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The Effect of Different Designs of Fins and Nose Cones towards the Stability and Performance of a Sugar Rocket

Ahmad Hussein Abdul Hamid[1], Zuraidah Salleh[1*], Mohamad Amirul Muhammad[1,2], Khalkhalas Kamaludin[1], Mohammad Juani Sujana[2], Mohd Ismail Khamis[2]

[1] *School of Mechanical Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam 40450 Selangor, MALAYSIA.*

[2] *MTC Defence Sdn Bhd, High Energy Material Research Laboratory (HEMREL), Universiti Teknologi MARA, Shah Alam 40450 Selangor, MALAYSIA.*

**Corresponding Author (Tel: +6 0122617275, Email: szuraidah@ uitm.edu.my).*

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Abstract

Due to the high demand for model rocket competitions, interest in model rocket design has steadily increased. However, there is a small amount of research done so far on making the design process simpler and considering the physics behind the design process. Hence, this research proposes to determine how the combination design of fins and nose cones affects the stability and performance of a sugar rocket and to determine the most optimized design of nose cones and fins of a sugar rocket in terms of its stability and performance. In this study, each nine model rockets with different combinations of nose cones and fin design were tested. Open Rocket software is used to determine the stability of a rocket and simulate the flight of a model rocket. The designs of the model rockets are created using the design software Catia. Ansys software is used to run airflow analysis as it can determine the streamline of a rocket as well as consider the wind velocity of the model rocket. Results show that a model rocket with an ellipsoid nose cone and triangular fins is the most stable model rocket while a model rocket with a conical nose cone and triangular fins flies the highest.

Discipline: Aerospace Engineering, Aerodynamics, Computational Fluid Dynamics (CFD)

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1 Introduction

Rocket industries have been around for so many decades. The production of rockets has been used for various kinds of purposes from military purposes for weaponry to space exploration for astronauts. A rocket consists of four main parts which are the nose cone, fins, rocket body and engine. Each of these four main parts has its own roles and functionality that leads to the stability of a rocket. It is very important to produce a stable rocket so that rocket can fly in the desired direction and hence reduces the possibility of the rocket causing accidents during the flight.

In this study, the parts of a sugar rocket have been narrowed down to focus only on two main parts which is the nose cone and fins. The function of a nose cone in a rocket is usually to carry the payload or cargo during the flight. The common payload in a rocket is the astronauts for space exploration and explosives for weaponry. The function of fins is to keep the rocket fly straight into the air. Without the fins, the rocket may fly inconsistently in the air which makes it hard to adjust them to fly in the right direction. Although both nose cone and fins may have different main function, both shares the same purpose which is to maintain the stability of a rocket. There are plenty of designs and shapes for nose cones and fins for different sizes and shapes of a rocket. Each of its designs and shapes may lead to different stability of a rocket and hence affect the performance of a rocket.

Recently, due to model rocket competitions such as the Intercollegiate Rocket Engineering Competition (IREC) and the Teknofest Rocket Competition, interest in model rocket design has steadily increased (Pektas et al., 2019). There are so many alternatives to model rocket design, and each alternative provides competitors with another benefit. There is a small amount of research done so far to make the design process simpler and to consider the physics behind the design process. Therefore, conducting this study will help other students or other people who are interested in model design rockets to continue and use the results that will be completed to be further developed and designed to achieve better results in the future. A lot of studies have been done regarding the fins and nose cones of a rocket as both of these parts are essential in a rocket design model as they can maintain the stability of a rocket and hence increase the flight performance of a rocket. It seems that this study has a good potential to be used further for studies or in rocket industries. Therefore, the objectives of this study are to determine how the combination design of fins and nose cones affects the stability and performance of a sugar rocket as well as to determine the most optimized design of nose cones and fins of a sugar rocket in terms of its stability and performance.

2 Literature Review

This chapter reviews the previous research work on sugar propellants, sugar rockets, rocket stability, rocket fins, and other literature related to this research. Generally, a sugar rocket is a simple home craft that employs powdered sugar and potassium nitrate (KNO3) as fuel. While making a sugar rocket is simple, it is advised to proceed with caution because it is also extremely dangerous. Sugar propellants are used in this study due to their simplicity to use and to test the stability and performance of different designs of fins and nose cones of a model rocket.

2.1 Sugar Propellant

Sugar propellants are propellants of moderate performance in which one of the typical sugars such as sucrose, dextrose, maltose, and sorbitol is the binder fuel. Technically, because they have distinct fuel and oxidizer elements, sugar propellants are composite propellants (Leslie & Yawn, 2002). Sucrose and potassium nitrate are used as the basic propellant in the field of experimental rocketry where sucrose is a fuel and potassium nitrate acts as an oxidizer. Various experiments are conducted using this basic propellant and the results provide a desirable result of specific impulse (Palekar, 2015). In performance, sugar propellants are also intermediate. The average delivered specific impulse, which is not highly dependent on the fuel, is about 130 seconds. Specific black powder impulse is commonly stated as 80-90 seconds for comparison, whereas most ammonium perchlorate composite propellants (APCP) have 190-210 seconds of specific impulse (Singh, 2013). Figure 2 shows the example of a sugar rocket with potassium nitrate and sorbitol.

2.2 Rocket Stability

The aim of fins on rockets is to increase stability by moving the pressure center (Cp) behind the gravity center (Cg). Cg is a geometric property known as a single point which is the mean position of the object's weight (Hall, 2015a). The Cg is the point at which the gravity force acts and the point around which free-floating objects rotate. The Cp is a single point at which aerodynamic forces act through, caused by pressure variations across the surface of the rocket (Hall, 2015b). Since it generates a restorative force that provides equilibrium, the Cp needs to be behind the Cg (Benson, 2014). There are no external forces on a rocket in an ideal state and all forces work through the Cg as the rocket moves linearly along the thrust line (Nakka, 2001). External forces such as wind are almost always present in actual use. External forces trigger a change in the pressure forces working through the Cp around that rocket (Nakka, 2001). This creates a moment around the Cg and slightly rotates the rocket, or changes its attack angle, and a lift force is generated (Nakka, 2001).

3 Method

In this study, there are 3 different designs of fins and 3 different designs of nose cones. The 3 designs of fins that are used are clipped delta fins, swept fins and triangular fins (Table 1) while the 3 designs of nose cones are ogive nose cone, elliptical nose cone and conical nose cone (Table 2). These designs of fins and nose cones are being picked because these designs are frequently used in rocket modelling. These 3 designs of nose cones and fins are combined to form a model rocket. Therefore, there are a total of 9 model rockets that are tested to determine their stability and performance.

Table 1: Shape of rocket fins.

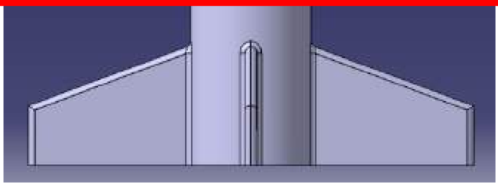
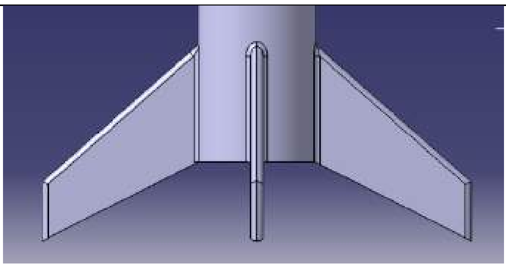
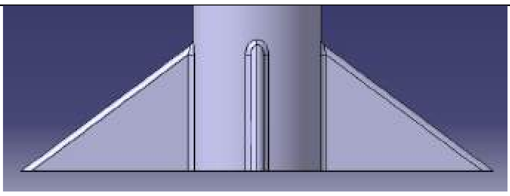
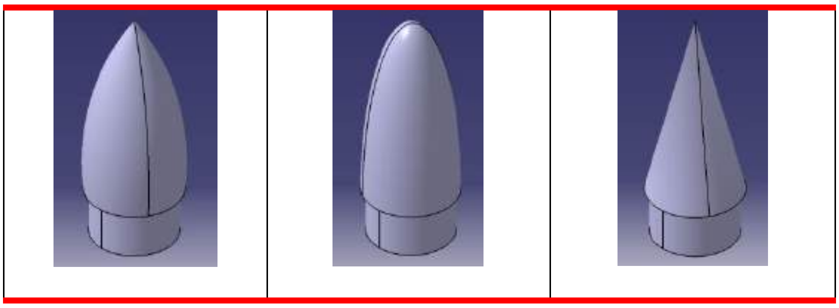
Name	Rocket Fin Shapes
Clipped Delta Fins	
Swept Fins	
Triangular Fins	

Table 2: Nose cone shapes.

Ogive Nose Cone	Elliptical Nose Cone	Conical Nose Cone



3.1 Rocket Engine Selection

The rocket engine that is used for flight rocket simulation in this study is a standard 18 mm diameter with a 70 mm long Estes C5-3 Engine as shown in Table 3. At the moment of ignition, the Estes C5 motor has a large thrust spike (Inc., n.d.). It means that the rocket gets a bigger kick at lift-off which translates to greater speeds and higher acceleration. The Estes C5 motor is made of 'black powder propellant' which consists of charcoal, potassium nitrate and sulphur. It has low to moderate thrust levels in general, so the rockets that use them take off slower than other types of rocket propellants.

Table 3: C5-3 Rocket engine specifications.

 Estes C5-3 Engine.	Length: 70 mm Diameter: 18 mm Estimated Weight: 23.6 g Total Impulse: 10 Ns Max Thrust: 20.4 N Initial Weight: 23.6 g Propellant Weight: 11 g

3.2 Model Rocket Specifications and Dimensions

Figure 1 and 2 shows the model rocket specifications and dimensions kept constant for all the model rockets that are conducted in this study. The material used for all parts of the rocket is polylactic acid (PLA) which is commonly used for 3D printing. The dimensions given below as well as the number of fins which is 4 are kept constant for all model rockets. The shapes of the nose cone and fins are the only manipulated variables to determine the stability and performance of the model sugar rocket. All model rockets have added the same weight of payload and parachute.

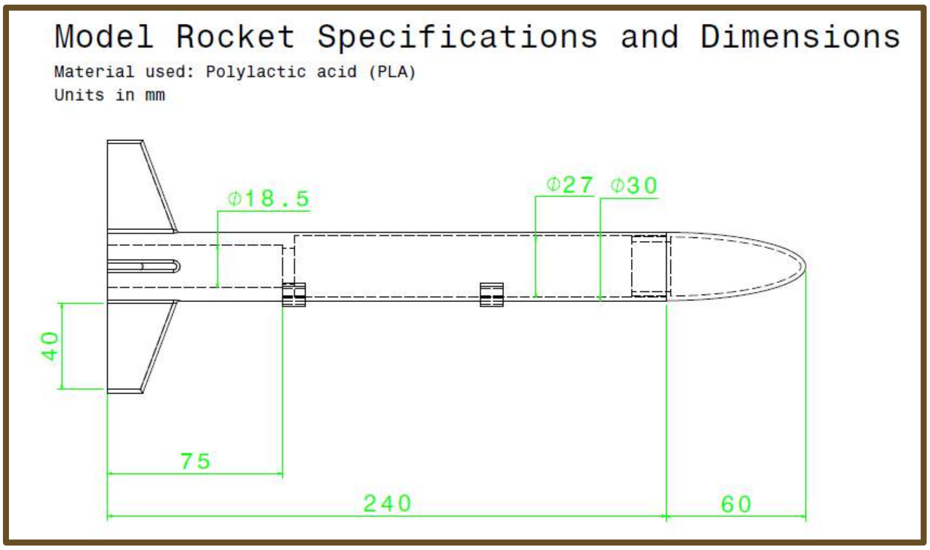


Figure 1: Model rocket specifications and dimensions.

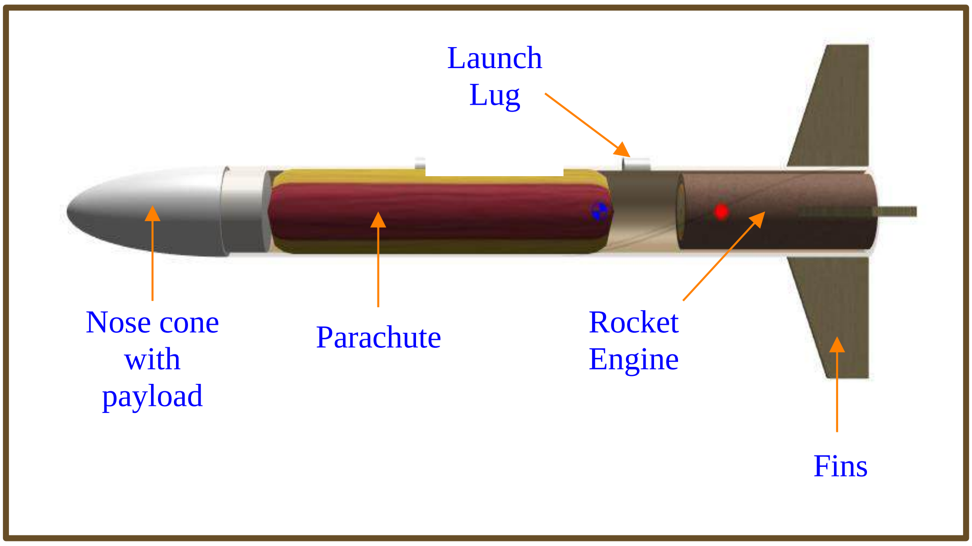


Figure 2: Model rocket composition.

3.3 Open Rocket Software

Open Rocket software is used to design the desired model rockets and simulate them and the details are shown in Figure 3. This model of rockets using this software can be designed by inputting the desired dimensions of a rocket, the density of the materials as well as the type of materials built for the rocket that can be chosen from a massive catalogue of existing components and materials. This software also managed to calculate the model rocket stability and simulated them after inserting the desired rocket motors onto the design.

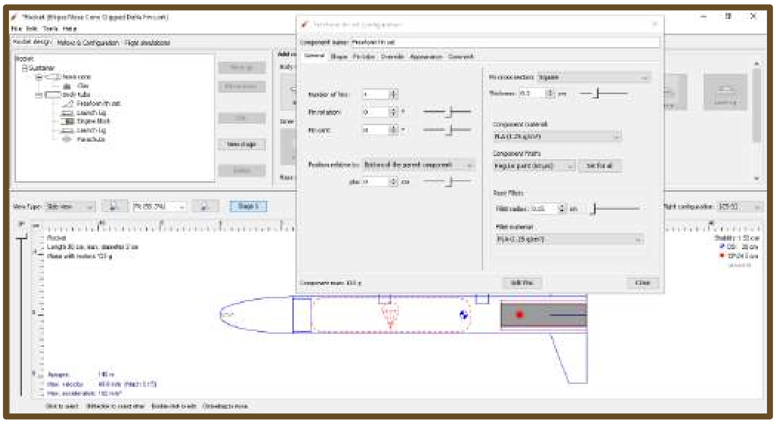


Figure 3: Open rocket software.

3.4 Catia Software

Catia software is used after identifying the dimensions required using the Open Rocket software (Figure 4). This software is used to draw the model rockets in 3D models, so it can be inserted for the Ansys software later for further analysis.

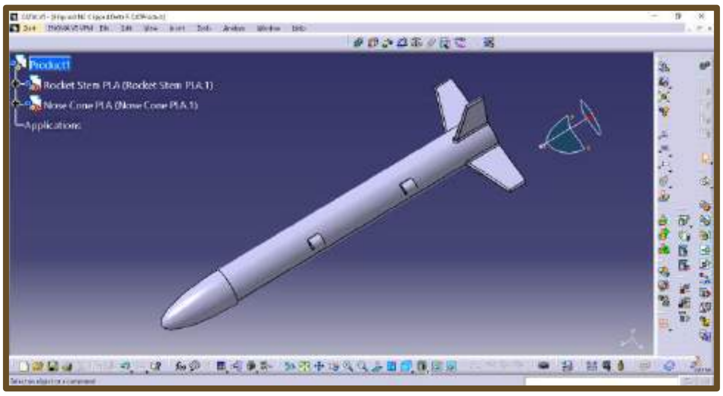


Figure 4: Catia software.

3.5 Ansys Software

The aerodynamic analysis is performed for all 9 model rockets by using Ansys software which is Ansys FLUENT as illustrated in Figure 5. For industrial applications, Ansys FLUENT software provides the vast physical modelling capabilities required to model flow, turbulence, heat transport, and reactions (Ozen Engineering Inc, n.d.). Some modifications and assumptions are made in this software such as the airflow towards the model rockets is in laminar flow, polylactic acid (PLA) is used as the material for the model rocket with the density of 1250 kg/m3 and the magnitude velocity for the airflow is assumed to be the same value as the maximum velocity obtained for the model rockets through simulation that has been done in Open Rocket software.

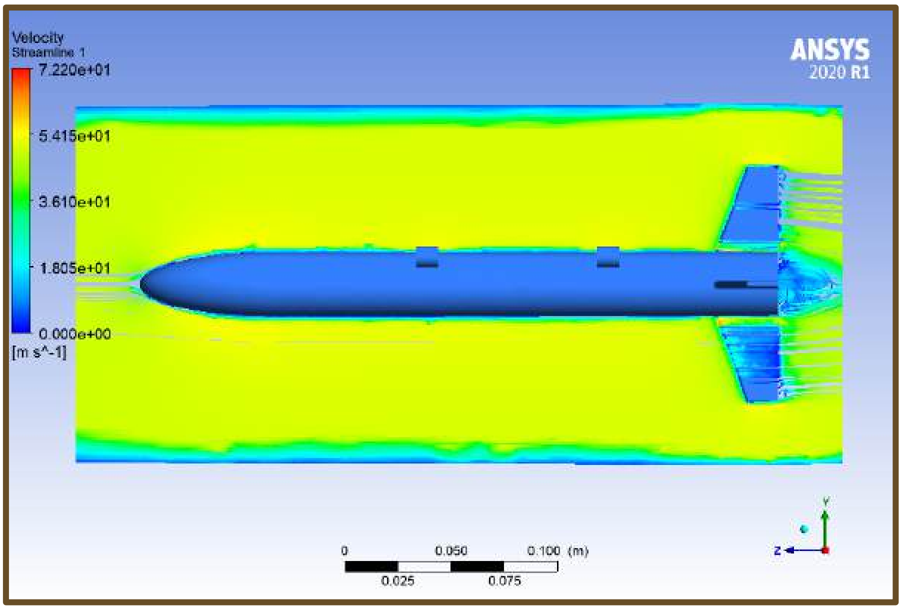


Figure 5: Airflow analysis on the model rockets.

4 Result and Discussion

4.1 Model Rocket Stability and Performance

Table 4 shows the model rocket stability and performance with different combination designs of fins and nose cones of the model rockets.

Table 4: Model rocket stability and performance.

Model Rocket Design	Stability (cal)	Apogee (m)	Maximum velocity (m/s)	Maximum acceleration (m/s^2)	Time to Apogee (s)	Flight Time (s)
Elliptical Nose Cone Clipped	1.52	139	49.8	165	5.26	30.2

Delta Fin						
Elliptical Nose Cone Swept Fin	1.64	147	50.9	165	5.35	32.0
Elliptical Nose Cone Triangular Fin	1.39	151	52.8	172	5.32	33.2
Conical Nose Cone Clipped Delta Fin	1.42	143	51.0	171	5.26	31.5
Conical Nose Cone Swept Fin	1.55	150	52.5	171	5.33	32.7
Conical Nose Cone Triangular Fin	1.31	155	54.3	178	5.31	34.1
Ogive Nose Cone Clipped Delta Fin	1.48	141	50.4	168	5.26	30.9
Ogive Nose Cone Swept Fin	1.60	149	51.8	168	5.33	32.1
Ogive Nose Cone Triangular Fin	1.35	153	53.5	175	5.33	33.7

Based on table 4, shows that different designs of fins and nose cones of model rockets do affect the stability and performance of the model sugar rocket. Higher rocket stability means that the tendency of a rocket to change its attitude during the flight is lowered (Benson, 2014). Therefore, it is important to obtain the optimum value of stability which is in the range of 1 to 2 caliber. The stability of model rocket with swept fins has the highest stability value compared to other model rocket fins. This is because the swept fins angle backward while clipped delta fins and triangular fins do not angle backward. Therefore, this makes the center of gravity and center of pressure of the swept fins model rockets to be far apart from each other which makes the model rocket with swept fins has a higher stability value compared to others. The distance between rockets CG and CP is used to determine a rocket's stability (Aeronauticsastronautics, 2018). The CP should be at least one body diameter behind the CG, according to empirical evidence and mathematical models (Stine, G Harry and Stine, 2004). Meanwhile, model rockets with triangular fins do have the worst stability value compared to others. The model rocket of triangular fins has lower stability than the model rocket of clipped delta fins because the area of the clipped delta fins is higher than triangular fins. The higher area of the fins makes the center of pressure of the model rockets move downwards towards the fins which makes the position of the center of pressure to be far apart from the center of gravity that makes the model rocket more stable (Huang et al., 2016).

In terms of the model rocket nose cone, it shows that the elliptical nose cone has the highest stability value compared to others' nose cones. The reason is that the area of the elliptical nose cone is higher than others' nose cones which makes the center of gravity far from the center of pressure which leads to higher stability.

On the other hand, the triangular fins model rocket has the highest apogee, maximum velocity, maximum acceleration, time to apogee and flight time compared to other fins despite having the lowest stability. This is due to the fact that the fin is longer near the body tube, it orients more of the lift force closer to the body tube of the rocket. Because the fin is shorter at the tip of the fin, there is less lift force created near the tip of the fin which makes the pressure difference a lot lower near the tip (Milligan, 2017). As a result, less air passes through the tip. Hence, the resultant drag force is reduced. Lower drag means the rocket's speed is not hindered as much, allowing it to soar higher into the sky.

The nose cone design does not contribute a lot to the performance of the model rocket but there is a slight difference between them. The conical nose cone has slightly the upper edge in terms of its apogee, maximum velocity, maximum acceleration, time to apogee and flight time compared to other nose cones. The conical nose cone has more optimal streamlined shapes and contains higher surface smoothness at the tip of the nose cone compared to others which make the airflow easier to pass the model rocket with a conical nose cone (Rajan Iyer & Pant, 2020). Therefore, the model rockets with conical nose cones tend to fly higher compared to others' nose cones. Based on Figure 6, really shows that a model rocket with a different combination design of fins and nose cone does slightly affect the performance of a model rocket. The graph shows that all model rockets have the same flight pattern but produce different maximum altitudes with different flight times. For the first 5 to 6 seconds, all the model rockets rose quickly from 0 meters of altitude to the maximum altitude due to the ignition of the rocket engine inserted inside the model rocket. Rocket engines are able to produce thrust by discharging a high-temperature gas through a nozzle (Emrich, 2016). The force that propels the rocket through the air and towards space is called thrust. The thrust generated by a model rocket is the result of a reaction from a high-speed model rocket's momentum directed in the opposite direction as the model rocket's acceleration (Bragg, 1962). Through the application of Newton's third law of motion, thrust is generated by the rocket's propulsion system (Emrich, 2016). After the model rocket reaches maximum altitude, it descends slowly afterward due to the applied parachute inside the model rocket. The parachute is utilized to slow down the downward fall of a model rocket falling through the sky to prevent any accidents of the people or buildings from the falling model rocket by creating drag (Al-Ebiary et al., 2017). The model rocket with a conical nose cone and triangular fins reaches the highest altitude while the model rocket with an elliptical nose cone and clipped delta fins obtains the lowest altitude among the other model rockets.

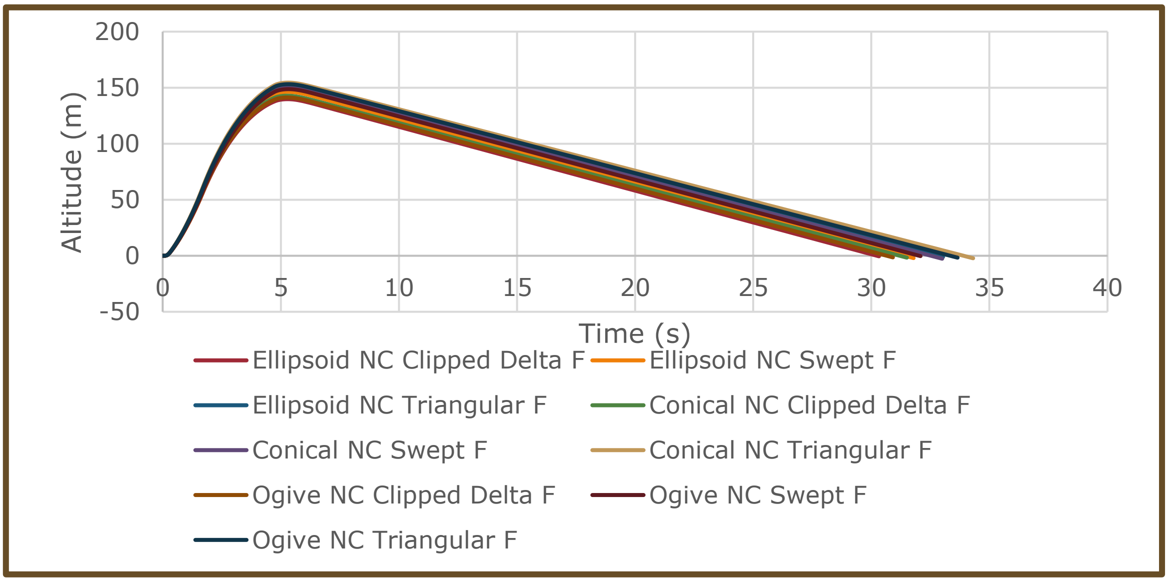


Figure 6: Graph of altitude against time for a model rocket with different combination designs of nose cone and fins.

4.2 Model Rocket Airflow Analysis

Figure 7 to Figure 16 shows the model rocket airflow analysis with different combination designs of fins and nose cones of the model rockets.

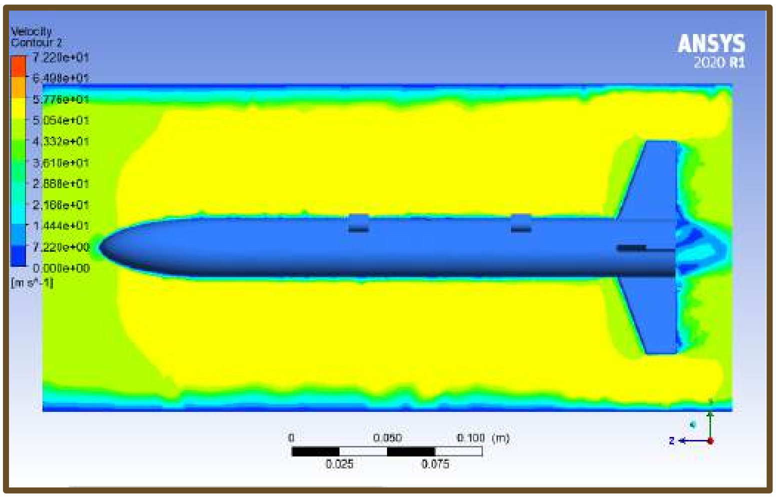


Figure 7: Elliptical nose cone clipped delta fin airflow analysis.

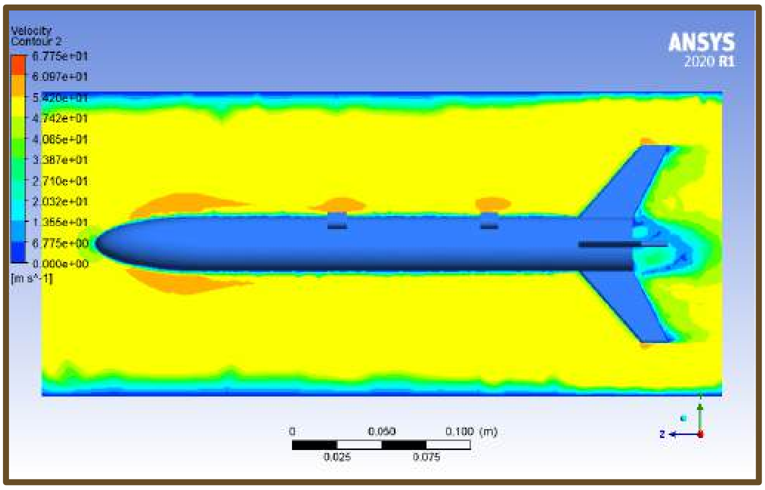


Figure 8: Elliptical nose cone swept fin airflow analysis.

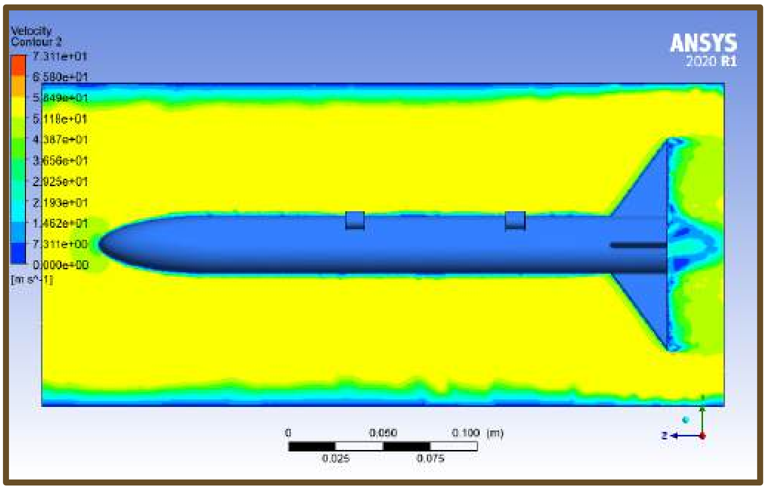


Figure 9: Elliptical nose cone triangular fin airflow analysis.

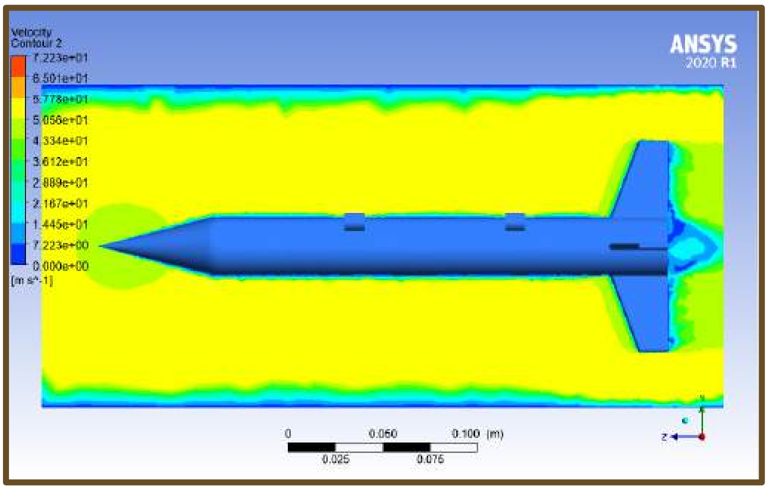


Figure 10: Conical nose cone clipped delta fin airflow analysis.

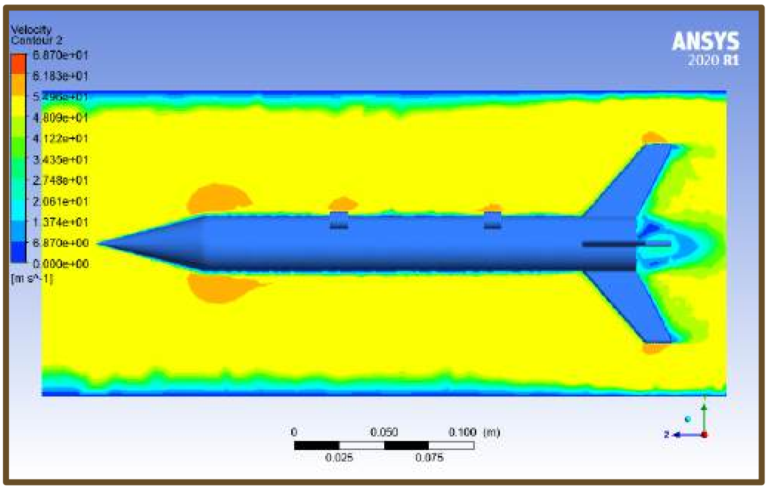


Figure 11: Conical nose cone swept fin airflow analysis.

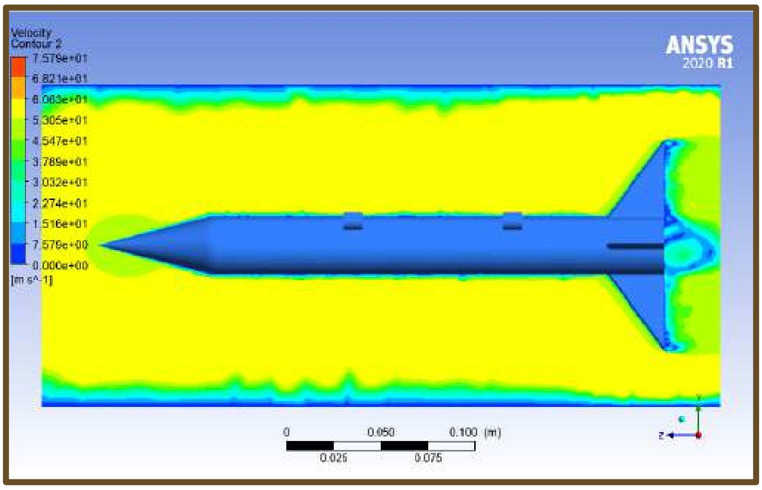


Figure 12: Conical nose cone triangular fin airflow analysis.

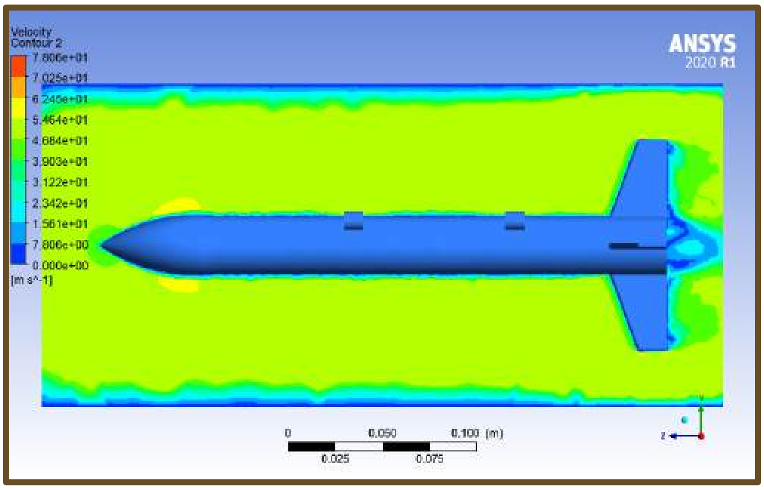


Figure 13: Ogive nose cone clipped delta fin airflow analysis.

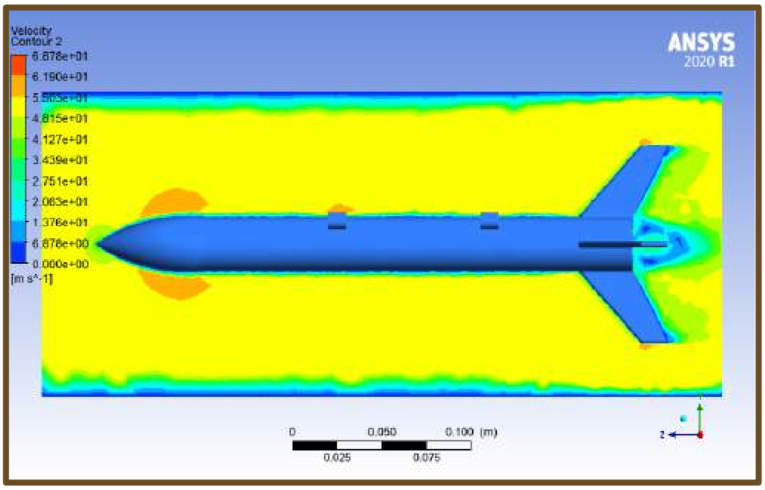


Figure 14: Ogive nose cone swept fin airflow analysis.

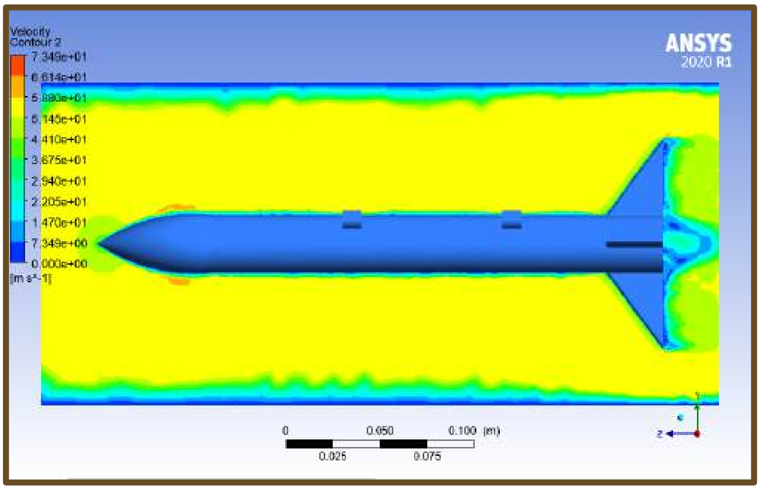


Figure 15: Ogive nose cone triangular fin airflow analysis.

Figure 7 to Figure 15 shows the model rocket airflow analysis for different combination designs of nose cones and fins. Based on all airflow analysis, it clearly shows that each model rocket design has its own pattern of airflow and each of them is different from the other. For all the model rockets with elliptical nose cones, it seems the airflow through the elliptical nose cone has the lowest velocity at the tip of the nose cone compared to other nose cones. It means that the airflow nearly stops at the tip of the elliptical nose cone due to the higher surface area of the tip of the elliptical nose cone. A higher surface area at the tip of the nose cone indicates higher pressure which leads to lower airflow velocity toward the tip of the nose cone.

Based on Figure 7 to Figure 15, it undoubtedly indicates that the model rocket with an ogive nose cone contributes to higher velocity airflow at the tip of the nose cone compared to a conical nose cone due to the higher surface area at the tip of the ogive nose cone. Therefore, the airflow through the conical nose cone model rockets experiences the smoothest airflow compared to the elliptical nose cone and ogive nose cone. It also signifies that the performance of the model rocket with conical nose cones will fly the fastest and longest in the sky compared to others.

On the other hand, all model rockets with clipped delta fin undergo the lowest velocity at the leading edge of the fins compared to other fins. This is because the span at the leading edge of the clipped delta fins is almost perpendicular to the airflow angle of attack. The more perpendicular the span of the fins to the airflow angle of attack, the higher the tendency of a model rocket to produce form drag, which is the amount of parasite drag caused by the aircraft as a result of its shape and surrounding airflow (Federal Aviation Administration, 2016).

Next, both model rockets with swept fins and triangular fins do have the same span angle toward the airflow angle of attack. However, the model rocket with triangular fins has the highest velocity airflow towards the leading edge of the fins compared to the other fins. The length of the span of the triangular fins is smaller compared to the swept fins. A higher length of span leads to lower performance of the model rocket due to the higher tendency of the model rocket to produce form drag. Therefore, the model rockets with conical nose cones and triangular fins have the highest performance rating in terms of the model rocket speed and time in the sky compared to others.

5 Conclusion

In conclusion, the study carried out can be considered a successful study because this study manages to fulfil all the objectives of this study which are to determine how the combinations design of fins and nose cones affects the stability and performance of a sugar rocket and to determine the most optimized design of nose cones and fins of a sugar rocket in terms of its stability and performance. Due to the same and reliable Estes C5-3 rocket engine, all of the nine model rockets manage to fly properly towards the sky. The different designs of nose cones and fins on the model rocket cause only a slight difference in the stability and performance of model sugar rockets. All of the model rockets are stable since the range of the stability of a rocket is between 1 to 2 caliber which all of the model rockets that have been tested are able to be achieved. However, the most stable model rocket is the model rocket with an elliptical nose cone and swept fins. Since all the model rockets have only slightly different in terms of their stability, the same concept goes for the performance of the model rockets. All the model rockets have only a slight difference in terms of their performance. Therefore, the model rocket with a conical nose cone and triangular fins is considered to have the greatest performance as it obtained the highest apogee and the longest flight time in the sky.

6 Availability of Data and Material

Data can be made available by contacting the corresponding author.

7 Acknowledgement

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Ts. Dr. Ahmad Hussein Abd Hamid is an academic staff in the School of Mechanical Engineering, Universiti Teknologi MARA, Malaysia. He received his M.Sc. degree in 2008 from the same university. In 2016, he obtained his PhD in Mechanical Engineering from Monash University, Melbourne, focusing on Magnetohydrodynamics and Heat Transfer. His research interests include the Wake Flow of a Bluff Body, Magnetohydrodynamic Flow, Heat transfer, liquid atomization and renewable energy.

Prof. Madya Ts. Dr. Zuraidah Salleh is an Associate Professor at the School of Mechanical Engineering, Universiti Teknologi MARA, Malaysia. She received her Bachelor's degree in Mechanical Engineering from Universiti Teknologi MARA and her MSc. from Universiti Sains Malaysia (USM). Her research interests include Composites, Coatings, Welding and Rocketry. Currently, she is Head of the Industrial Research Laboratory (UiTM-MTC HEMREL), UiTM Shah Alam.

Mohamad Amirul Muhammad is an engineer at MTC Defence Sdn. Bhd, Malaysia. He received his Bachelor's degree in engineering (Mechanical-Aeronautics) from Universiti Teknologi Malaysia and currently doing a Master of Science at Universiti Teknologi MARA. His work is related to the research and development of solid rocket propellants. He is also working on CAD, strength analysis, fabrication, testing, data acquisition, extraction of data and presentation of data as well as manufacturing process.

Khalkhalas Kamaludin is a student at School of Mechanical Engineering, Universiti Teknologi MARA, Malaysia. He achieved his Bachelor's degree in Mechanical Engineering from Universiti Teknologi MARA, Malaysia. His research interests include Computational Fluid Dynamics, Aerodynamics and Rocketry.

Lt Col Ir. Mohammad Juani bin Sujana RMAF (R) is a retired Royal Malaysian Air Force Professional Military Aircraft Engineer and Advanced Weapon System Engineer, with a background in Electrical Engineering and graduated from Universiti Teknologi Malaysia. He is certified as a Professional Engineer by the Board of Engineers Malaysia. Currently doing research at Islamic International University Malaysia. His research interest includes Energetic Additive and Rocketry.

Mohd Ismail bin Khamis is a Senior Technician at MTC Engineering. Received Certificate from Hindustan Aeronautics Limited Nashik India in Airframe discipline in 2007. He has served 21 years in Royal Malaysian Air Force as an Aircraft Technician that contribute to many disciplines such as Aircraft structure, Hydraulic System, Aircond System and Engineering Management. Currently he is part of Research Team in High Energy Material Research Lab conducting development of Solid Propellant Technology and Hybrid Propellant Technology.