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Aerodynamic Development of a Solar Car

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***Abstract*— Reduction in running resistance plays a crucial part in designing of a solar car which is mainly contributed by aerodynamic drag. So reduction in Coefficient of Drag is required to optimize the performance of the solar car. This paper introduces aerodynamic consideration in designing body for a solar car which is to participate in World Solar Challenge, the world's top solar car race. The body is sub-divided into three parts namely: basic body shape, canopy and wheel fairings. The parts were modeled in Solidworks followed by computational fluid analysis in ANSYS Fluent. The results were critically analyzed in order to arrive at an aerodynamic design of body for a solar car.**

Keywords*— *Aerodynamics, airfoil, canopy, drag, fairings

I. INTRODUCTION

Consumers in automotive world are growing every year and demand of highly fuel efficient vehicles is on a rise. Due to increasing number of vehicles running on fossil fuels, environmentalists are concerned over vehicle emissions all around the globe. The effects of the combustion engine automobile are diverse and widespread. In order to combat the pollution problem associated with internal combustion engines, electric cars were developed [1]. The development of electric vehicles as practical, economic automobiles has been a continual, though slow process. Numerous technologies have developed that aims to increase range and performance and at the same time reduces the expense to consumers.

Considerable academic efforts have been applied to the development of solar powered cars which are eco friendly and at the same time are within the reach of common man [1]. However, such efforts have not resulted in an economic solar car due to several reasons. The solar cars are not economical because the cost of the solar cells employed is very high and efficiency of such cells is low. Aerodynamics is one such area where considerable work can be carried out for developing an energy efficient solar car. Aerodynamic consideration of a solar car can greatly increase the range by reducing the aerodynamic drag on the body. Reduced drag will result in low power loses thereby increasing the range. This paper deals with the aerodynamic development of a solar car purposed to be participated in world solar challenge, Australia 2015 and covers three main parts of the body namely canopy, airfoil and wheel fairings. Each of these party have been critically analyzed in order to arrive at a consolidated optimum design producing minimum drag. Such an analysis will prove instrumental for designing a commercial solar car for near future.

II. CONTRIBUTION OF AERODYNAMICS TO SOLAR CARS

Aerodynamic drag in solar car must be minimized to a very low level to achieve good performance. Solar cars have low available energy in comparison to conventional internal combustion engine powered vehicle. So in order to achieve same performance level low aerodynamic drag is necessary. As a result of development in aerodynamics a properly designed solar car requires 10-15% of the driving force of a conventional car. The coefficient of drag of a solar car is around 0.1 as compared to around 0.32 for conventional mass produced cars.

Speed is an important factor for a car [2]. The cruising speed of solar car is determined by balance between energy produced via solar cells and energy consumption to drive and overcome running resistance. If the solar car has a higher energy generation or low consumption/higher efficiency motor and smaller running resistance the car will have a higher cruising speed. Amongst these factors improvement in energy generation is limited as area for solar cells is limited in the competition regulations. So reduction in running resistance would be the most effective and viable option. Running resistance for a car includes rolling resistance, which occurs due to weight and tire factors, and aerodynamic drag, which depends on body shape. As in the World Solar Challenge competition most of the time car is required to be cruising and not accelerating or decelerating, aerodynamic drag effects the running resistance more than rolling resistance because drag force is proportional to square of velocity and solar car are lightweight which results in low rolling resistance [2].

The figure 1 compares the running resistance of a conventional vehicle and '96 Dream, a solar car which participated in World Solar Challenge.

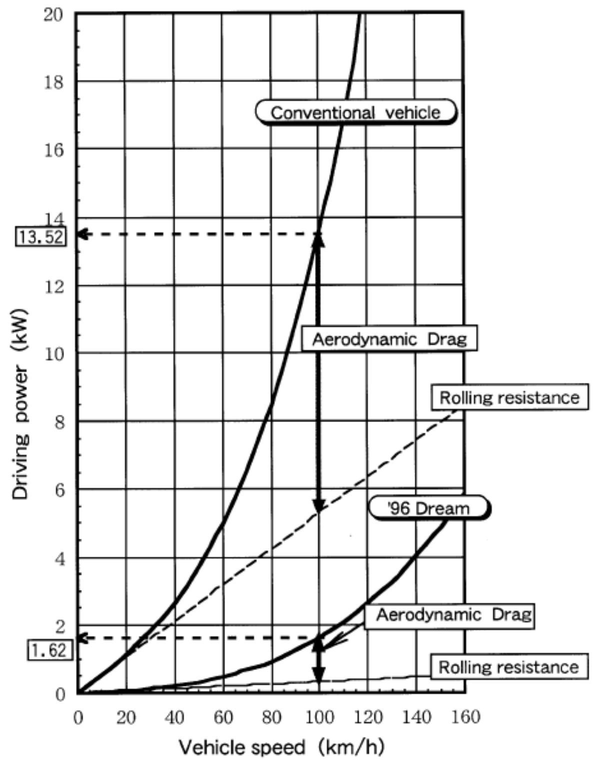

Figure 1 . comparison of running resistance of '96 Dream and conventional car [2].

A sensible analysis shows that for a 10% reduction in aerodynamic drag force the cruising speed of vehicle increases by 2.5 km/h [2]. So focus on aerodynamics in solar car designing is very important.

III. METHODOLOGY

A. Design Criteria

Solar car should be designed in order to establish a balance between the generating capacity of solar cells and aerodynamic performance so as to achieve the highest overall efficiency possible. Generating capacity can be improved by:

1. Improving the generation efficiency of solar cells

2. Increasing the area of solar cells exposed to sunlight

3. Modifying the vehicle body shape to allow solar cells to receive more solar energy for increased output.

Aerodynamic performance can be improved by following considerations:

1. Interference drag: This is the drag force caused due to imperfections in the body and drag due to mating of canopy and body.

2. Skin friction: Air flowing over a streamlined body causes friction to exist between air and body resulting in drag force on the body. Skin friction is the dominant drag force on solar cars. This force is proportional to the total surface area of the car. In order to reduce skin friction drag, surface area of the car should be reduced.

3. Flow separation: Flow separation occurs in bluff bodies like automobile near the sharp corners in the body shape. This creates spinning vortices of turbulence leading to high drag force on the body and should be avoided. Streamlined body like solar cars have very little flow separation.

4. Projected frontal area: The drag force acting on the car is proportional to the projected frontal area. Therefore, while designing the projected frontal area should be kept as small as possible.

5. Coefficient of drag: The shape of the body should be designed in such a way so as to achieve minimum coefficient of drag because drag force is proportional to it. So, in order to reduce drag force, coefficient of drag should be kept as small as possible.

6. Boundary layer pressure loss: The boundary layer is a layer of air between the body and the free stream flow. Its thickness increases as we progress from front to rear of the car. There is a pressure drop along the length of the body as pressure at the rear end of the car is less as compared to that at the front end. This causes drag force on the body. So boundary layer pressure losses should be reduced to minimum while designing the body of solar car.

The highest aerodynamic performance will be pursued under the above-mentioned restrictions.

B. Selection of material

The material of the body should have following properties

- Lightweight: It should be lightweight in order to decrease the overall weight of the body
- Resistance to extreme climatic conditions: It should be moisture proof, rust free and warp free since the body is exposed to humid conditions.
- Thermal stability: Since the solar cars travel at a speed of 70km/h and are exposed to sunlight, the surface temperature of the body can reach as high as 70 °C. Therefore, the material of the body should be thermally stable at such high temperatures.
- Machinability: The material should have good machinability because the shape of the body has many curves from aerodynamic point of view.

Taking into considerations the above properties, Polypropylene honeycomb was selected for body material because it fulfils all the above criteria of material selection. Some of the salient features of this material are:

- It is strong, lightweight, moisture proof, warp free and rust free.
- It is thermally stable up to 80 °C.
- Honeycomb panels can be connected endlessly with a variety of connecting aluminum profiles

IV. IMPLEMENTATION

We are focusing on main 3 parts of solar car body namely: basic body shape, canopy and wheel fairings (wheel fairings). Details on each part and corresponding analysis can be seen below:

A. Basic body shape

The minimum three dimensional drag shape is teardrop shape. We need to modify that shape to accommodate the solar array. The solar array needs to be installed in a rectangular shape as per competition rules. The shape that can accommodate the entire solar array and have aerodynamic shape can be achieved by widening and flattening the teardrop shape. This widening and flattening increases the aerodynamic drag but gives space for mounting solar array. So a balance between these two is required. This flattening and widening produces a constant width shape which is easier to produce. This factor is also to be taken into consideration.

The teardrop shape has the lowest drag when it is traveling in free stream air high above the ground. But for modified shapes to be used for the solar car which has to travel near ground, a ground effect is also to be taken into consideration. Ground effect increases the drag on the teardrop shape as it travels near to the ground [3]. It is also proven that cambering the teardrop shape will result in reduction of drag. As the body travels more near the ground more camber has to be provided. It is easier to manufacture chassis for a cambered shape as camber yields approximately flat bottom. The symmetric and cambered shape will have same length and maximum width but the symmetric shape is better in free stream flow and cambered shape is better for near ground flow. So cambered shape is opted for side view of a solar car.

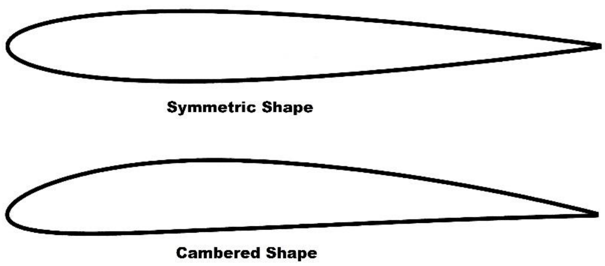

Figure 2. Cambering the airfoil

The National Advisory Committee for Aeronautics (NACA) 66 series air-foils were developed such that flow was laminar over much of its length. They have poor lift to drag characteristics. So they are not suitable for aircraft wings but are very much suitable for solar car body. So for the body shape cambered NACA 66 profile has to be used.

The NACA 66 profile have maximum thickness at 45% of length, so they are well suited for cars that have driver in the middle. So side view is fixed. For the top view flat rectangular is chosen as it is easier to manufacture and can accommodate maximum solar array (compromising on aerodynamic drag).

The x and y coordinates for the cambered NACA 66 profile are given by Table 1 as follows. The length of the car is 5m and maximum width is chosen as 40 cm width.

Table 1. Cambered airfoil development

X	Y
0	0
0.025	0.032575
0.0375	0.039834
0.0625	0.051136
0.125	0.071493
0.25	0.10463
0.375	0.13233
0.5	0.156755
2.00	0.3049
2.25	0.3102
2.50	0.3101
3.75	0.21053
4.00	0.171
4.25	0.12769
4.50	0.08223
4.75	0.03747
5.00	0
4.75	-0.000483
4.50	-0.002089
4.25	-0.014147
4.00	-0.0285
3.75	-0.04355
3.50	-0.05797
3.25	-0.07078
3.00	-0.079738
2.75	-0.0844
2.50	-0.08752
2.25	-0.08979
2.00	-0.0912
1.75	-0.091983
1.50	-0.091934
1.25	-0.091028
1.00	-0.0888
0.75	-0.08442
0.50	-0.0766
0.375	-0.070547
0.25	-0.06232
0.125	-0.049787
0.0625	-0.040147
0.0375	-0.033208
0.025	-0.028147
0	0

By using these coordinates a 3D model was developed using Solidworks as shown in figure 3

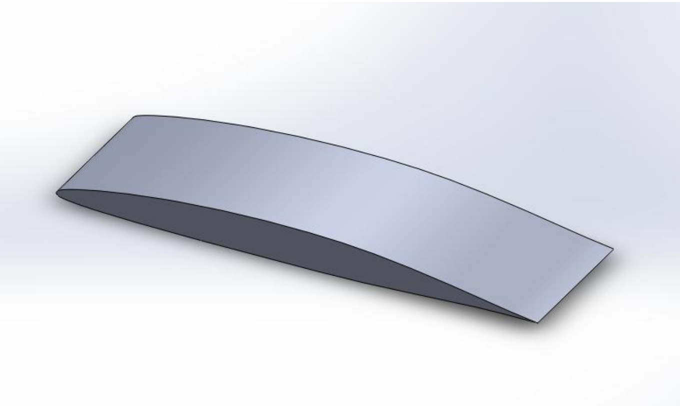

Figure 3. 3D CAD model of cambered NACA 66 wing

FLOW ANALYSIS

We considered air flowing over cambered NACA 66 profile. The free stream velocity is 30 m/s (around 100 km/h). Assume standard sea level values for the free stream properties.

Pressure = 101,325 Pa

Density = 1.2250 kg/m^3

Temperature = 288.16 K

Kinematic Viscosity v = 1.4607e^{-5} m^2/s

We will determine pressure and velocity distribution on the profile.

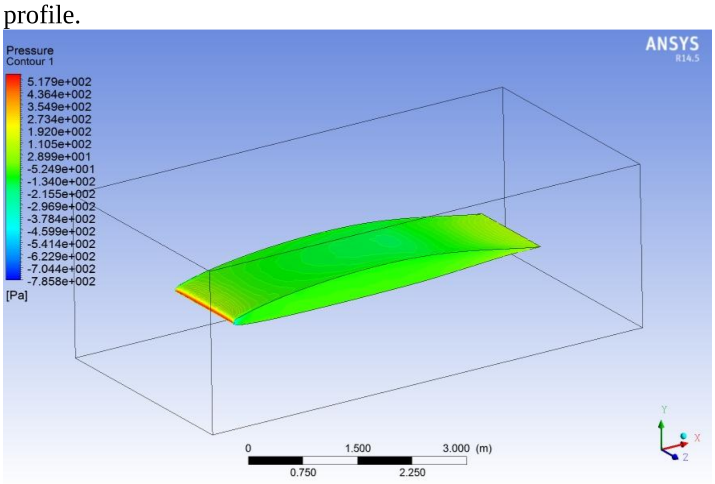

Figure 4. Pressure contour along the profile

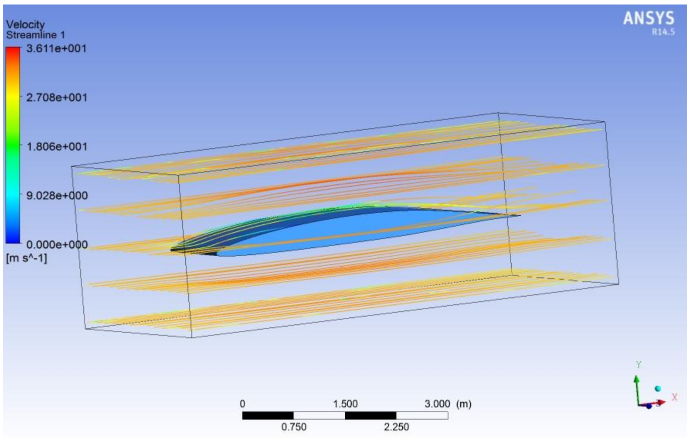

Figure 5. Velocity distribution along the profile

As we can infer from the figure 4 that pressure on the top of airfoil is slightly lesser than the pressure at the bottom of the airfoil which means we are getting slight lift force in accordance with the design criteria. The high pressure line on the leading edge, as shown by red region, is the main reason for aerodynamic drag. The velocity lines can be read by figure 5. We can see that velocity on top of airfoil is more in magnitude than free stream velocity. From this we infer that there is a low pressure zone in accordance with Bernoulli's Theorem.

B Canopy

Canopy is an extrusion in the basic body shape which enables the driver to view the roadside conditions. This extrusion has drag associated with it. In order to reduce this drag, canopy should be kept low in height and long in length. Height of the canopy is decided by degree of sight required as per regulations. Angle of attack can be provided to the car to minimize canopy height. A basic ellipsoidal shape can be used for canopy. In addition to drag on ellipsoid shape there is also interference drag caused due to interference of flow over canopy and flow on the body.

Ellipsoid shape was chosen for the canopy. An ideal canopy when viewed from front should be blended into body with small radius to minimize drag area. When viewed from side, it should blend in with large radius. This ideal shape has significantly less amount of drag than ellipsoidal shape. However this shape takes a lot of area on top of body which minimizes the size of solar array [3]. L/D ratio of ellipsoidal canopy should be maximized to reduce drag, but D should be kept large enough to accommodate driver's head. So a height of 25 cm was taken. The CAD model of canopy is shown in figure 6.

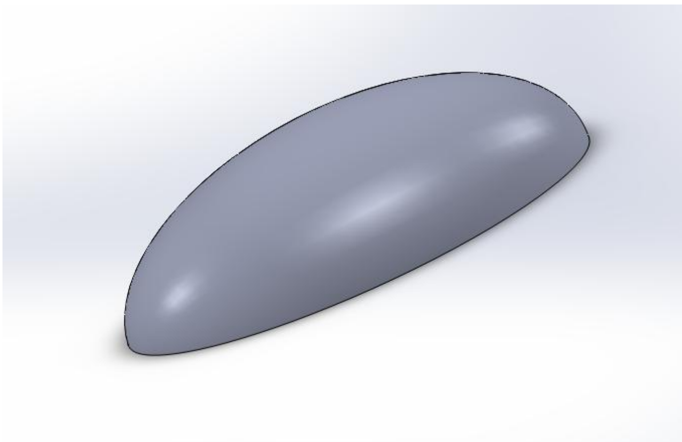

Figure 6. CAD model of canopy

FLOW ANALYSIS

We considered air flowing over ellipsoidal canopy. The free stream velocity is 30 m/s (around 100 km/h). Assume standard sea level values for the free stream properties.

Pressure = 101,325 Pa

Density = 1.2250 kg/m^3

Temperature = 288.16 K

Kinematic Viscosity v = 1.4607e^{-5} m^2/s

We will determine pressure and velocity distribution on the canopy.

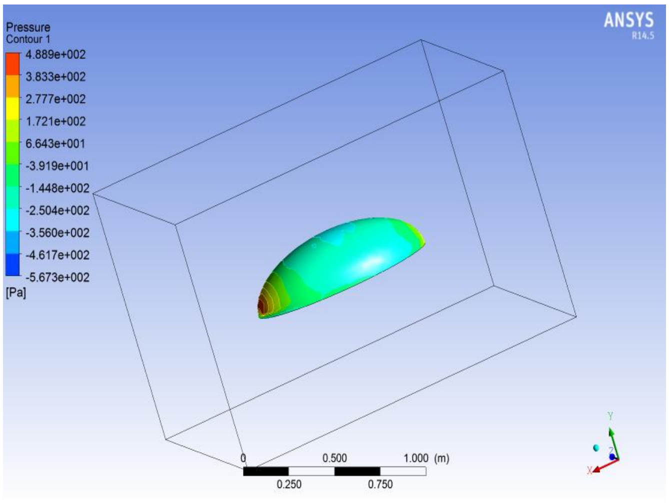

Figure 7. Pressure distribution across the canopy

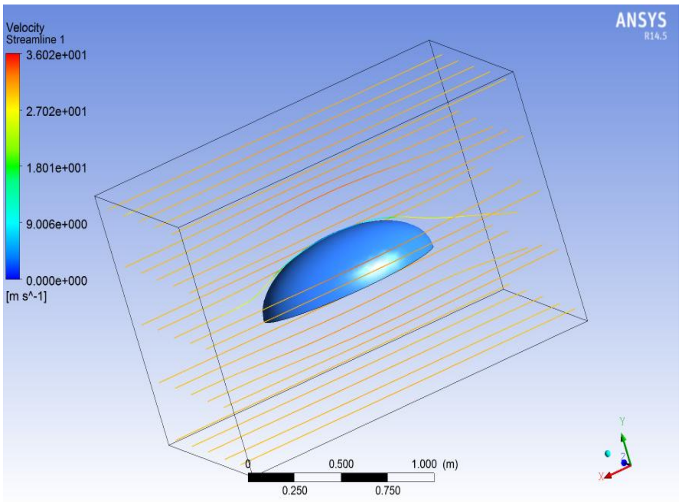

Figure 8. Velocity Distribution along the canopy

We can infer from figure 7 that there is a high pressure zone on the leading edge because it is a sudden obstruction in free-stream flow. Moreover there is a vacuum zone near the leading edge due to sudden change in curvature as the curve and flat faces are orthogonal to each other. This vacuum zone creates more turbulence. The pressure distribution is symmetric about y axis so no drag occurs along these directions. The velocity distribution can also be seen through the figure 8.

C Wheel fairings

Wheel fairings are used to cover the wheels which if left open contributes to significant drag. As flow separation exists around all exposed portions of wheels, so fairings are used to prevent flow on rotating wheels. Fairings should be kept as close to the tires as possible and sealed to prevent air from flowing up into the car. The air flowing up into car causes ventilation drag [3].

Elliptical shape is chosen for wheel fairings. The CAD model for the wheel fairings was developed using Solid Works as shown in figure 9 demonstrating the various dimensions considered during designing.

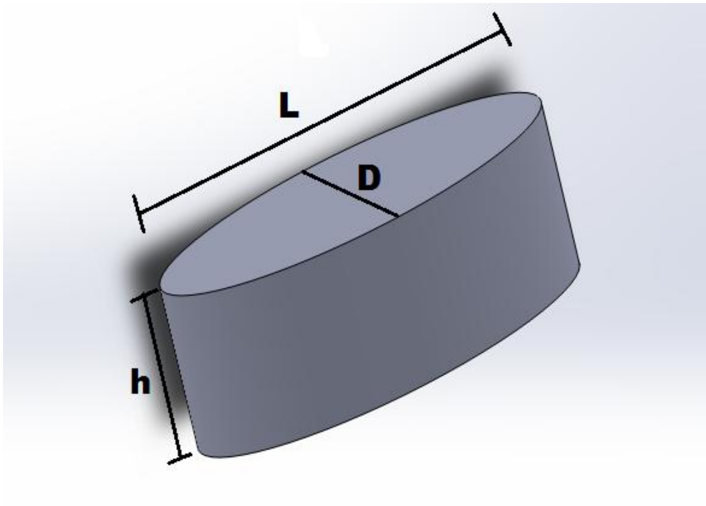

Figure 9. CAD model of a wheel fairing

The thickness D of the ellipse is to be kept minimum and is decided by considering maximum turning angle and due clearance for front wheels and only thickness and clearance for rear wheels. Considering this, D was decided as 0.4 m. The corresponding length L should be kept maximum for keeping the L/D ratio maximum which gives lower drag. Length is limited due to ventilation drag, length of vehicle and clearance between front and rear fairings. L/D ratio of 3 was selected which gave us L=1.2 m which is well under limits. Height h is decided by taking into consideration the ground clearance associated with the vehicle.

FLOW ANALYSIS

We considered air flowing over elliptical wheel fairing. The free stream velocity is 30 m/s (around 100 km/h). Assume standard sea level values for the free stream properties.

Pressure = 101,325 Pa

Density = 1.2250 kg/m^3

Temperature = 288.16 K

Kinematic Viscosity v = 1.4607e^{-5} m^2/s

We will determine pressure and velocity distribution on the body.

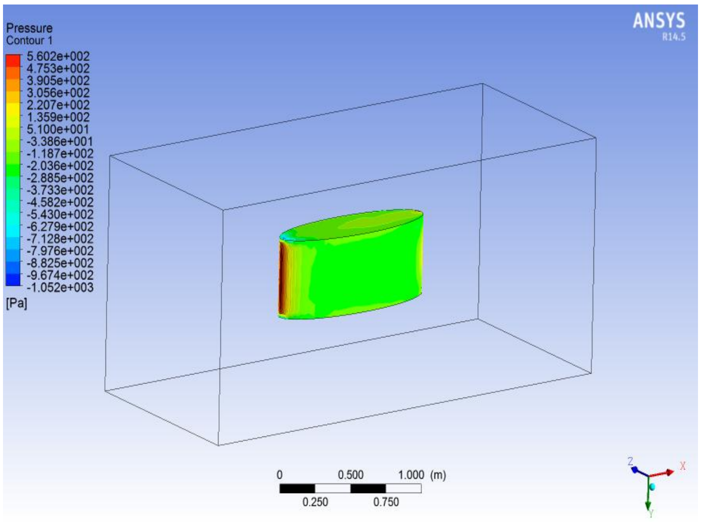

Figure 10. Pressure variation on fairing

We can infer from figure 10 that there is a high pressure zone on the leading edge because it is a sudden obstruction to the free stream flow. Moreover there is a vacuum zone near the leading edge due to sudden change in curvature as the curve and flat faces are orthogonal to each other. The pressure distribution is symmetric about y and z axis, so no drag occurs along these directions. The velocity distribution can also be seen through the figure 11.

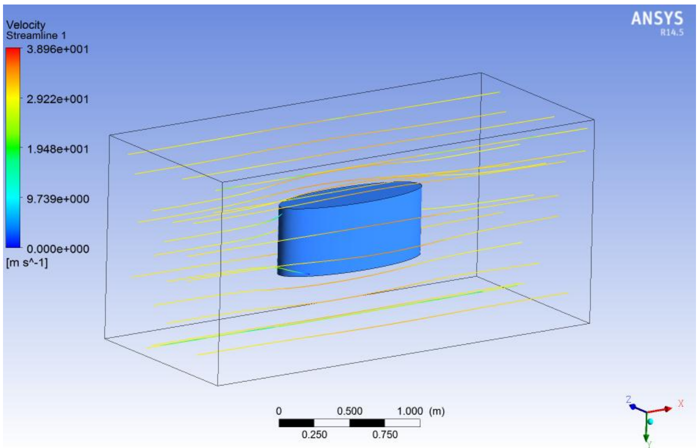

Figure 11. Velocity distribution along fairing

CONCLUSION

Performance of a solar car is limited due to low power generation by solar cells and running resistance. The running resistance is mainly contributed by aerodynamic drag and rolling resistance. Significant improvement can be done only in reduction of aerodynamic drag. In order to achieve this, so body of solar car was divided into 3 parts namely: basic body shape, canopy and wheel fairings. Each of the part was modeled using Solidworks and was analyzed using ANSYS Fluent. Most practical design for each part was obtained considering the advantages and disadvantages of each option and an integrated body design was obtained as shown in figure 12. Designing was done considering one dimensional flow only which may not result in the best overall performance as the body is subjected to three dimensional flow in real conditions.

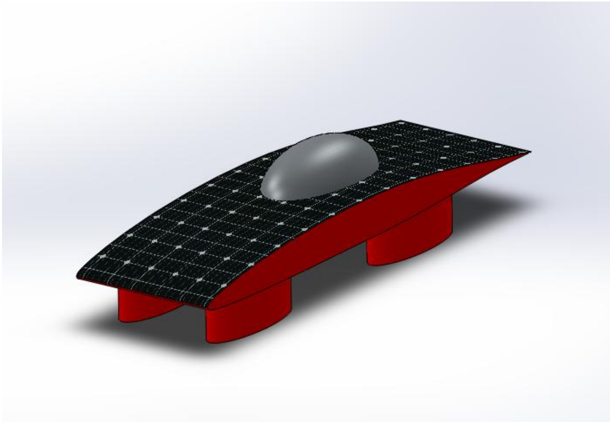

Figure 12. Design of Solar Car

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