMIC OPTIMIZATION OF FORMULA RACE CAR

[1]Bhrugu Machhar, [2]Prof. Hitesh Raiyani
[1]Research Scholar, [2]Assistant Professor
[1]Mechanical Engineering Department (CAD/CAM),
[1]L.J. Institute of Engineering and Technology, Ahmedabad, Gujarat, India.

Abstract: This paper presents an analysis of front and rear wing of the formula race car for different airfoil profile selected and modified number of blades in front and rear wings. The coefficients of aerodynamic forces and flow properties of formula race car were investigated with the results of CFD calculations. The investigation shows that the use of 3 blade wing as front and rear wing of formula race car can produce increased downforce than the downforce produced by formula race car with single blade wings. So, this paper focuses on the design of aerodynamic devices like front and rear wing of formula race car to develop force opposing the aerodynamic lift so that the traction of tires is not lost and proper tire road interaction is obtained.

***IndexTerms* – Formula Race Car, Airfoil Profile, CFD Analysis, Front Wing, Rear Wing.**

I. Introduction

Aerodynamic devices are defined as the devices used for optimizing the interaction of the vehicle with the air flowing around it, further results in advantage in terms of performance of the vehicle.

The front wing and rear wing of the formula race car are the significant aerodynamic device which can produce sufficient amount of downforce and reduce the drag force on car. It improves the car's aerodynamic properties by increasing the transition between the high-velocity air flow over the car and much slower free stream flow of the ambient atmosphere. The rear wing of the car should be designed in such a way that it does not cause excessive flow separation and drag, by providing an extensive amount of pressure recovery so that the flow separation is not caused. When front and rear wing is used, the air flows over the car in such way that the flow does not separate from the car and smoothly flows over it. So, there is a peak of low pressure under the front and rear wing of the formula race car.

The role of front and rear wings of the formula race car is to generate maximum downforce and minimum drag force at higher speeds, in turn to produce a pressure potential, which will accelerate the flow underneath the wing resulting in reduced pressure and desired improvement in downforce generation.

The front wing is closer to the ground than the rear wing, hence the force generated is amplified by utilizing its proximity to the ground. The rear wing is placed little higher from the ground, so the ground proximity is not effective for the rear wing of the car.

II. Literature Review

1. The influence of different aerodynamic setups on enhancing a spots car braking[1]: This study presented how a large aerodynamic element such as a rear wing can influence the flow around the car body and how it could be used to increase a car's downforce as well as drag force. The calculation of braking distance proved that aerodynamically enhanced braking can reduce the braking distance (up to 31%), and thus increase safety.
2. Turbulence modeling effects on the CFD predictions of flow over NASCAR Gen 6 racecar[2]: The flow field changes affected by the turbulence modeling approaches were highlighted through generated delta images, both on the entire vehicle surface and at a few topologically significant sections. Most of the prediction disagreements between the models appeared to be in the separation and recirculation regions towards the vehicle rear end indicating that the modeling effect mainly occurs in the separation region where strong vortices or rotational flow structures exist. Overall, AKN turbulence model offers advantages over other two (i.e. RKE and SST) in terms of predictions of realistic flow fields in the operation and wake regions.
3. The effects of simplifications on isolated wheel aerodynamics[4]: Geometric variations can alter the details in flow of either rotating or stationary wheel and as a result create significant changes to the final lift and drag values obtained for a wheel. Removing the wheel hubs proved to be influential with regards to predict lift (30% less), but less so in terms of drag (8%), despite significantly altered wake structure.
4. Numerical study on aerodynamic drag reduction of racing car[6]: Aerodynamic drag reduction by rear under body modification results in up to 22.13% and rear under-body diffuser results 9.5% reduction of drag coefficient. Exhaust gas redirecting towards the low-pressure zone at the rear of the car is proved to be effective to some extent. About 3.3% drag coefficient can be reduced by this procedure considering the ideal exhaust gas composition.
5. Aerodynamic study of formula SAE car[7]: To increase the aerodynamic performance of race car, an attempt is made to modify the design of a Formula SAE car. Comparative study is done on three car models by carrying out CFD simulations. Cutting out the section of firewall and providing wing at front end. Drag co-efficient is found to get reduced from 0.85 for the standard race car to 0.70 for the modified car with front wing, whereas negative lift is increased from 0.2 for standard race car to - 0.25 for the model 3. Model 3 having wing at the front end and having cut section at firewall shows less drag and lift, shows better aerodynamics characteristics than other two models.
6. Aerodynamic design optimization of race car rear wing[8]: In this paper, 2 blade rear wing is used. When the angle of attack of aileron is small, the downforce and aerodynamic drag both increase with the angle of attack increasing. According to the principle of 'greater downforce and less aerodynamic drag', an optimization project is determined which

is of 6.0% more downforce and 5.0% less aerodynamic drag compared to the initial one. When the angle of attack of the aileron is large, the downforce decreases with the angle of attack increasing, while the aerodynamic drag increases with it, which has to be avoided when designing the rear wing.

III. DESIGN AND ANALYSIS OF FORMULA RACE CAR WINGS

The airfoil profile selected for front and rear wing of the race car is NACA 4412 airfoil for front wing, NACA 2408 and S1223 airfoil for rear wing. Here, these airfoil profiles were inverted for getting downforce (negative lift), instead of getting lift. In formula race car, the engine will be at rear of end of the car. Hence, the weight of the engine will also create the downforce. So, thin airfoil profiles were selected for the rear wing (S1223 and NACA 2408) compared with front wing (NACA 4412).

3.1 Design and Analysis of Front and Rear Wing with Single Blade

The airfoil profile selected for the front wing is NACA 4412 (Figure 1) and rear wing is S1223 (Figure 2) and NACA 2408(Figure 3). The model of front and rear wing is generated by importing the coordinates of airfoil profiles and inverting it in SOLIDWORKS 2018. The dimensions for front and rear wing were taken from the 2019 Formula One Technical Regulations FIA (Federation Internationale de I'Automobile)[10].

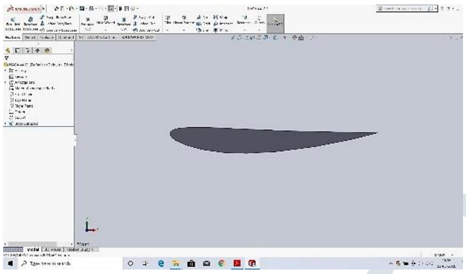

Fig.1 Front Wing NACA 4412

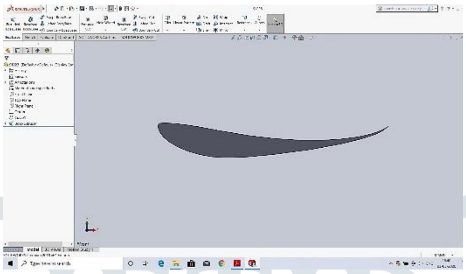

Fig.2 Rear Wing S1223

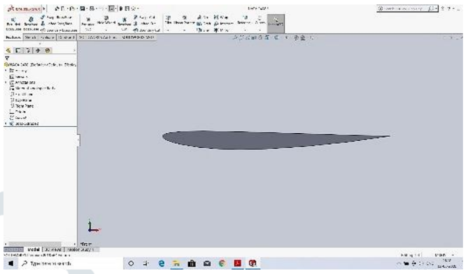

Fig.3 Rear Wing NACA 2408

The models created in SOLIDWORKS 2018 were imported in ANSYS Workbench 2019 R3 for doing CFD analysis. For getting the solution of the front and rear wing at different Angle of Attack (AOA), the simulation software ANSYS Fluent 2019 R3 is used. For the meshing of the models, Patch Confirming Algorithm (Tetrahedral Mesh) is used and element size taken was 50 mm. The boundary conditions applied for the CFD analysis is,
Mathematical Model: k-ω SST (Shear – Stress Transport)
Inlet: Velocity inlet at 95 m/s (342 km/h) (Maximum speed of the car)
Outlet: Pressure outlet at absolute 0 pressure
The results were obtained during simulation are shown in following table.

Table 1: Result Table for Variations in Angle of Attack of Front and Rear Wing

Angle of Attack (Degree)	Front Wing NACA 4412		Rear Wing S1223		Rear Wing NACA 2408	
	Lift (N)	Drag (N)	Lift (N)	Drag (N)	Lift (N)	Drag (N)
0°	-2391.94	63.2519	-1427.98	42.3372	-111.228	7.64749
5°	-4394.89	118.628	-2090.27	68.3092	-380.59	11.9771
10°	-4807.57	279.215	-2631.27	106.088	-522.563	74.3163
15°	-5061.05	529.134	-2385.88	235.43	-521.169	124.825
20°	-4609.29	873.924	-2191.48	400.951	-439.052	153.582

3.2 Design and Analysis of Front and Rear Wing with 3 Blades

From the results obtained in above section, the front wing with 3 blades consists of all three blades of airfoil profile NACA 4412. The first blade having an Angle of Attack (AOA) of 5° and last two blades having an Angle of Attack (AOA) of 10°. The rear wing with 3 blades consists of first blade of airfoil profile S1223 and last two blades of airfoil profile NACA 2408. The first blade having an Angle of Attack (AOA) of 5° and last two blades having an Angle of Attack (AOA) of 10°. These are the optimum conditions for the front and rear wing selecting from Table 1. This type of arrangement of front wing (Figure 4) and rear wing (Figure 5) is modeled in SOLIDWORKS 2018. The dimensions for front and rear wing were taken from the 2019 Formula One Technical Regulations FIA (Federation Internationale de I'Automobile)[10].

The models created in SOLIDWORKS 2018 were imported in ANSYS Workbench 2019 R3 for doing CFD analysis. For getting the solution of the front and rear wing, the simulation software ANSYS Fluent 2019 R3 is used. For the meshing of the models, Patch Confirming Algorithm (Tetrahedral Mesh) is used and element size taken was 50 mm. The boundary conditions applied for the CFD analysis is,

Mathematical Model:	k-ω SST (Shear – Stress Transport)
Inlet:	Velocity inlet at 95 m/s (342 km/h) (Maximum speed of the car)
Outlet:	Pressure outlet at absolute 0 pressure

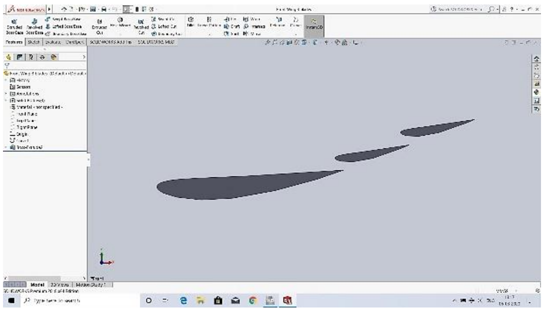

Fig.4 Front Wing with 3 Blades

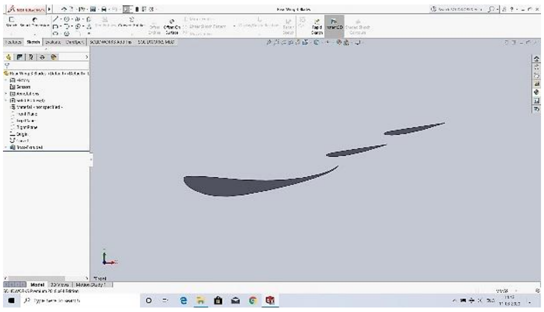

Fig.5 Rear Wing with 3 Blades

The result of the simulation is achieved in form of pressure contour as follows.

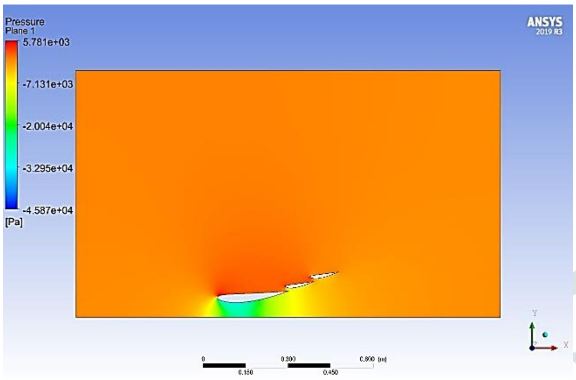

Fig.6 Pressure Contour of Front Wing with 3 Blades

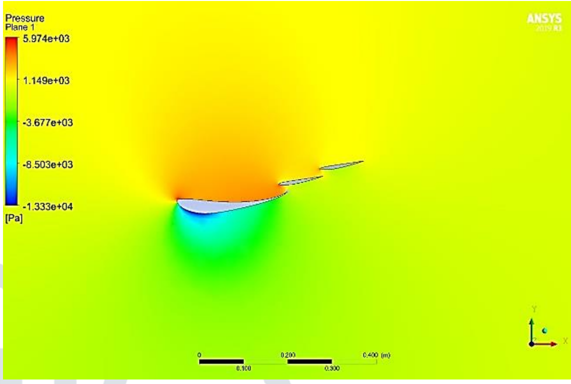

Fig.7 Pressure Contour of Rear Wing with 3 Blades

Table 2: Result Table for Front and Rear Wing with 3 Blades

Formula Race Car Wing with 3 Blades	Lift (N)	Drag (N)	Coefficient of Lift (C_l)	Coefficient of Drag (C_d)
Front Wing	-15108	496.34	-2.733	0.08979
Rear Wing	-2962.3	117.79	-0.53589	0.02309

3.3 Comparison of Results and Discussion

Table 3: Comparison Table of the Results of Front & Rear Wing with Single Blade and Front & Rear Wing with 3 Blades

Number of Blades in Wing	Front Wing		Rear Wing	
	Lift (N)	Drag (N)	Lift (N)	Drag (N)
1	-4394.9	118.63	-2090.27	68.392
3	-15108	496.34	-2962.3	117.79

From above table, it is seen that, we can achieve 243.76% increased downforce by using front wing with 3 blades compared with front wing with single blade. And we can achieve 41.72% increased downforce by using rear wing with 3 blades compared with rear wing with single blade. Usage of three blades will increase the drag on the car a little, but we can afford that little increase in drag to achieve maximum downforce.

IV. Analysis of Formula Race Car

In above section, the focus is only on the front and rear wing of the formula race car and not on the combined effect of the car body and the wings. So, in this section, the focus is on formula race car and wings both combined. In this study, CFD analysis of formula race car with single blade wings and formula race car with 3 blade wings are carried out. By the comparison of the result of these simulations, the optimum condition for formula race car can be achieved.

4.1 Analysis of Formula Race Car with Single Blade Wings

In CAD model of Formula Race Car without front and rear wings, adding Front Wing of airfoil profile NACA 4412 at an Angle of Attack (AOA) 5° and adding rear wing of airfoil profile S1223 at an Angle of Attack (AOA) 10°. The model of Formula Race Car with Single Blade Wings (Figure 8 and Figure 9) was created in SOLIDWORKS 2018 by following 2019 Formula One Technical Regulations FIA[10].

The CAD model formula race car with single blade wings are then imported to ANSYS Workbench 2019 R3. For getting the solution, simulation software ANSYS CFX 2019 R3 is used. Following are the mesh details, (Figure 10)

Type: Tetrahedral Mesh
Mesh Algorithm: Patch Confirming Method
Element size: 1.248 m (Default)
Node: 341533
Elements: 1832294

The boundary conditions applied for simulations are as follows, (Figure 11)

Mathematical Model: SAS SST (Shear – Stress Transport based Scale – Adaptive Simulation)
Inlet: Velocity inlet 95 m/s (342 km/h) (Maximum speed of the car)
Outlet: Pressure outlet at absolute 0 pressure

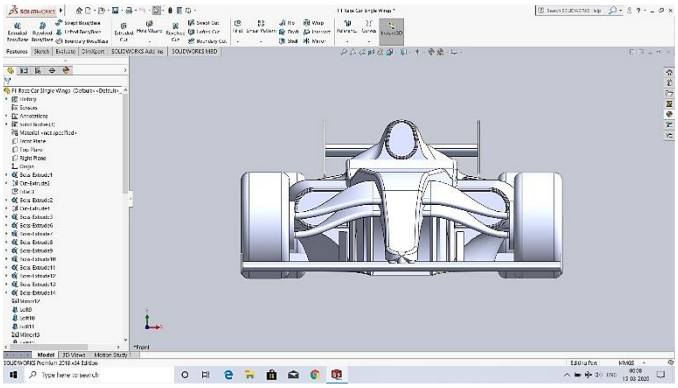

Fig.8 Formula Race Car with Single Blade Wings (Front)

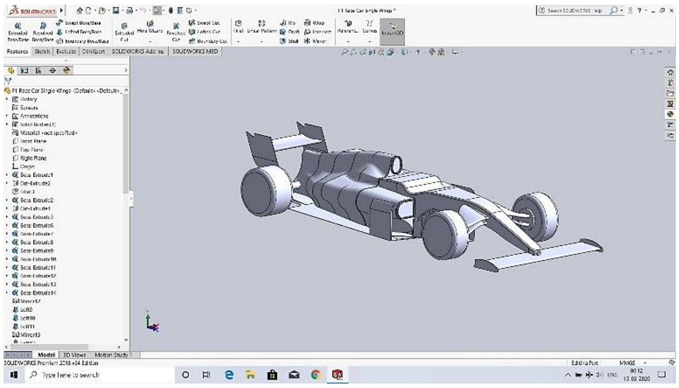

Fig.9 Formula Race Car with Single Blade Wings

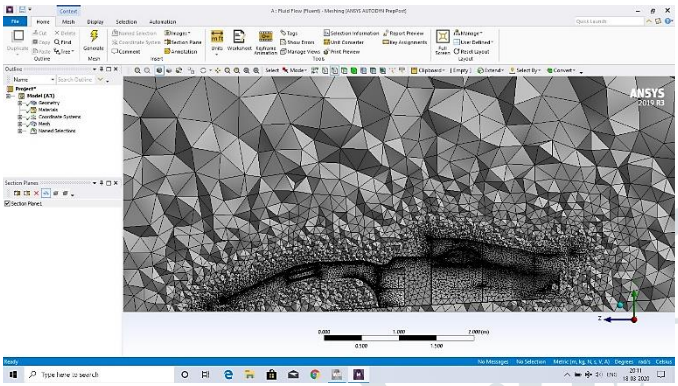

Fig.10 Applied Meshing

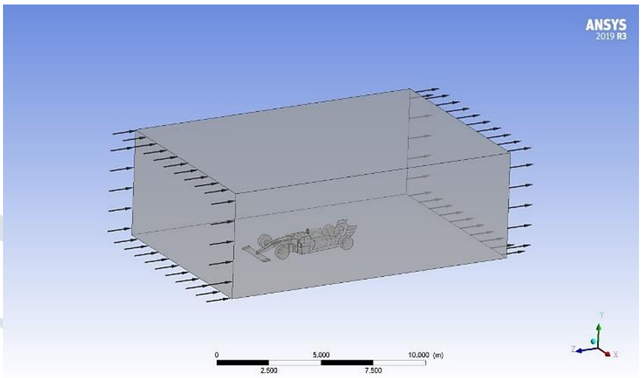

Fig.11 Applied Boundary Conditions

The results of simulation can be obtained in different forms like pressure contour on the car, velocity streamlines form the car, etc.

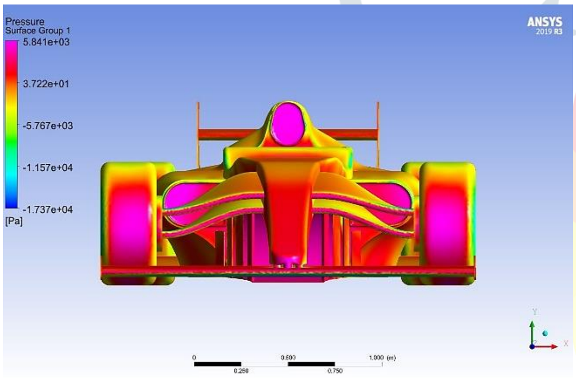

Fig.12 Pressure Contour on Formula Race Car with Single Blade Wings Body (Front)

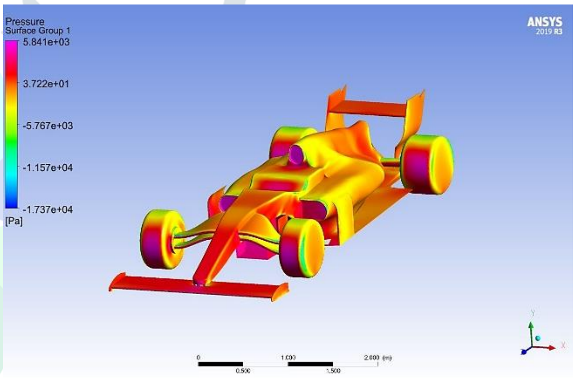

Fig.13 Pressure Contour on Formula Race Car with Single Blade Wings Body

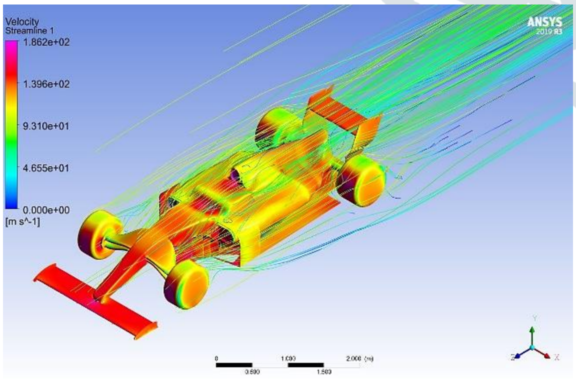

Fig.14 Velocity Streamline from Formula Race Car with Single Blade Wings Body

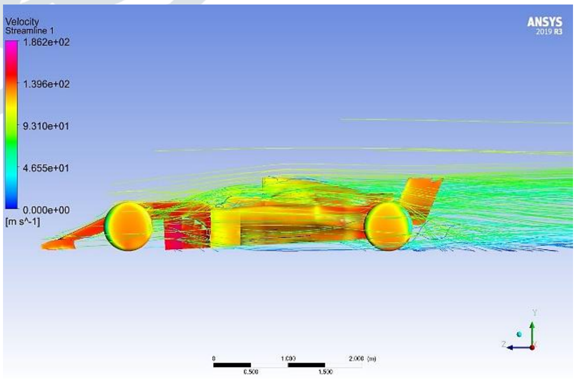

Fig.15 Velocity Streamline from Formula Race Car with Single Blade Wings Body (Side)

The results were obtained during simulations are, total lift force generated on car is -2709 N (here the lift force generated has negative sign, viz. downforce) and total drag force generated is 5419.09 N.

4.2 Analysis of Formula Race Car with 3 Blade Wings

In CAD model formula race car without front and rear wings, adding 3 blades as front wing and 3 blades as rear wing. In front wing, all three blades are of airfoil profile NACA 4412. First blade having 5° Angle of Attack (AOA) and last two blades having 10° Angle of Attack (AOA). In rear wing, first blade is of airfoil profile S1223 having 5° Angle of Attack (AOA) and last two blades are of airfoil profile NACA 2408 having 10° Angle of Attack (AOA). This arrangement is selected from the results obtained in section III. This model is created in SOLIDWORKS 2018 (Figure 16 and Figure 17).

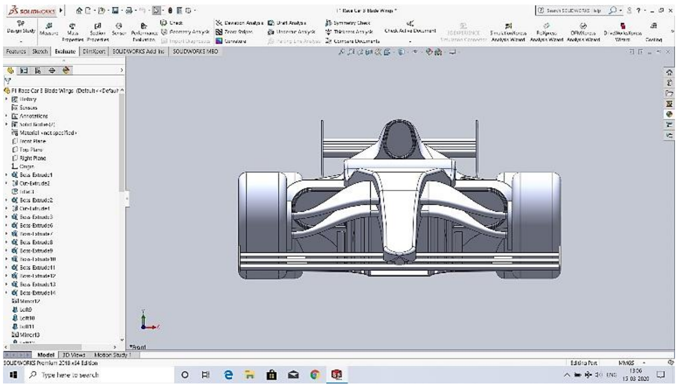

Fig.16 Formula Race Car with 3 Blade Wings (Front)

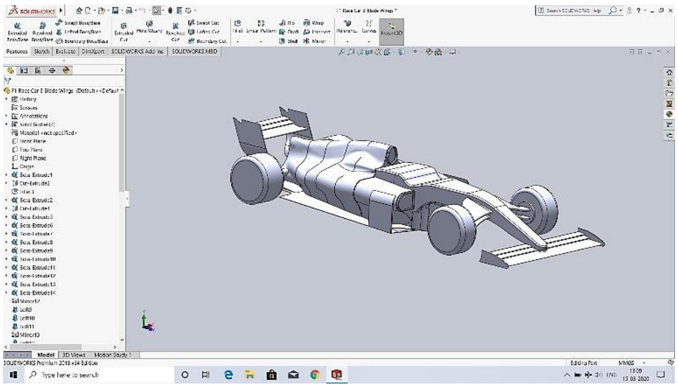

Fig.17 Formula Race Car with 3 Blade Wings

The CAD model formula race car with single blade wings are then imported to ANSYS Workbench 2019 R3. For getting the solution, simulation software ANSYS CFX 2019 R3 is used. Following are the mesh details, (Figure 18)

Type: Tetrahedral Mesh
Mesh Algorithm: Patch Confirming Method
Element size: 100 mm (Max. Element Size: 200 mm)
Node: 2285728
Elements: 12406071

The boundary conditions applied for simulations are as follows, (Figure 19)

Mathematical Model: SAS SST (Shear – Stress Transport based Scale – Adaptive Simulation)
Inlet: Velocity inlet 95 m/s (342 km/h) (Maximum speed of the car)
Outlet: Pressure outlet at absolute 0 pressure

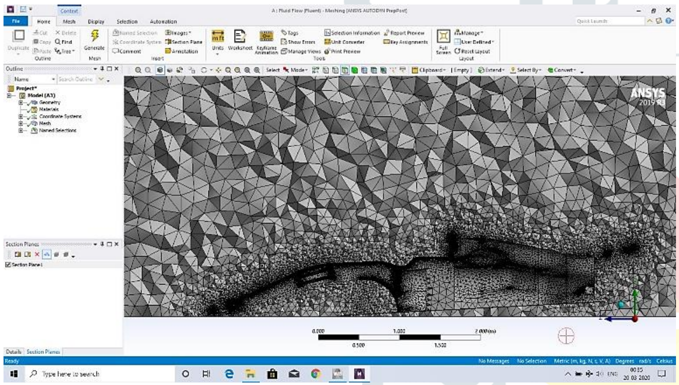

Fig.18 Applied Meshing

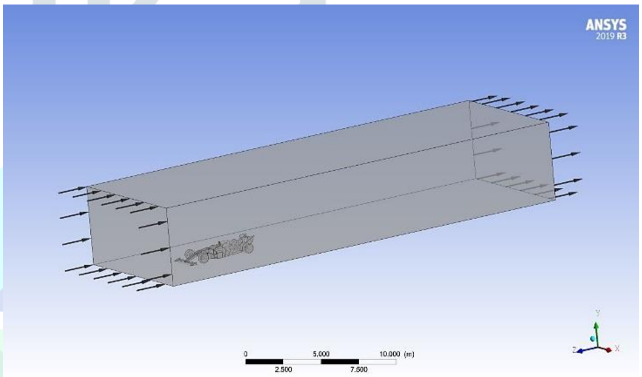

Fig.19 Applied Boundary Conditions

The results of simulation can be obtained in different forms like pressure contour on the car, velocity streamlines form the car, etc.

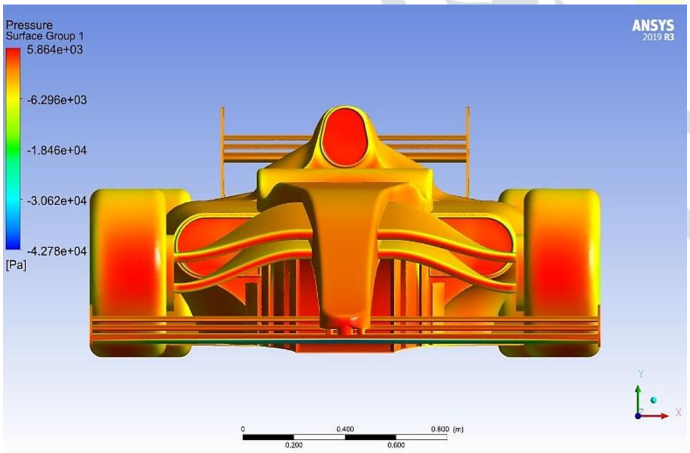

Fig.20 Pressure Contour on Formula Race Car with 3 Blade Wings Body (Front)

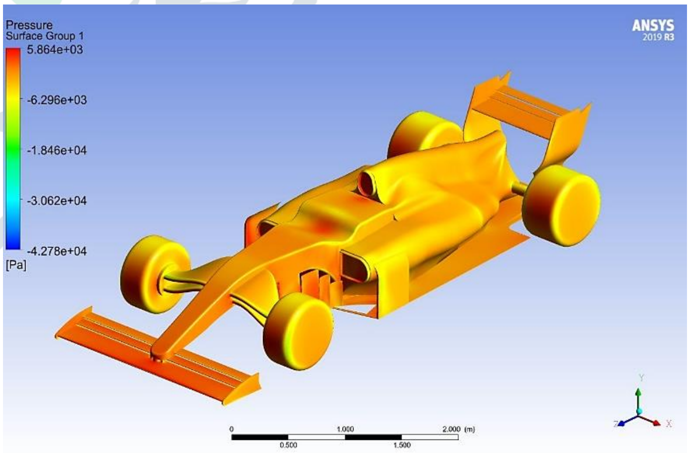

Fig.21 Pressure Contour on Formula Race Car with 3 Blade Wings Body

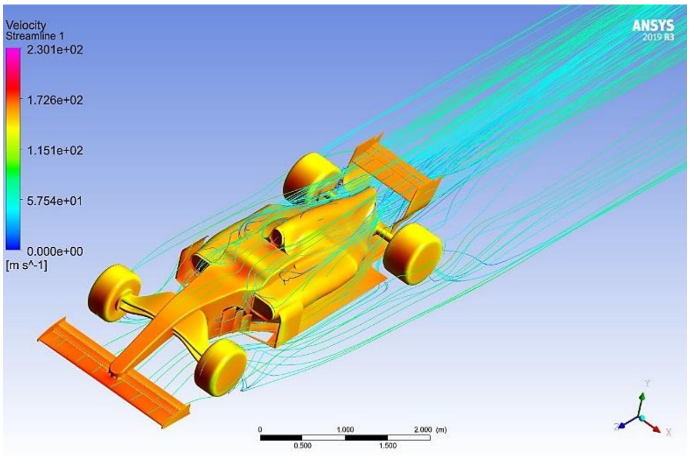

Fig.22 Velocity Streamline from Formula Race Car with 3 Blade Wings Body

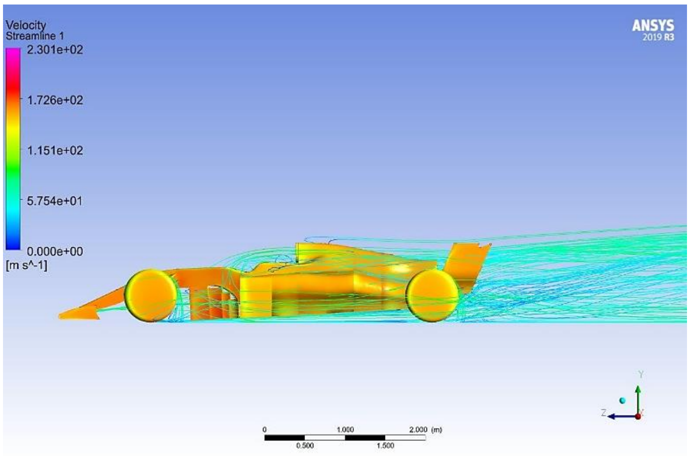

Fig.23 Velocity Streamline from Formula Race Car with 3 Blade Wings Body (Side)

The results were obtained during simulations are, total lift force generated on car is -7991.6 N (here the lift force generated has negative sign, viz. downforce) and total drag force generated is 5453.3 N.

4.3 Comparison of Results and Discussion

Table 4: Comparison of the Results of Formula Race Car with Single Blade Wings and Formula Race Car with 3 Blade Wings

Number of Blades used in Wings of Formula Race Car	Lift (N)	Drag (N)
1	-2709	5419.09
3	-7991.56	5453.3

From above table we can notice that, the drag force on formula race car with single blade wings and formula race car with 3 blade wings is almost similar. But if we compare the downforce for these two cases, then we get 195% increased downforce from formula race car with 3 blade wings than formula race car with single blade wings.

V. CONCLUSION

This study presented how large aerodynamic elements such as front wing and rear wing can influence the flow around the formula race car body and how it could be used to increase the downforce as well as the drag force on the car. From CFD analysis of front wing and rear wing with single blade individually, and CFD analysis of front wing and rear wing with 3 blades individually, achieved downforce is 243.76% increased by using front wing with 3 blades and 41.72% increased downforce can be achieved by using rear wing with 3 blades.

From CFD analysis of formula race car with single blade wings and formula race car with 3 blade wings, 195% increased downforce on the car could be achieved by using the 3 blade wings. Although, the drag force is almost similar for both of these cases. Hence, the aerodynamically optimum condition for car is formula race car with 3 blade wings. It was also shown how smaller elements can be used to enhance the handling of a car by increasing the downforce without significant change in the drag coefficient.

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