1 Introduction

1.1 The importance of aerodynamic studies

At the beginning of writing of this appendix, it is valuable to emphasize the importance of aerodynamic studies in case of designing the rocket. Not only do they decrease significantly the mass of the rocket but also they take a huge part in optimization of length and usage of materials, which are beneficial to our not so enormous budget. Apart from that, they increase the safety of the rocket in regards to testing its stability. Hence, by preforming these studies, you are capable of determining how the whole structure would behave before launching, which is necessary bearing in mind that it is not often that you get to test rocket models. This study was mainly based on “The Modern Exterior Ballistic” written by Robert L. McCoy.

1.2 The problem of aerodynamic drag

Rockets have several aerodynamics characteristics that are worth attention in order to estimate the performance after launch. However, in the event of designing non-controlling aerodynamically rockets such as ours, the most crucial factor is aerodynamic drag coefficient. Thanks to this variable it is possible to compare different configurations of the rocket so as to be able to choose the most lightest one. Although, R6 rocket doesn't exceed 1 Mach, drag coefficient may slightly vary depending on velocity of the rocket. This variable was calculated using following formula:

$$F_d = \frac{1}{2}\rho v^2 C_d A \quad \equiv \quad C_d = \frac{2F_d}{\rho v^2 A} \tag{1}$$

Where: F_d - drag force gained from aerodynamic simulations, C_d - drag coefficient, ρ air density, v- velocity of the rocket, A - projectile reference area.

1.3 Methodology of the present work

For simulations, two programs were chosen to compare the results. The first program, Solidworks, was used for model preparation, reference simulations and parametric studies. The second program utilized was Ansys Fluent.

To determine optimal sweep angles and endcone angles, models of R6 Endcone and R6 NoEndcone were initially prepared in Solidworks. They were subsequently subjected to tests ranging from 0.1 to 1.0 Mach, serving as reference points for future research. Following this, parametric studies were independently conducted for the endcone and fins. Each angle of the study underwent analysis at six different velocities. The results were subsequently analyzed and compared to ascertain the rocket's optimal configuration.

For simulations in Solidwors and in Ansys, adiabatic flow was assumed and friction forces were neglected. Ansys solver calculated denisty changes using ideal gas equation.

Furthermore, the stability of the models was assessed using OpenRocket, accounting f or stability changes arising from variations in endcone and fins angles.

1.4 Tested models

Various variations of the rocket were tested to ascertain the optimal configuration before finalizing its geometry. Firstly, the PrawieR5 rocket model, a modified version from the previous year's competition was examined. Subsequently, research was conducted to evaluate the impact of the endcone on aerodynamic parameters. This involved testing two models: R6 Endcone and R6 NoEndcone. Both models exhibited identical stability. Afterward, the endcone and fins optimalization was contucted on R6 Endcone model.

2 Initial study

The work was initiated with the remodeled R5, which had been prepared in Solidworks and featured an endcone, a modification in comparison to the original R5 model. Subsequent testing of the model was conducted using Solidworks Flow Simulation. However, this model was solely utilized for comparing the results of the older model with the new one. The results can be observed bellow.

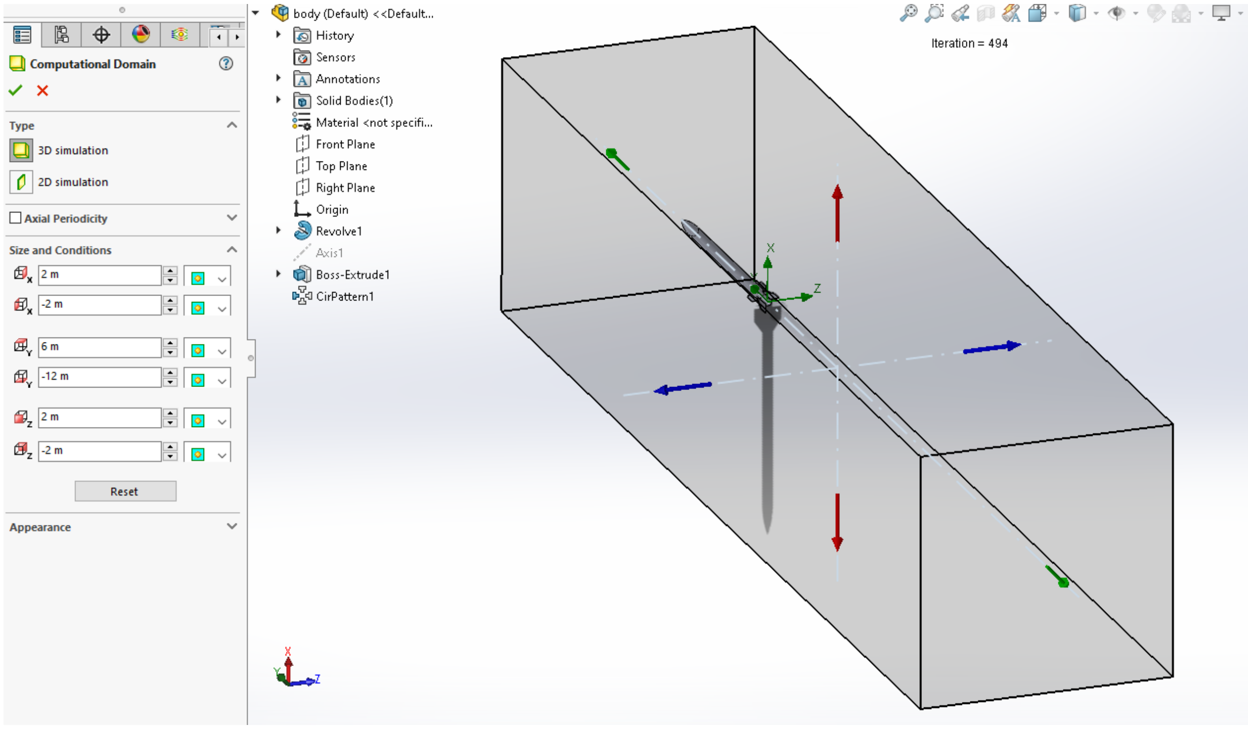

Figure 1: CD graph for PrawieR5 model at Mach 0.6

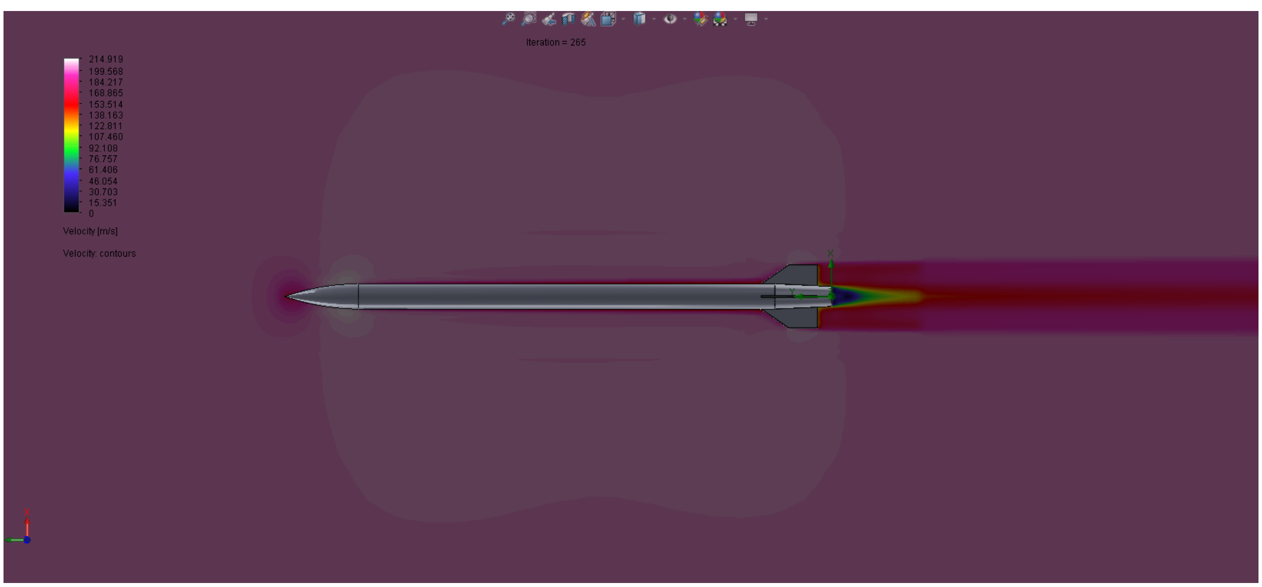

Figure 2: Velocity graph for PrawieR5 model at Mach 0.6

3 Preliminary research of endcone effect in Solidworks

3.1 R6 Endcone

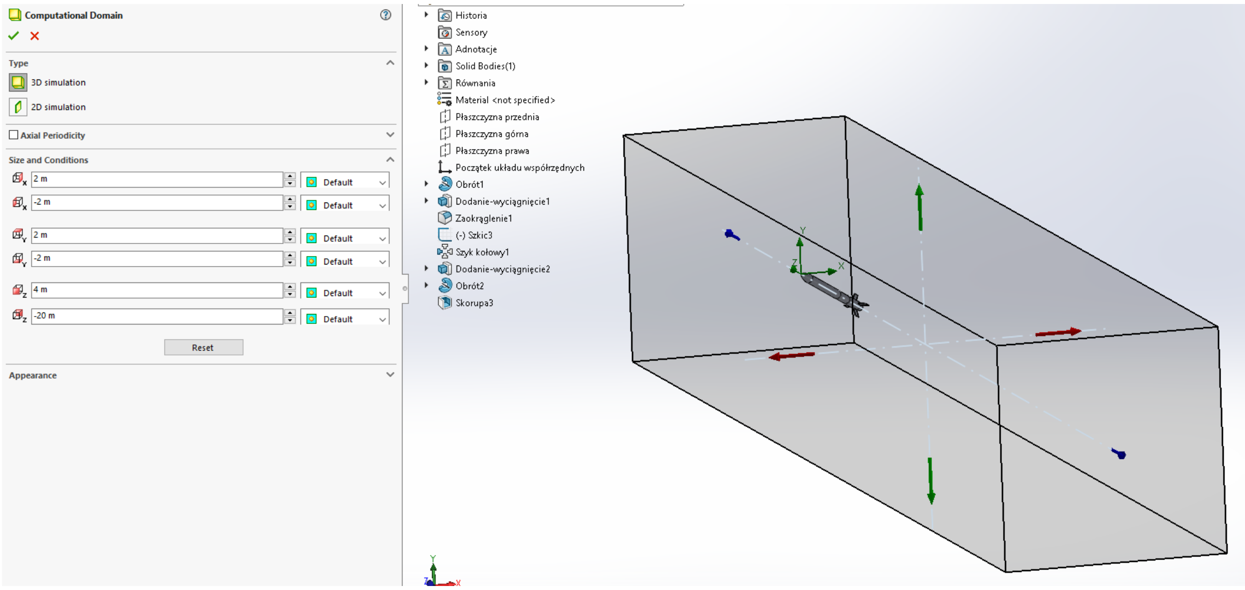

Figure 3: Computational domain for R6-Endcone model

Total cells	351,913
Fluid cells	351,913
Fluid cells contacting solids	51,217

Figure 4: Cell number for R6-Endcone model

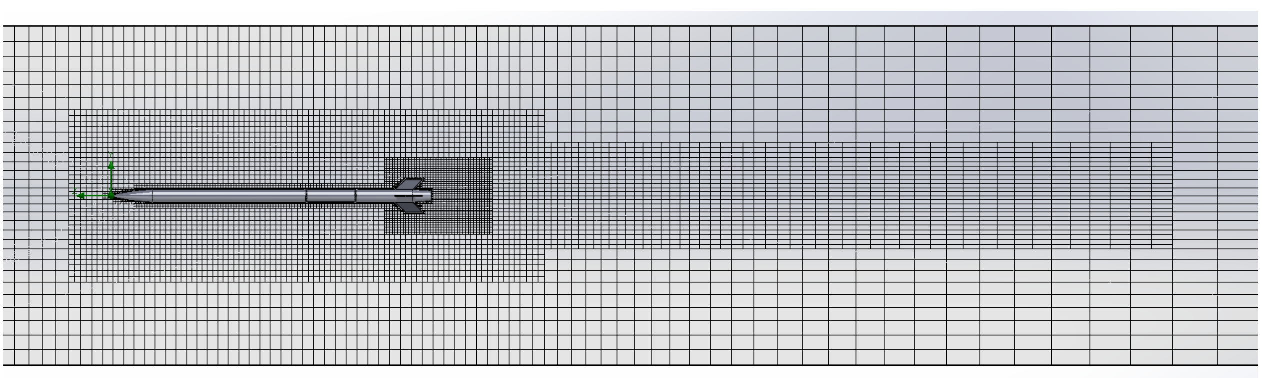

Figure 5: Mesh for R6-Endcone model

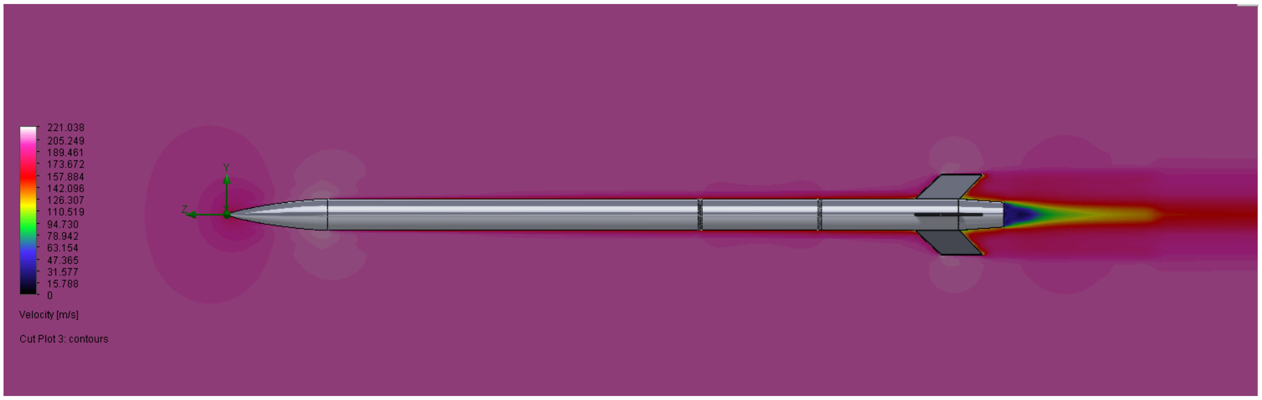

Figure 6: Velocity graph at 0.6 Mach for R6-Endcone model

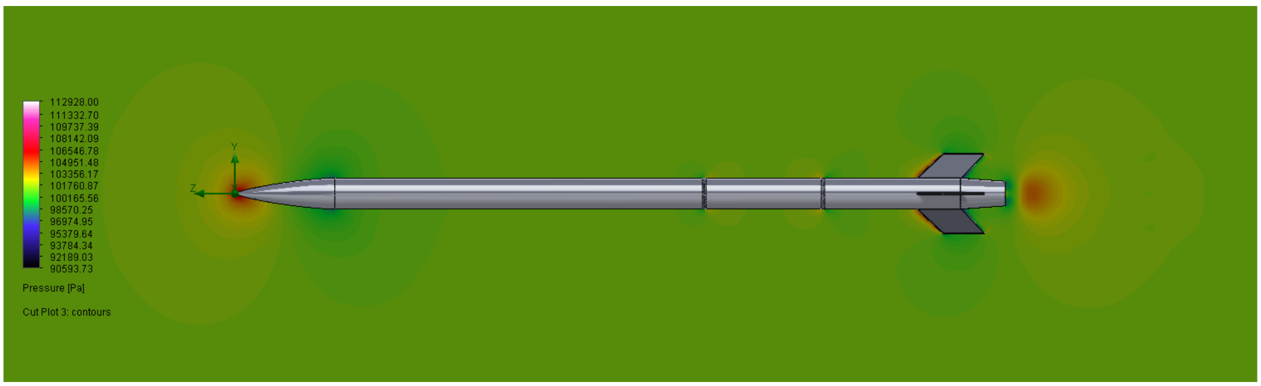

Figure 7: Pressure graph at 0.6 Mach for R6-Endcone model

3.2 R6 No Endcone

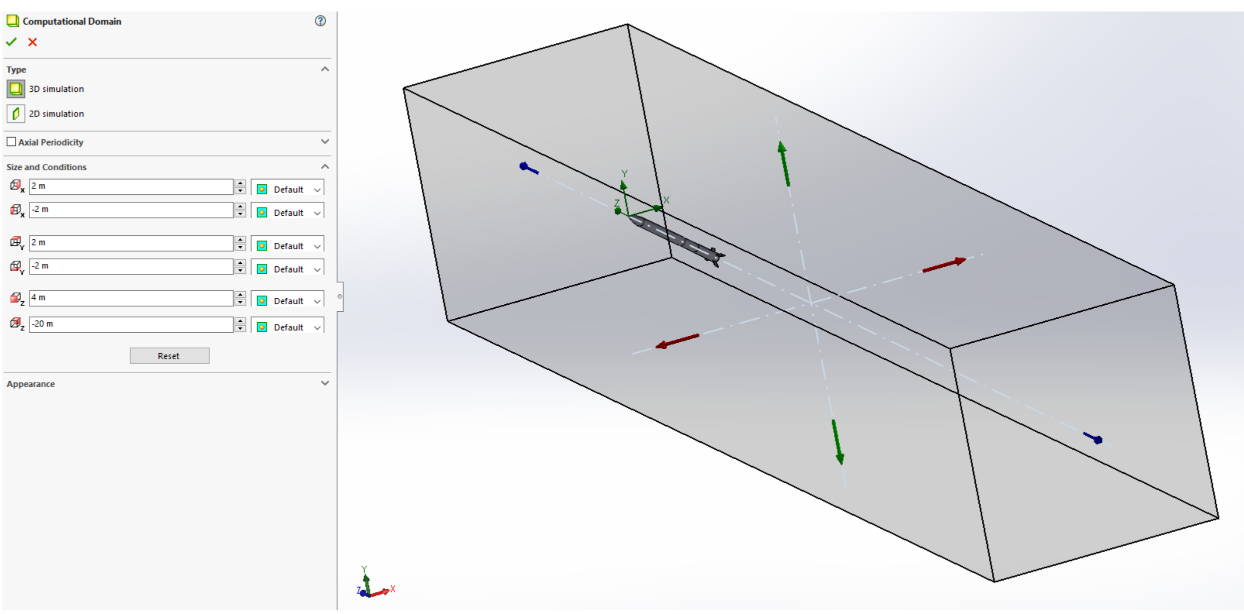

Figure 8: Computational domain for R6-NoEndcone model

Total cells	475,197
Fluid cells	475,197
Fluid cells contacting solids	74,456

Figure 9: Cell number for R6-NoEndcone model

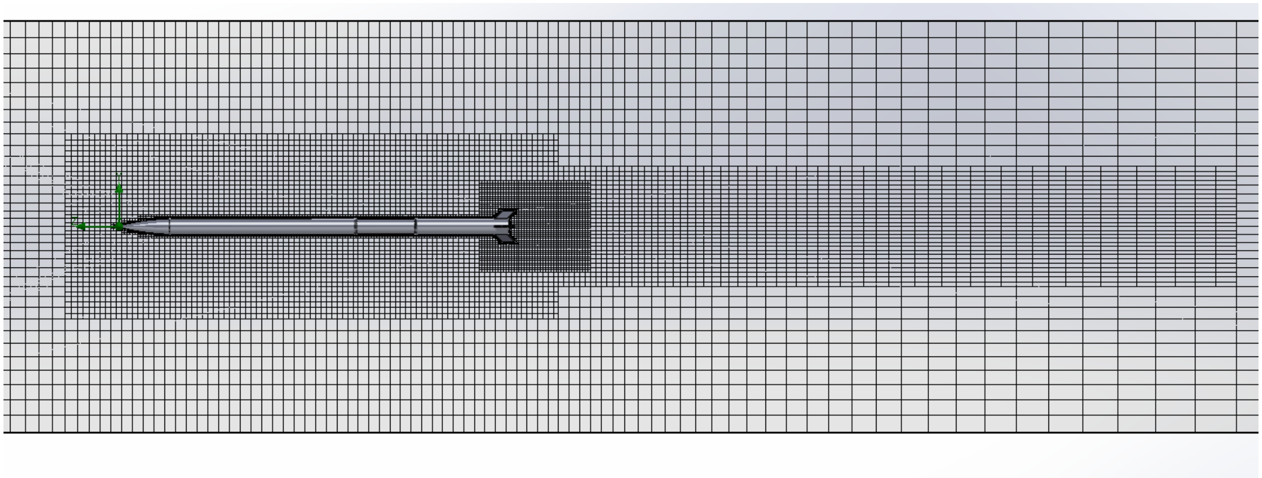

Figure 10: Mesh for R6-NoEndcone model

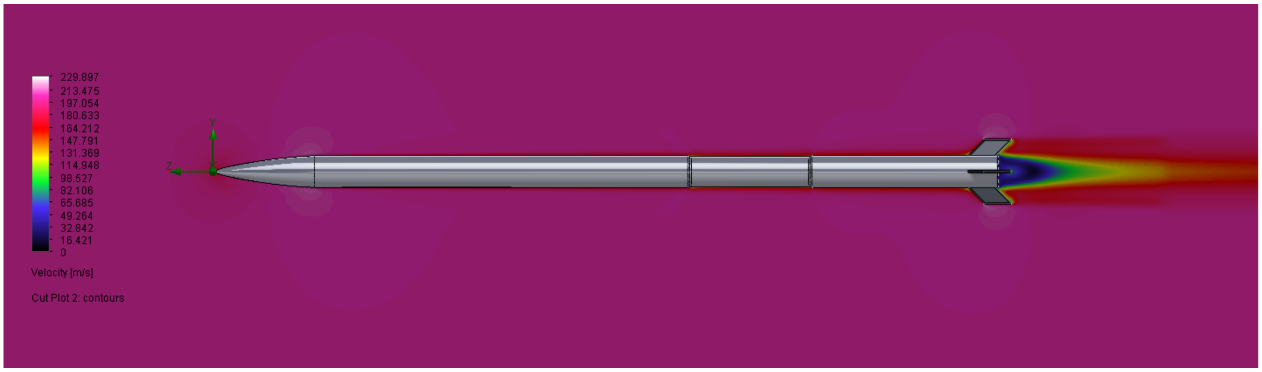

Figure 11: Velocity graph at 0.6 Mach for R6-NoEndcone model

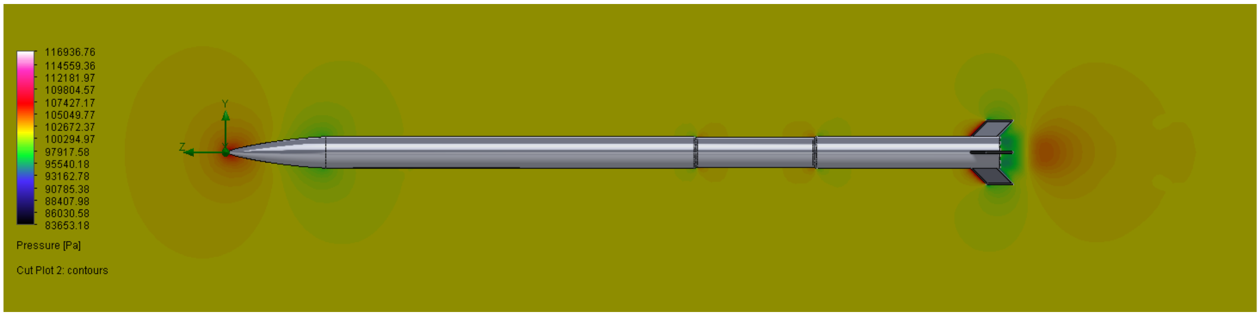

Figure 12: Pressure graph at 0.6 Mach for R6-NoEndcone model

4 Oplitmalization of the endcone in Solidworks

4.1 Range and goal of this study

The goal of this study was to find a minimum of the average drag force function, depending on the endcone angle, which was coupled to the lenght of the endcone. The range of the study was from 3 to 15 degrees, with a step of 1 degree. For each angle, simulations were preformed for 0.1 to 0.6 Mach, with a step of 0.1 Mach. In total 96 simulations were made, however it since lenghts of encone for angle values of 0 - 3 were too big, those where deleted from study.

Finding minimum of the average drag force function is crucial for the optimalization of the rocket since that would allow to reduce the drag force acting on the rocket, which would result in overall better performance of the rocket.

Function of drag coefficient for different Mach number depending on the endcone angle is also shown in the graph. It allows to determine the optimal angle for the endcone for specific velocity and can be compared with existing literature.

Mesh and domain settings for following simulations are the same as in the preliminary research for R6-Endcone model. Cell count changed slightly with the change of the endcone angle, but it was negligible.

4.2 Results

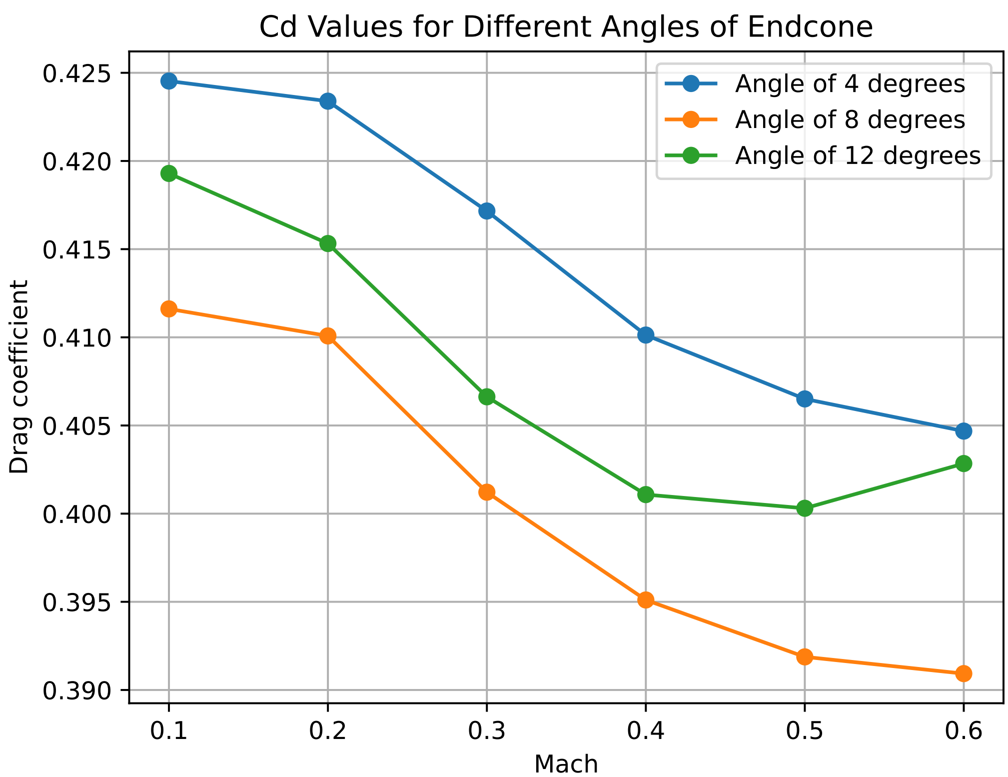

Figure 13: Example of CD graphs for different endcone angles

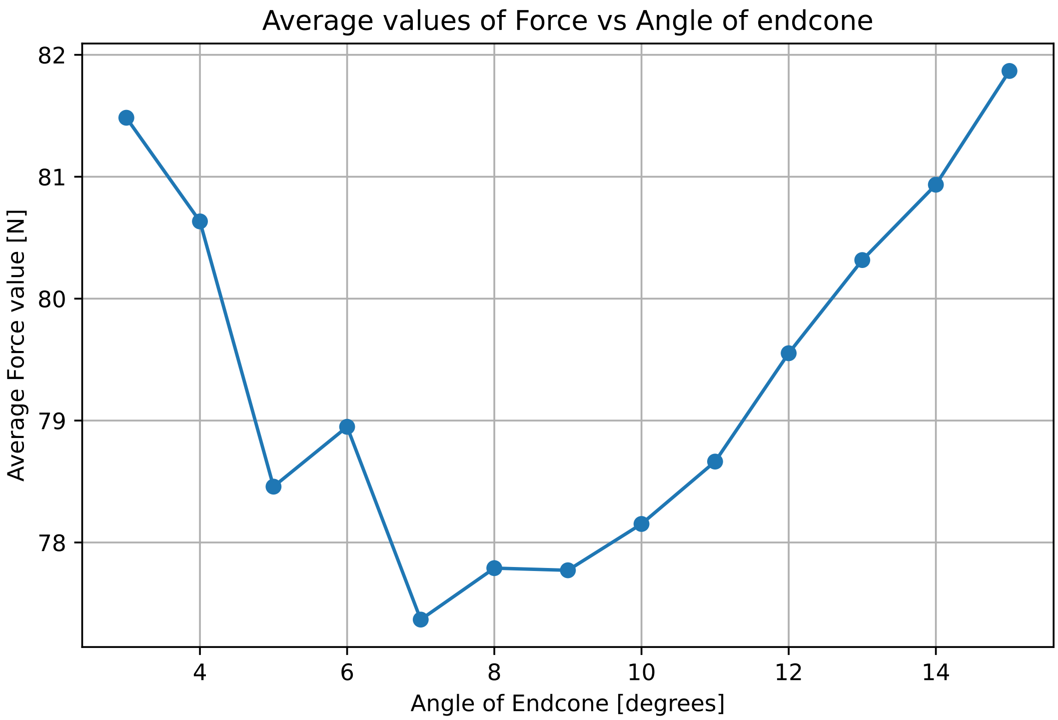

Figure 14: Average Force vs Angle graph

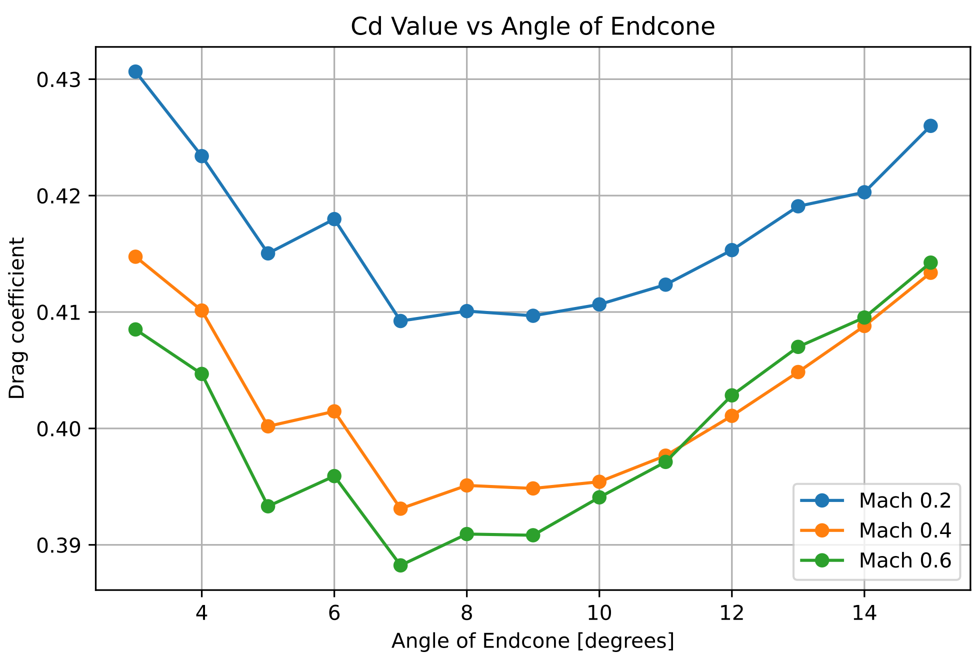

Figure 15: Drag coefficient vs Angle graph

5 Optimalization of the fins in Solidworks

5.1 Range and goal of this study

The goal of this study was to find the most optimal sweep angle of the fins for the R6 model. Only parameter was 90 degrees minus sweep angle, the lenght of top of fin, lenght of bottom of fin and height of fin were kept constant. The range of the study was from 30 to 90 degrees, with a step of 5 degree. For all sweep angle values, simulations were preformed for 0.1 to 0.6 Mach, with a step of 0.1 Mach.

Mesh and domain were kept the same as in prior simulations. Cell count changed slightly with the change of the sweep angle, similiar to the endcone study, it was negligible.

Endcone angle this time was kept at 4.29 degrees, since the physical model of it was already made.

One important note is that for the rest of this study, we will call the angle 90 degrees minus sweep angle just sweep angle.

5.2 Results

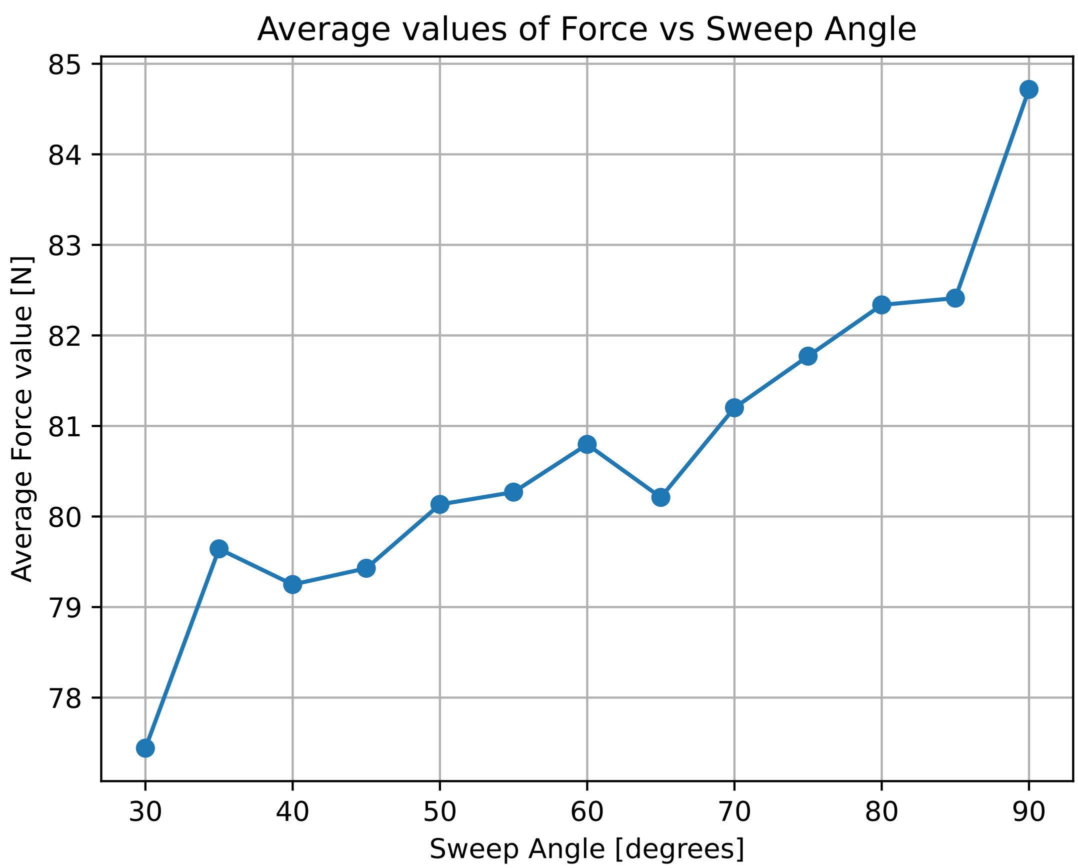

Figure 16: Average Force Value vs Sweep Angle

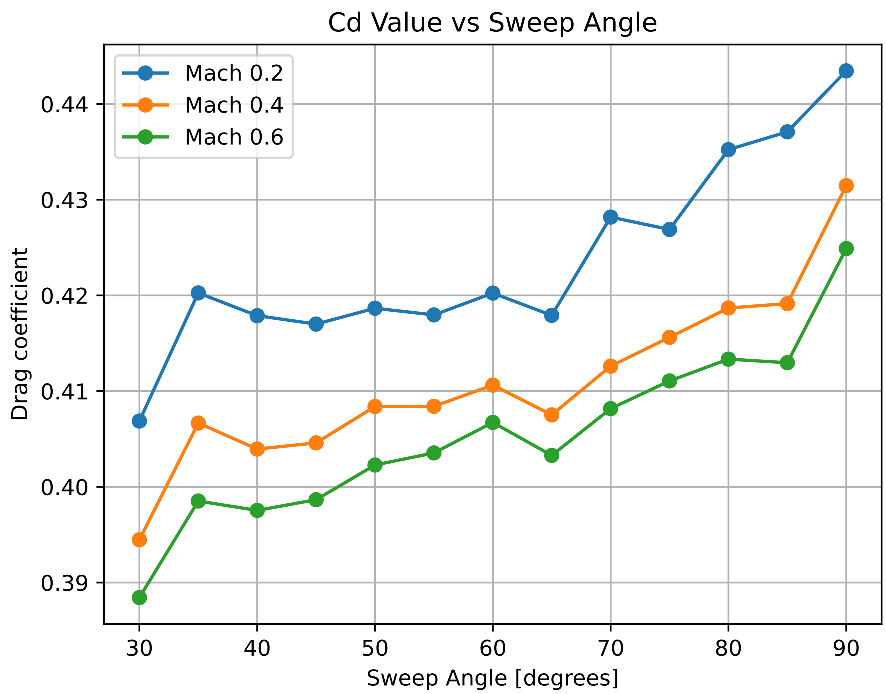

Figure 17: Drag coefficient vs Sweep Angle

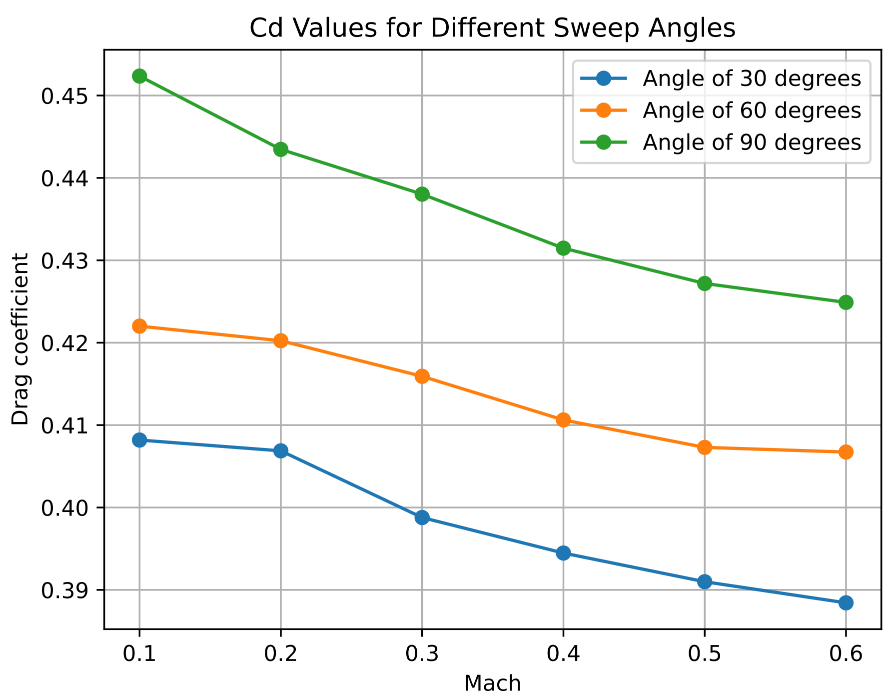

Figure 18: Similarity of curves of drag coefficient vs Mach for different sweep angles

6 Stability changes from OpenRocket

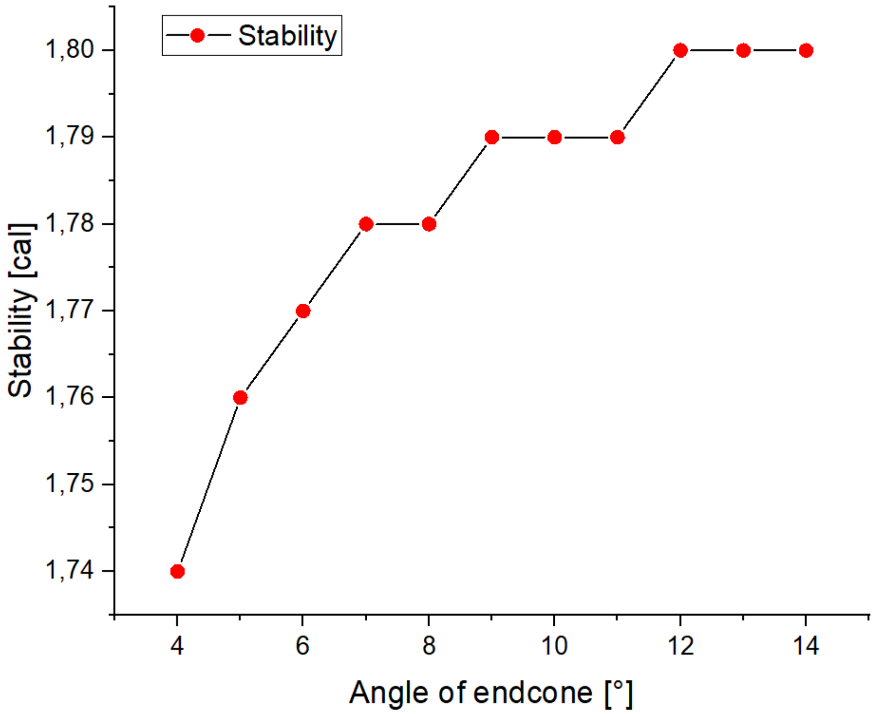

Figure 19: Stability graph vs Enconde Angle

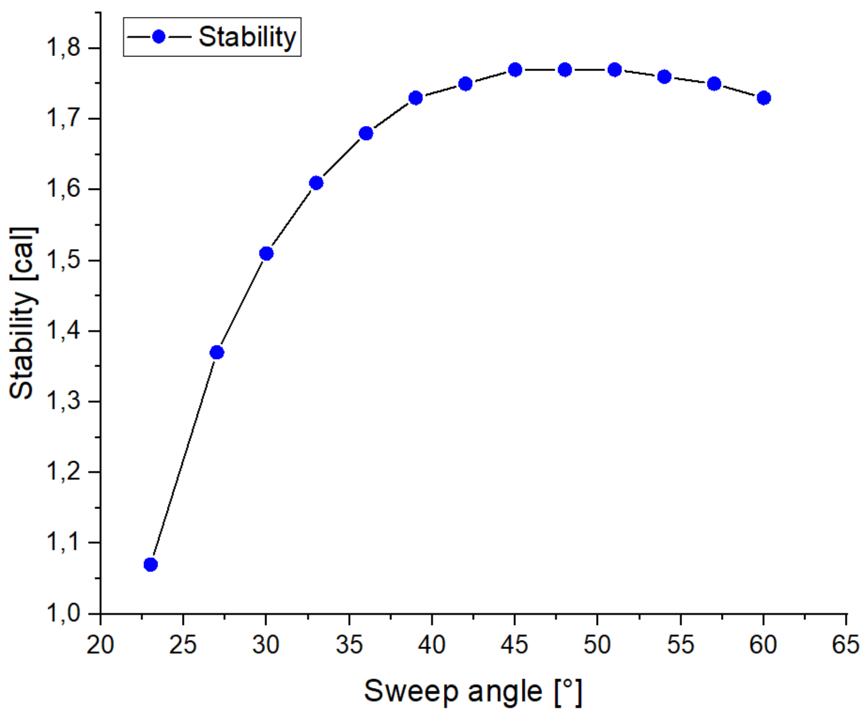

Figure 20: Stability graph vs Sweep Angle

7 Summary

In conclusion, it was found that the configuration with an endcone offers significantly better aerodynamic performance than the one without. Additionally, optimal sweep angle was found.

7.1 Results of the preliminary research

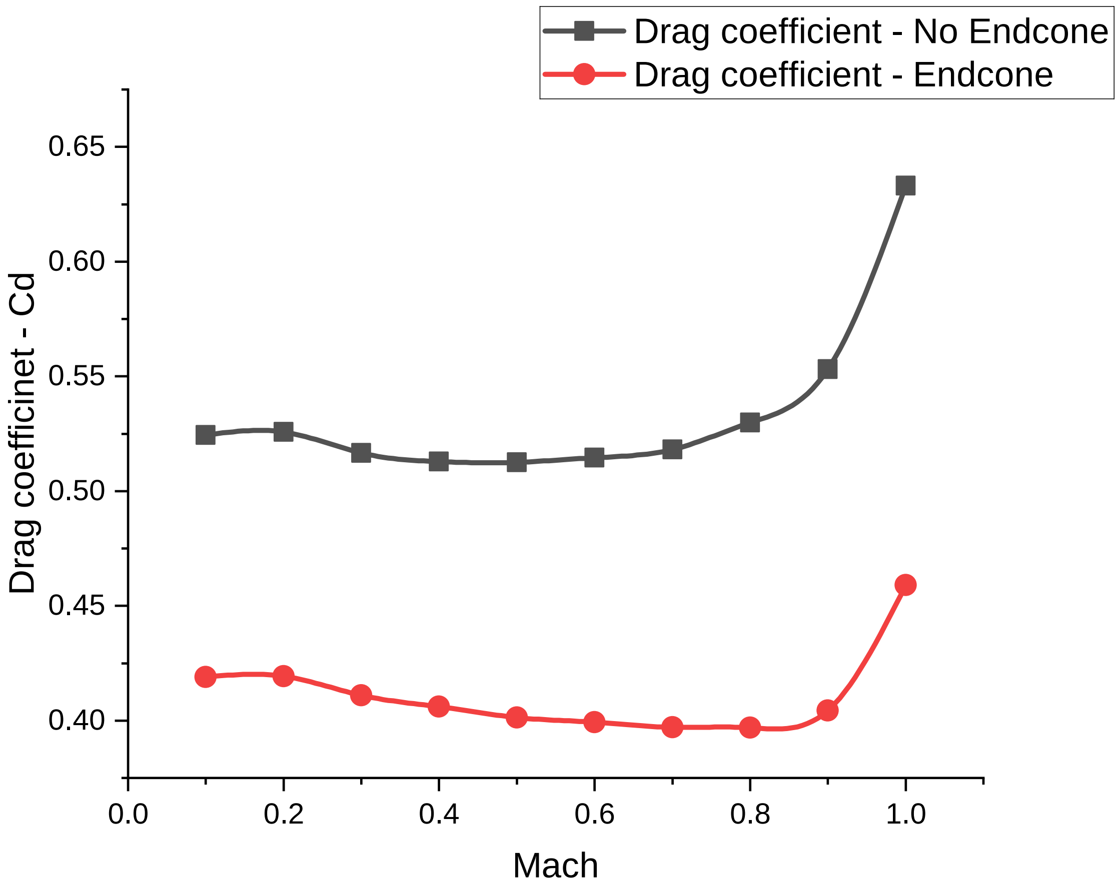

Figure 21: CD graph of R6-Endcone and R6-NoEndcone models

Preliminary research indicates that the endcone model exhibits significantly lower drag coefficient for 4.29 degrees endcone angle, while keeping similiar trends of change. Even more, for endcone model the trans sonic spike starts later compared to no endcone model. This would be very beneficial for the range of 0.6-0.9 Mach.

Table 1: Average values and differences

	R6 Endcone	R6 No Endcone	Difference	% Difference
0.1 - 1.0 Mach	0.411	0.534	0.123	29.8%
0.1 - 0.6 Mach	0.409	0.518	0.108	26.5%

For a range of 0.1 to 0.6 Mach, the endcone model exhibited a 26% lower drag coefficient in comparison to the no endcone model. This is a significant difference, indicating that the endcone model is much more aerodynamically efficient.

7.2 Results of Endcone Optimalization

The minimum of the average drag force function was found to be at 7 degrees. We can also observe a trend of the function, which is decreasing for the range of 3 to 7 degrees and increasing for the range of 9 to 15 degrees.

Spike at 6 degree is worth mentioning, it may be true value at this point or just a result of the simulation error. This would require further research to determine the validity of this spike, however it is not crucial for the optimalization of the rocket, since it is much higher than the minimum of the function and it's unlikely that noise of simulation was that high, especially that it can be seen at graphs of all example Cd vs Angle graphs for certain Mach number.

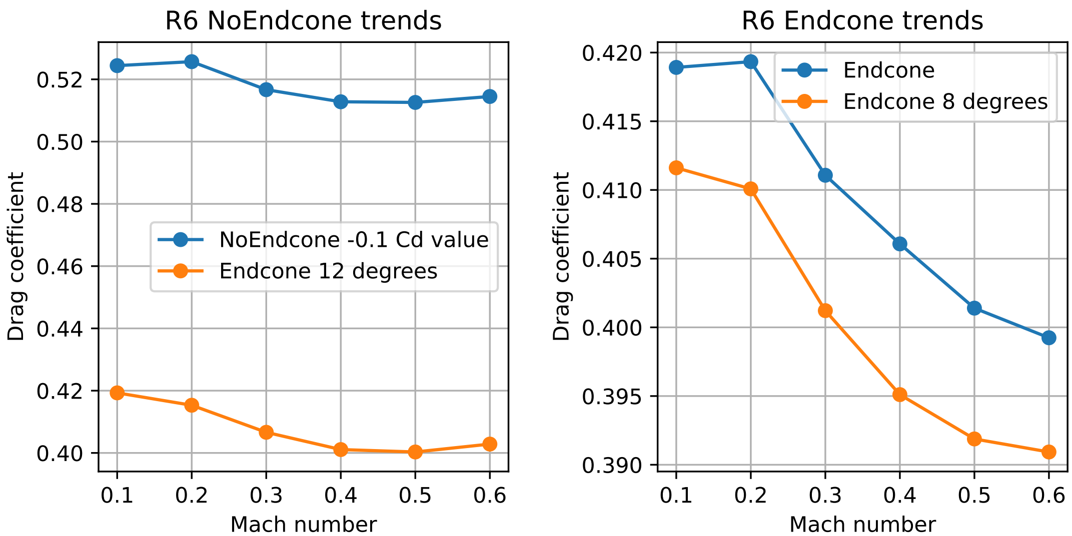

Figure 22: Comparison of Drag coefficient vs Mach graph trends for different endcone angles

Key observation is that the transonic spike starts later for the endcone model with optimal endcone angles, which is very beneficial for the range of 0.6 to 0.9 Mach. This is an important finding from the perspective of future rocket projects, where the rocket will be operating in this range of Mach. For such rockets, optimal endconoe angle could generate significant savings in energy.

This observation could be already noticed in the preliminary research, where the Endcone model exhibited decreasing trend of drag coefficient for the range of 0.6 to 0.8 Mach, while the NoEndcone model exhibited a significant increase trend from 0.5 Mach forwards.

7.3 Discussion of Fin Optimalization

As shown in the Figure 16, the minimum of the average drag force function is at 30 degrees. The function is increasing for whole tested range, with relatively small local extremums at 35 and 65 degrees. This means that the optimal sweep angle for the fins is 30 degrees. It could be also assumed that the trend will continue to decrease for the range of 30 to 0 degrees, however too small sweep angle would be impractical for the rocket, so it was not tested.

Figure 17 shows the same trend as the average drag force function, but also confirms the existence of characteristic local extremums at 35 and 65 degrees. This is a very important finding from the perspective of the optimalization of the rocket, since when desinginig the rocket, there was a prefered range of sweep angle. This study now clearly shows that when deling with the range of the sweep angle from 55 to 90 degrees, most aerodynamicly efficient point likely to be close to 65 degrees.