Supersonic Rocket Analysis

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Abstract**– *Since the beginning of the space age, the main actors in space exploration have been governmental agencies, enabling a privileged access to space, but with very restricted missions. The last decade has seen the rise of space tourism, and the founding of ambitious private space travel companies, showing the beginnings of a new exploration era, that is based on a more generalized and regular access to space and which is not limited to the Earth's vicinity. However, the cost of launching sufficient mass into orbit to sustain these inspiring challenges is prohibitively expensive and the necessary infrastructures to support these missions is still lacking. To provide easy and affordable access into orbital and deep space destinations, there is the need to reduce the drag forces that effects on the vehicles negatively and consume weights, that's means money.***

This is a vision for a new space age based on small launch vehicles. An introduction to micro launchers and micro launchers technology with a general overview of rocket design and engineering but at a popular and student level. Written for those who have a basic understanding of design & Analysis [1].

Keywords-- Rocket Design, End Body Effect, Transonic After Body, Boom Barrier.

I. Introduction (Heading 1)

Mostly when we want to go farther away or increase the speed of any vehicle, we inject more fuel, in case of the rockets specially the solid propellant we decide to select bigger motor which bigger weight and volume what takes us to design bigger rocket, that means more drag. We can increase our speed with decreasing the fuel consume in same time by reduce the air resistance in friction surfaces, stagnation faces and expansion areas.

Total Drag

The total drag isn't simply the sum of the drag of each component, because when the components are combined into complete configuration can affect the flow field, and hence, the drag of another [1].

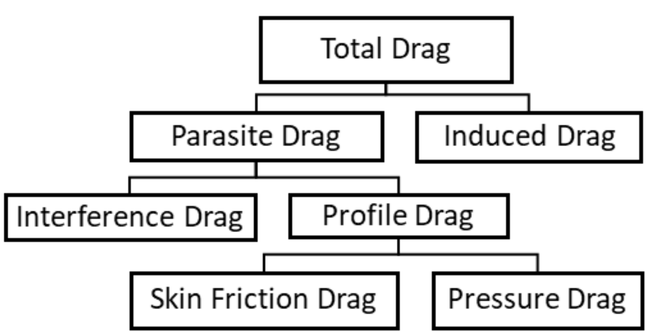

Figure 1 Drag decomposition.

Induced Drag

The induced drag is a pressure drag caused by the induced flow (downwash) associated with the vortices created at the tips of rocket fins.

Parasite Drag

The drag used for the profile drag for complete vehicle, integrated over the complete rocket surface.

Interference Drag

An additional pressure drag caused by mutual interaction of the flow fields around each component of the rocket. Can be minimized by proper fairing & filleting which induces smooth mixing of air past the component.

Profile Drag

It is the total drag on an aerodynamic shape due to viscous effect, it is sum of skin-friction & form drag that both come due to the shape & size of the rocket body so it is called profile drag.

Skin-friction Drag

It is the drag due to shear stress and flow viscosity integrated over the surface (Boundary layer effect).

Form Drag

This is the drag that is generated by the resolved components of the force due to pressure imbalance acting normal to the surface at all points, caused by flow separation.

Wave Drag

This is the drag associated with the formation of Oblique & Normal shock waves at high speeds, it represents the effect of compressibility in Transonic & Supersonic flow.

We can easily target any specific altitude or speed only with the rocket which work with liquid motors by adjusting the mass flow rate of exit gaseous (fuel + oxidizer) with the rocket weight which represents the thrust as follows in momentum equation ($F = M*V$). But it's completely different with solid propellant rocket motor which is commonly used in sounding rocket as we use based on the competition (spaceport America) requirements which represents in lunching a rocket between (Mach =1) to (Mach =1.1) which is highly critical flight speed specially in solid propellant motors what will be discussed in the rocket configuration part [2].

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Mainly the rocket configuration isn't so complicated, so after we went through a process of calculations and usage of several software to design a rocket fitting the competition objectives, we design the rocket body as three separate parts, Figure (2) made of Blue Tubes that provides a low density and high strength, which can withstand the flight loads [6].

The Recovery tube is 400 mm in length, 57.4 mm outer diameter, 54.2 mm inner diameter, and 1.6 mm wall thickness. For the motor tube, it is cut from a 57.4 mm Blue Tube with dimensions of 350 mm in length, 54.2 mm inner diameter and 1.6 mm wall thickness. For the e-bay tube, it is cut from a 57.4 mm Blue Tube with dimensions of 30 mm in length, 54.2 mm inner diameter, with coupler Made of Blue tube, the coupler tube extends no less than one body caliber on either side of the joint measured from the separation plane to make the rocket stiffer.

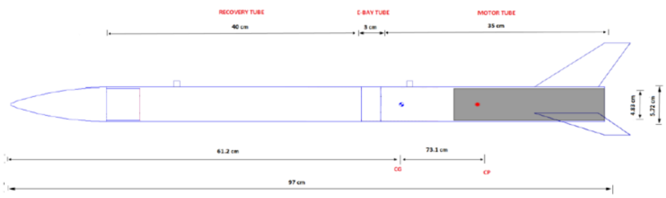

Figure 2 Design of the Rocket Body [2].

II. PROBLEM SETUP

After making a survey on sounding rocket nose cones, it is found that similar rocket utilizes a fineness ratio around 1.5 to 3 to be optimum illustrated in Figure (3), therefore of a fineness ratio of about 2.6 is chosen for our rocket. Figure (4) shows a typical variation of axial force coefficient with nose cone fineness ratio.

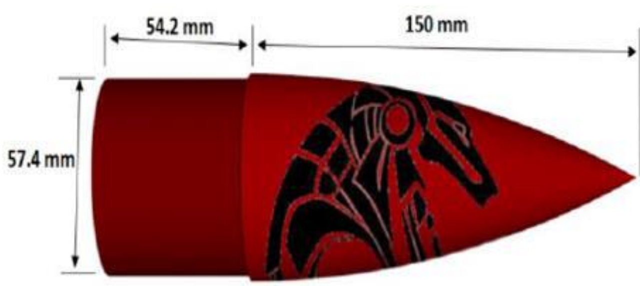

Figure 3 Nose Cone Design [2].

Ogive-shaped nose cone is chosen for its relatively better volumetric efficiency, and for minimization of the drag on the rocket. The ogive curve has a smooth transition to the body tube, which result in gradual decrease for the pressure and hence lower total pressure, it is 150 mm in length, 57.4 mm in diameter, 4 mm in thickness. It has a shoulder of 54.2 mm in diameter, 54.2 mm in length and 2 mm in thickness [2].

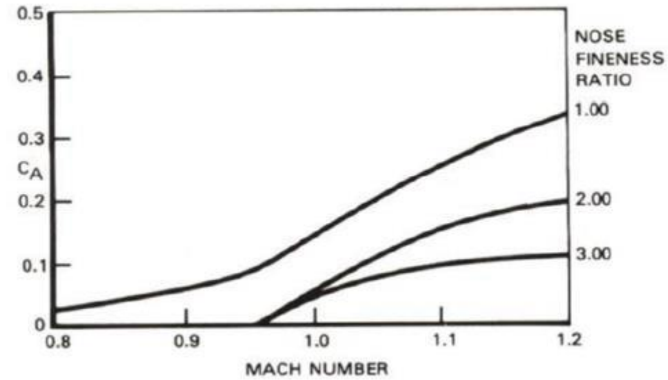

Figure 2 Nose Cone Fineness Ratio [2].

Fins were made in order to improve our rocket performance, the utilization of airfoiled cross section is considered rather than ordinary squared one to minimize drag as possible. After surveying about optimum airfoiled shape for our fin it is found that hexagonal diamond shape will be the optimal one for flights. the fins have swept angle of 34.3deg, which will ensure minimum possible drag as the fin will be inside the Mach wave [2].

Fin is fabricated using aluminum with swept trapezoidal shape with a dimension illustrated in Figure (5) and 3 mm thickness to provide the necessary center of pressure distance that is required to make the rocket stable [2].

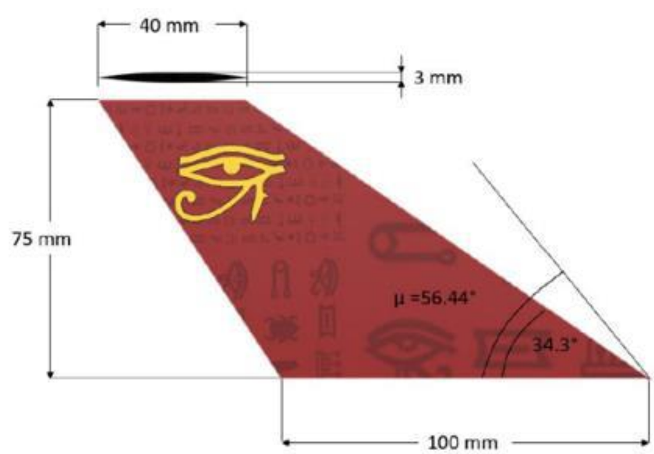

Figure 5 Fin Dimensions [2].

For propulsion specifications and after passing through several calculations. A parametric study is done using an excel sheet to select a motor that satisfies the advanced flight mission (supersonic flight between 1M & 1.1M), and that provides minimum thrust-altitude-total impulse combination so the options for solid propellant motors, based on the rocket design requirements (dimensions & weights) we chose the optimum two motors, their software simulations as followed:

- The first is being Cesarani Technology 475-I445-16A. This motor provides an average thrust 446 N, a maximum thrust 526.2 N, and a total burnout time of 1.1 s. The motor's launch mass is 575 g, and the empty mass is 313g. Figure (6) illustrates the thrust-time curve for the motor [4].

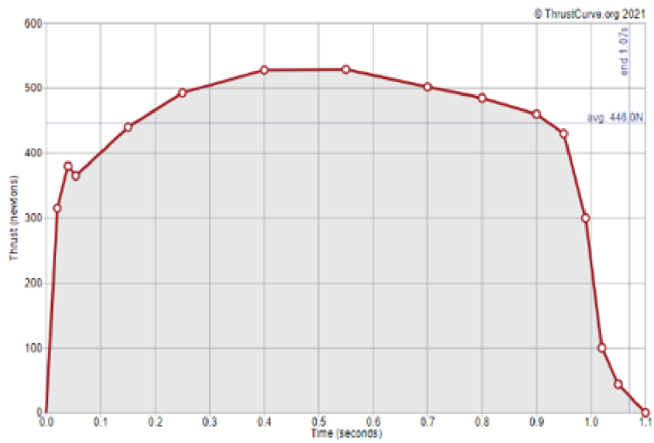

Figure 6 Thrust Time Curve (16A) [4].

- The second is the Cesarani Technology 821-J430-18A. This motor provides an average thrust of 432.4 N, a maximum thrust of 546.8 N and a burnout time of1.91 s. This motor is a reloadable type with a launch mass of 800 g and an empty mass of 384 g. Figure (7) illustrates the thrust-time curve for the motor [4].

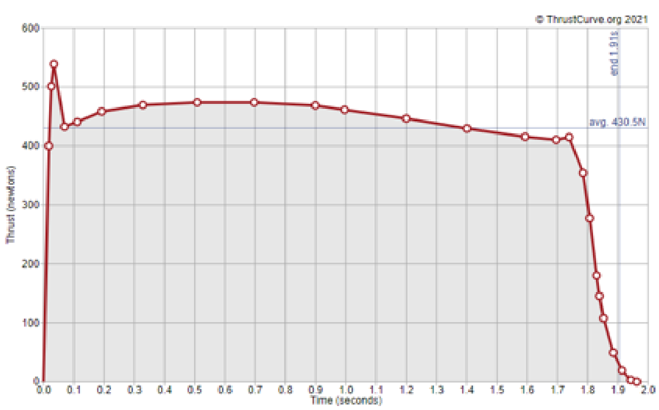

Figure 7 Thrust Time Curve (18A) [4].

III. OBJECTIVE

Design & experiment a Supersonic Rocket can fly in Transonic region between (1: 1.1) Mach.

IV. HYPOTHESIZES

After we launch the rocket with each motor individually on the (Open Rocket) software flight simulator we found that the rocket speed with the first motor (16A) will be supersonic but more than 1.1M what we didn't want. But with the second motor (18A) the motor speed didn't reach the supersonic it Flew at High-subsonic (Transonic) speed below 1M that also what we didn't want to be our flight speed. So, we decide to use one of them with applying some modification on the rocket as followed:

- Change the allover rocket configuration & motor
- Increase the rocket weight & using the first motor(16A)
- Reduce the rocket weight & using the second motor(18A)
- Use aerodynamics tricks to reach the minimum drag & using(18A)

The last solution was the best, so based on our knowledge of the drag types & its definitions we chose the modification in profile drag to be the reduction target that means work on skin friction & form drag. For the skin friction drag we can't change it more than we did based on commercial materials selection (Blue tube). For the form drag as its definition is drag due to flow separation, in our case the flow separated from the rocket body surface at the body end which is lead to pressure loss due to the formed vortices caused by flow 90 deg expansion after the rocket end. So, the modification we will make being in the rocket body specially in the end section is to design a part which decreasing the expansion angle to reduce the pressure losses due to the form drag of the rocket therefore, reducing the overall drag at the transonic speed Region Figure (8) at the rocket back.

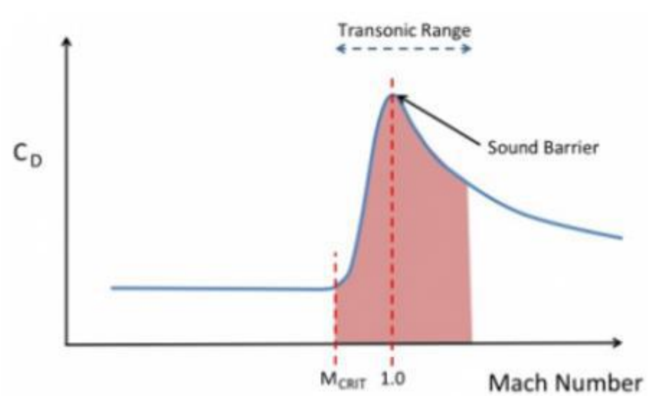

Figure 8 Drag coefficient Transonic Region (Sound Barrier) [7].

So, we design the tapered rear closure as boat tail called AFTER BODY. It is made of 54 mm aluminum of a 2.65 cm transition length, 5.72cm fore diameter, 4.83 cm aft diameter at (15 deg) tabard angle and 0.2 cm wall thickness as shown in Figure (9).

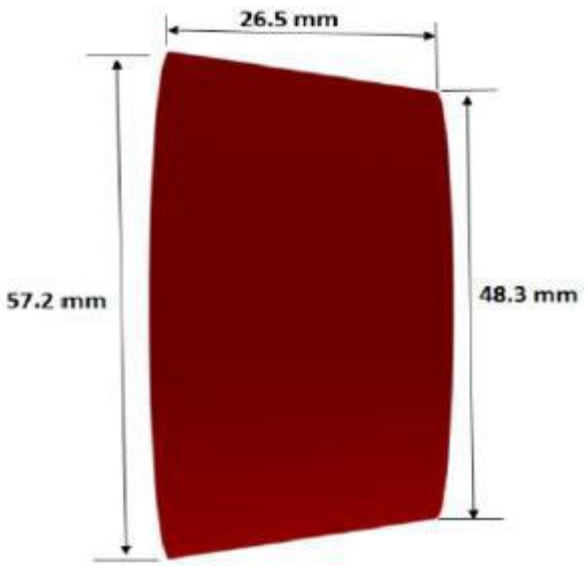

Figure 9 After Body Dimensions [2].

V. Design & Model Experiment

After we redesigned the rocket on the Open Rocket software with the After Body part to readjust the CG & CP points with the other weights and payloads as shown in Figure (10), we decide to draw a 3D-model to test the new forces under fluent simulation.

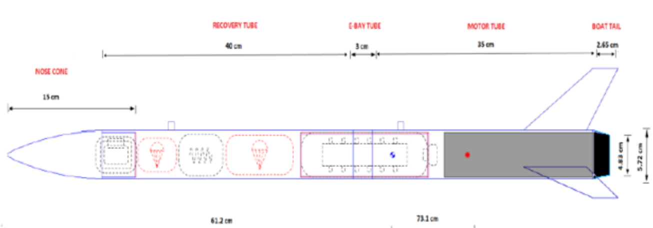

Figure 10 Rocket Body Full Dimensions with End Body [2].

we chose solidworks software for drawing, first we drawn the rocket parts separately [body (3 parts), fins(3copies), nosecone and after body] with their dimensions as followed in Figure (11).

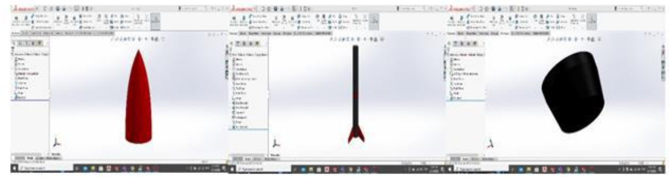

Figure 11 Rocket Parts Drawn by Solidworks [8].

We utilized the Solidworks software flow simulation analysis to know the difference between the existence of the after body and its absence under special conditions which simulate the real flight and the following Figure (12) are some pictures of simulated air flow over the surfaces of both bodies (without & with) after body in order.

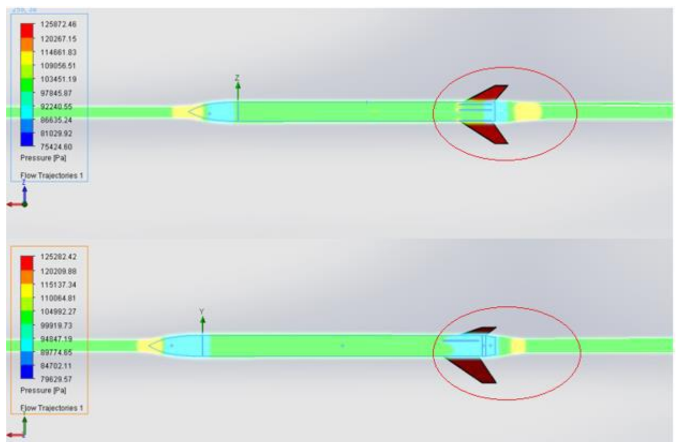

Figure 12 Flow Over Rocket Bodies [8].

VI. Problem Setup

The following is a review for the pressure distribution on the rocket body without the after body, Figure (14).

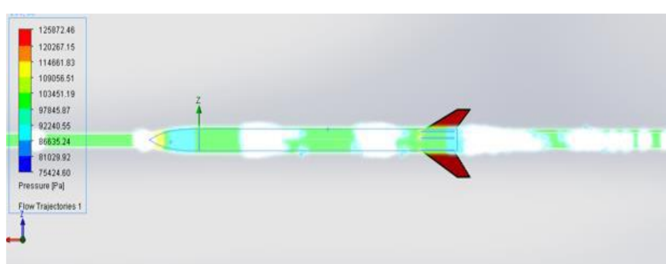

Figure 14 Pressure Distribution Without After Body [8].

As we can see the process and results of software analysis data of the drag forces at flight speed (V = 900 km/h) on the rocket without after body in the shown Figure (13).

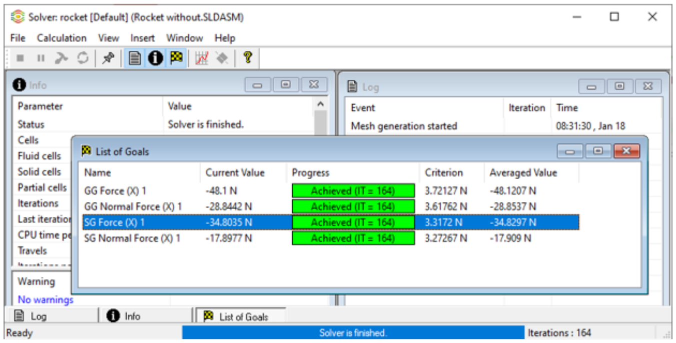

Figure 13 Process & Results of CFD Analysis Without After Body [8].

And the following is a review for the pressure distribution on the rocket body without the after body, Figure (16).

Figure 16 Pressure Distribution with After Body [8].

The processes and results of software analysis data of the drag forces at flight speed (V = 900 km/h) on the rocket with after body in the shown Figure (15).

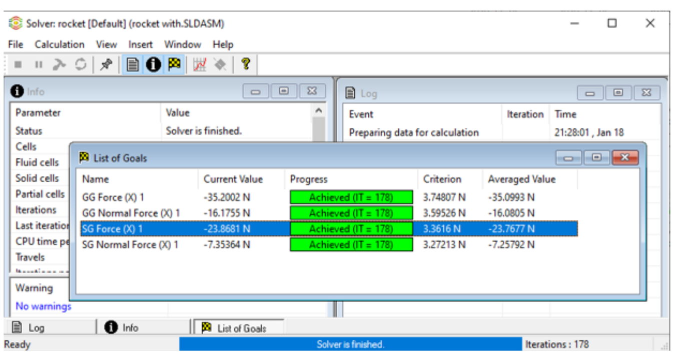

Figure 15 Process & Results of CFD Analysis with After Body [8].

VII.RESULTS AND DISCUSSIONS

The results of the software solution are a drag (D) force in Newton unit and we need to calculate the drag coefficient (CD) dimension less parameter, from the following equation previewed in Figure (17) can calculated.

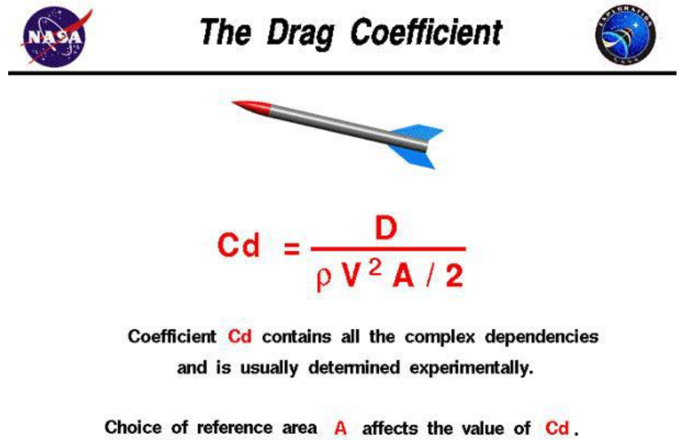

Figure 17 Drag Coefficient Equation [5].

A. *For the rocket without after body the drag coefficient*

- (CD) = [$4.39*10^{-4}$] substituting in the equation with this calculated data:
  - The drag of air (D) = 34.8 N
  - the air density (ƒ) = 1.225 kg/$m3$
  - the flight velocity = 900 km/h
  - the reference area = 0.16 $m2$

B. *For the rocket with after body the drag coefficient*

- (CD) = [$2.4*10^{-4}$] substituting in the equation with this calculated data:
  - The drag of air (D) = 23.9 N
  - the air density (ƒ) = 1.225 kg/$m3$
  - the flight velocity = 900 km/h
  - the reference area = 0.2 $m2$

From the past data we found ΛCd = 2 $*10^{-4}$ it means about 1 kg reduction when putting the after body which's massive difference between the two cases, that difference helps the rocket to skip the sound barrier at the Transonic region with the second motor (18A).

VIII. CONCLUSION

After we finished the rocket construction, Figure (18). we started preparing the ground station waiting the countdown sound for the Zero second to launch our rocket Figure (18) which achieved its mission successfully and flew supersonically below 1.1 Mach.

Figure 18 Rocket while Ignition sequence Started.

IX. Recommendation

we recommend to use the ANSYS software at fluent simulation and use wind-tunnel testing specially in low subsonic models.

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