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Thermal Analysis on Solid Rocket Motor Casing

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Abstract

A cloud seeding rocket comprises several parts such as the nozzle, propellant, and casing. The CRV7 C-15 rocket motor is the benchmark for current cloud-seeding rockets. A solid rocket motor casing is a hollow cylinder that acts as a combustion chamber for the propellant. This results in thermal and structural loads to the inner wall of the casing. The method to conduct the study was first verified against a Molybdenum casing with a thickness of 5mm and propellant N_2H_4 and N_2O_4. Simulation of static stress analysis and steady thermal analysis enables the simulation of overall stress analysis in ANSYS. Solutions were obtained using a steady solver due to the nature of the problem. Constant heat flux and constant pressure load were imposed to the inner wall of the casing for the thermal and structural analyses, respectively. This is to check that the rocket motor casing can withstand the combustion of the propellant. The system requires the safety factor of the rocket motor casing to be at least 1.5 when manipulating the thickness casing of 2.5, 3.5, and 5.0 mm which are CC 2.5, CC 3.5, and CC 5.0. The propellant for this study was solid AP/AL/HTPB propellant. After analysing the overall stress of the three models, the safety factor was calculated. CC 3.5 was undesirable as it had a safety factor of less than 1.5. CC 2.5 had a higher safety factor but was lower than CC 5.0. CC 2.5 was the most suitable casing as it had the smallest thickness, least in weight, and was less costly to fabricate compared to CC 5.0. This study serves as a guideline to indicate the safety factor of any chosen material with any propellant.

Disciplinary: Thermal Analysis, Modelling and Simulation, Rocket Analysis.

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1 Introduction

With climate change occurring all around the world, Malaysia is also affected. Severe floods and prolonged droughts are anticipated to occur as Malaysia will experience extreme and dry seasons [1]. Malaysia has experienced the El-Nino phenomenon over 12 times since 1951 with catastrophic incidents. Therefore, cloud seeding is a great alternative to effectively handle the dry seasons which is the process of modifying clouds to produce rainfall. Flying small aircraft to cloud seed is costly and dangerous to pilots [2]. Cloud seeding rocket is a better alternative. The CRV7 rocket motor is a small-sized rocket that is the benchmark for current cloud-seeding rockets.

Collaboration between UiTM and MTC Engineering was motivated by the construction of a cloud seeding rocket to counter the aforementioned problem. However, many obstacles occurred when utilizing small-sized rockets from other countries such as lack of full control over the design of the rocket. In response to this problem, making cloud seeding rockets from scratch would be ideal as full control over the specifications desired on the rocket may be obtained. There are many parts to a cloud seeding rocket but the main focus will be on the motor casing.

Combustion takes place in the motor case known as the combustion chamber which is usually made of metal or composite materials [3]. A thick-walled cylinder analysis is used as the dimensions conform to the specifications of this analysis. Thermal analysis is concerned with the properties of materials that are studied as they change with temperature [4]. The thermo-structural analysis is concerned with the thermal and structural stress that occurs on the casing which is an imperative study as this computes the total stress acting on the casing upon combustion. The safety factor of the casing can then be computed to know if the casing can withstand the effects of combustion.

Therefore, the objective of this study is to understand the concept of a solid rocket motor case. Thus, analysing the structural and thermal effects of combustion in the case with varying thickness is necessary. Lastly, a suitable thickness must be determined based on the safety factor obtained upon combustion.

2 Methodology

Based on a study made on Molybdenum rocket motor casing of thickness 5mm with propellant N_2H_4 and N_2O_4, the heat exchange coefficient differs from AP/AL/HTPB at 416.89W/m2K. Evaluation of static stress analysis, thermal analysis, and overall stress analysis was first conducted via an analytical approach. The simulation was then conducted for three models with varying thicknesses of 2.5mm, 3.5mm, and 5.0mm which were labelled as CC 2.5, CC 3.5, and CC 5.0 where CC stands for Combustion Chamber. The best combustion chamber or rocket motor casing is then selected.

2.1 Material Properties

Initially, the properties of Molybdenum are recorded into the Engineering Data of ANSYS Workbench based on Table 1.

Table 1: The list of Molybdenum Properties in ANSYS

Material	Molybdenum
Density (g/cm^3)	10.24
Thermal Conductivity, k (W/m.K)	142
Yield Strength (MPa)	110
Coefficient of Thermal Expansion (1/K)	5.2^10^{-6} at 293.15K
Young's Modulus (MPa)	3.2´10^5
Specific Heat (J/kg.K)	251
Poisson's Ratio	0.32
Emissivity	0.64 on outer wall & 0.038 on inner wall

Notes: Taken from MZJ Team Resources

2.2 Propellant Parameters

The heat exchange coefficient for propellant was calculated as shown below in Equation (1) whereas the Chamber Temperature was obtained from PROPEP software for AP/AL/HTPB solid propellant.

$$h = 3.075\,\frac{\left(1.203\frac{J}{gK}\right)\left(64.283\ kg/m^2s\right)^{0.8}}{0.045\ m^2}\left[1+\left(\frac{0.045\ m}{0.1\ m}\right)^{0.7}\right] = 302.17\ W/m^2K \qquad (1)$$

where h is the convective heat transfer coefficient. The properties of AP/AL/HTPB are shown in Table 2.

Table 2: Propellant Properties of AP/AL/HTPB

Type of Propellant	Solid
Composition	68 : 17 : 15
Inner Pressure	6.895MPa
Mass of AP/AL/HTPB/IPDI (g)	204 : 45 : 51 : 6.63
Convective heat coefficient	302.17 W/m^{2}K
Chamber Temperature	2854.64K
Characteristic Velocity (c*)	1548.08 m/s
Average molar mass	25.14 g/mol
Average C_p	1.203 kJ/kg.K
Mass flow rate	0.10221 kg/s
Specific Impulse	192.643 s
Burn time	3s

2.3 Combustion Chamber

The combustion chamber acts as a housing for the igniter, propellant, copper wire, and nozzle. Assumptions of thick-walled cylinders include that the cylinder is made up of isotropic and homogeneous material, longitudinal stresses are uniform across the thickness of the wall and the cylinder experiences uniform internal pressure.

The combustion chamber was designed in the Design Modeler with a thickness of 5mm and length of 100mm which was converted into ANSYS mechanical with 2D AxiSymmetric of 10° angle to show half view of a hollow cylinder. Element size of 1mm was chosen for meshing.

Static structural analysis was conducted with one end clamped and a pressure load of 6.895MPa on the inner wall of the casing. This is to obtain radial, hoop, and Von Mises Stress. Then, steady thermal analysis has boundary conditions of radiation and convection as in Table 1 and Table 2. This analysis is to compute the temperature distribution and heat flux. Thermo-structural analysis was then performed with applied thermal and structural load from the previous two analyses. This helps to compute the overall hoop, radial, and Von Mises stress to obtain the safety factor of the rocket motor casing.

3 Results and Discussion

Based on a study made on Molybdenum rocket motor casing of thickness 5mm with propellant N2H4 and N2O4, the heat exchange coefficient differed from AP/AL/HTPB at 416.89W/m2K. The following shows the evaluation of static stress analysis, thermal analysis and overall stress analysis. Table 3 shows a minor error of less than 0.28% for maximum radial, hoop and Von Mises stress calculated from Equations (2), (3), and (4).

Table 3: FEA and Analytical Results of Maximum Stress

Type of stress	FEA(MPa)	Analytical (MPa)	Error (%)
Maximum Radial Stress	-0.6481	-0.6500	0.28
Maximum Hoop Stress	3.2807	3.2825	0.05
Maximum Von Mises Stress	3.6482	3.6512	0.08

$$= -P_i \quad (2),$$

$$\sigma_{h,max} = P_i\left(\frac{{r_o}^2+{r_i}^2}{{r_o}^2-{r_i}^2}\right) \quad (3),$$

$$\sigma_{v,max} = \sqrt{\frac{(\sigma_{h,max}-\sigma_{r,max})^2+{\sigma_{r,max}}^2+{\sigma_{h,max}}^2}{2}} \quad (4),$$

$$T(r) = T_i + \frac{\dot{q}{r_o}^2}{4k}\left[2\ln\frac{r}{r_i} + \left(\frac{r_i}{r_o}\right)^2 - \left(\frac{r}{r_o}\right)^2\right] \quad (5).$$

where $\sigma_{r,max}$ is maximum radial stress, $\sigma_{h,max}$ is maximum hoop stress, $\sigma_{v,max}$ is maximum Von Mises stress, r_0 and r_i are the outer and inner radius, respectively, P_i is chamber pressure, T_i is chamber temperature and k is the thermal conductivity.

Temperature distribution towards the outer wall of the cylinder decreased in both FEA and analytical calculations from Equation (5). The analytical method was used in which the assumption of inner temperature was similar to simulation. The simulation showed a steady decrease in temperature whereas analytical results showed a slight curve. This is probably due to analytical calculations using a constant value of internal heat generation whereas the simulation shows the total effects of heat transfer.

Table 4 shows a small percentage error of 3.393% which meant that the simulation and analytical methods were acceptable. FEA utilized exact heat absorption for each thickness as the value of heat flow decreased with thickness. The analytical method used the value of overall heat flow for each thickness of the chamber. The maximum heat flux was calculated from Equation (6).

Table 4: FEA vs Analytical Maximum Heat Flux

FEA Heat Flux (W/mm^2)	Analytical Heat Flux (W/mm^2)	Percentage Error (%)
0.4491	0.4648	3.393

$$Q" = \frac{Q}{A} = \frac{\dot{q}(r_o{}^2 - r_i{}^2)L}{2(r_o + r_i)(L + r_o - r_i)} \quad (6),$$

$$\sigma_{rt} = \frac{\alpha E(T_i - T_e)}{2(1-v)(ln\, {}^{r_o}/_{r_i})}\left[- ln\frac{r_o}{r} + \frac{r_i^2}{r_o^2 - r_i^2}\left(\frac{r_o^2}{r^2} - 1\right) ln\frac{r_o}{r_i}\right] \quad (7),$$

$$\sigma_{tt} = \frac{\alpha E(T_i - T_o)}{2(1-v)(ln\, {}^{r_o}/_{r_i})}\left[1 - ln\frac{r_o}{r} - \frac{r_i^2}{r_o^2 - r_i^2}\left(\frac{r_o^2}{r^2} + 1\right) ln\frac{r_o}{r_i}\right] \quad (8),$$

$$\sigma_{zt} = \frac{\alpha E(T_i - T_o)}{2(1-v)(ln\, {}^{r_o}/_{r_i})}\left[1 - 2\, ln\frac{r_o}{r} - \frac{2r_i^2}{r_o^2 - r_i^2} ln\frac{r_o}{r_i}\right] \quad (9),$$

where Q is the rate of heat transfer, A is the cross-section area, L is the wall thickness and E is Young's modulus.

The analytical calculations for Figures 1, 2, and 3 were calculated based on Equation (7), Equations (8) and (9). Figure 1 shows that overall radial stress decreased towards the center of the cylinder and increased towards the free end of the cylinder creating a U-shaped curve. This means that the overall radial stress has a maximum occurrence at the center of the cylinder due to thermal and structural loads. There was a similar graph trend from both of the results. Different parts of the cylinder may show different results in the simulation which is why it differs from the analytical calculation.

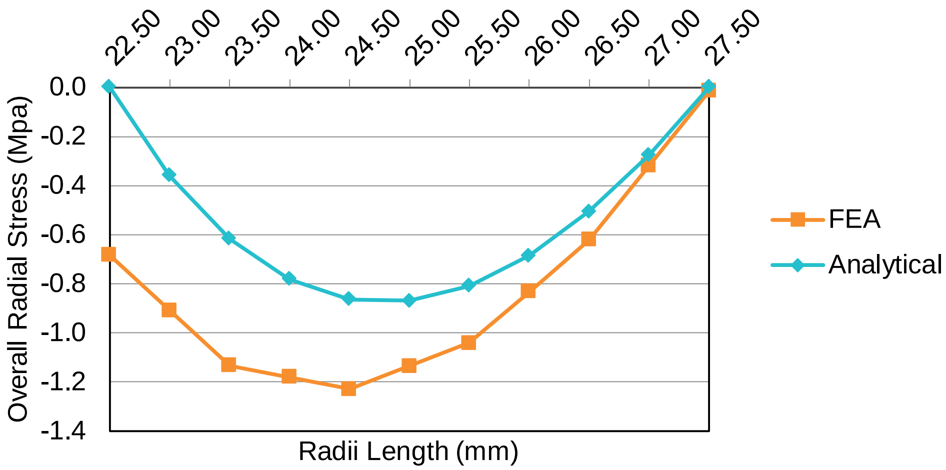

Figure 1: FEA vs. Analytical of Overall Radial Stress.

Figure 2 displays overall hoop stress increased linearly across the radius of the cylinder towards the free end of the cylinder. The maximum hoop stress occurred at the free end of the cylinder. There was also a similar graph trend from both of the results. The difference in results is probably due to FEA taking into account the structural load applied because the analytical result computes the thermal stress.

Figure 3 shows the overall Von Mises stress distribution throughout the cylinder as a whole overview. The Von Mises stress decreased towards the center of the cylinder and increased towards the free end of the cylinder as in radial stresses. This means that the Von Mises stress has a maximum occurrence at the free end of the cylinder.

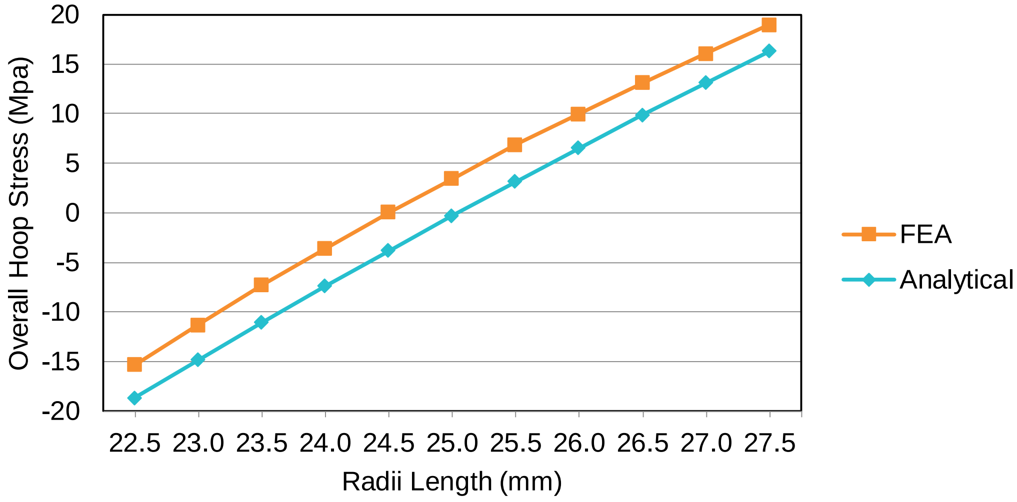

Figure 2: FEA vs. Analytical of Overall Hoop Stress

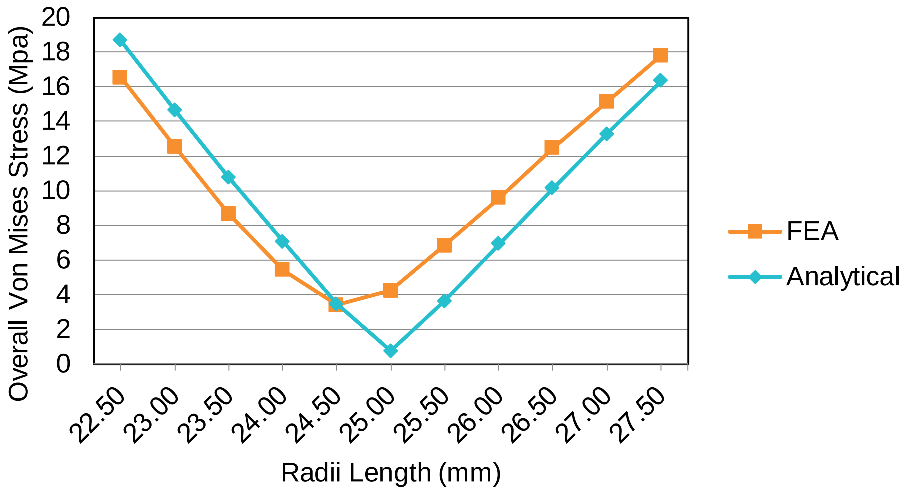

Figure 3: FEA vs. Analytical of Overall Von Mises Stress

The safety factor of this simulation was the ratio of yield strength and equivalent or Von Mises stress which was 4.98. This proves that the material used will not deform under the internal pressure of 0.65MPa and thermal loads from the combustion of the propellant.

Then, the simulation was conducted to analyse the Molybdenum rocket motor casing with the thickness of 2.5mm, 3.5mm and 5.0mm as CC 2.5, CC 3.5, and CC 5.0 respectively with the propellant of AP/AL/HTPB. The parameters are presented in Tables 1 and 2 in which Molybdenum had a varying thickness to choose the most suitable material for solid rocket motor casing.

3.1 Static Stress Analysis

Static stress analysis was used to find out the relationship between internal or external forces applied to the chamber with the corresponding stress. All the stresses were not necessary to design a rocket motor casing according to the ASME Code vessels. Only the governing stresses were required. The relation of these stresses to the vessel started with the design conditions or boundary conditions acting on the casing [5].

3.1.1 Radial Stress of CC 2.5, CC 3.5, and CC 5.0

Radial stress is concerned with the stress that is present in the direction in which it is coplanar but perpendicular to the axis of symmetry of the cylinder. Generally, it is equivalent to the amount of pressure applied [6].

Based on the simulation, on the inner radii length of 22.5mm, the model that possessed the lowest radial stress was CC 2.5 at -6.8715MPa. Based on Figure 4, moving towards the outer wall of the cylinder, all three models exhibited a linear increase of radial stress ending with a value of around 0.01MPa. With a thickness of 2.5mm, CC 2.5 showed a steeper increase of stress as compared to the thickness of 3.5mm, CC 3.5. CC 5.0 however had a thickness of 5mm and had a more spaced out radial stress than the other two thicknesses.

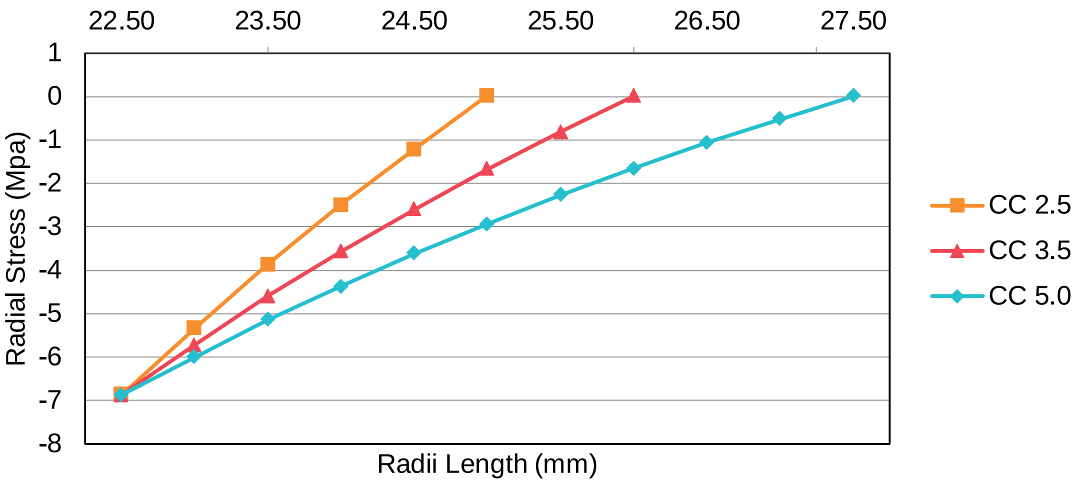

Figure 4: Radial Stress of CC 2.5, CC 3.5, and CC 5.0

Although CC 2.5 had a steep increase of radial stress from -6.8715MPa to 0.0172MPa, it is generally better than CC 3.5 and CC 5.0 as a steeper graph showed a quicker change in terms of stress for this particular situation. Minimizing the amount of stress applied is in accordance to the minimal thickness of the model. The gradual slope of CC 3.5 exhibited a slower change in radial stress but was faster than CC 5.0.

The simulation is in accordance to Lamé's Theory for thick cylinders as the maximum radial stress occurs on the inner wall of the cylinder. Negative values of stress mean that the stress occurs in compression instead of tension. Radial stress was equivalent to the amount of pressure applied which was observed as all three models showed radial stress of around -6.87MPa on the inner wall of the case based on Figure 4. Radial stress is always compressive stress as denoted by the negative sign on the pressure applied [7].

3.1.2 Hoop Stress of CC 2.5, CC 3.5 and CC 5.0

Hoop stress describes the type of stress in a cylinder which is the measurement of resistance to the force of applied pressure on the inner wall [6]. Figure 5 shows the comparison of the three models in graphical form.

According to Figure 5, CC 2.5 with an outer diameter of 50mm and thickness of 2.5mm showed a maximum value of 65.66MPa. This model decreased linearly throughout the thickness. The minimum value of this analysis was at 58.772MPa. CC 3.5 had an outer diameter of 52mm and thickness of 3.5mm which showed a maximum value of 48.002MPa. This analysis also decreased linearly throughout the thickness of the casing to a minimum value of hoop stress at 41.114MPa. The difference between the maximum and minimum values of this analysis for CC 2.5 and CC 3.5 was 6.888MPa.

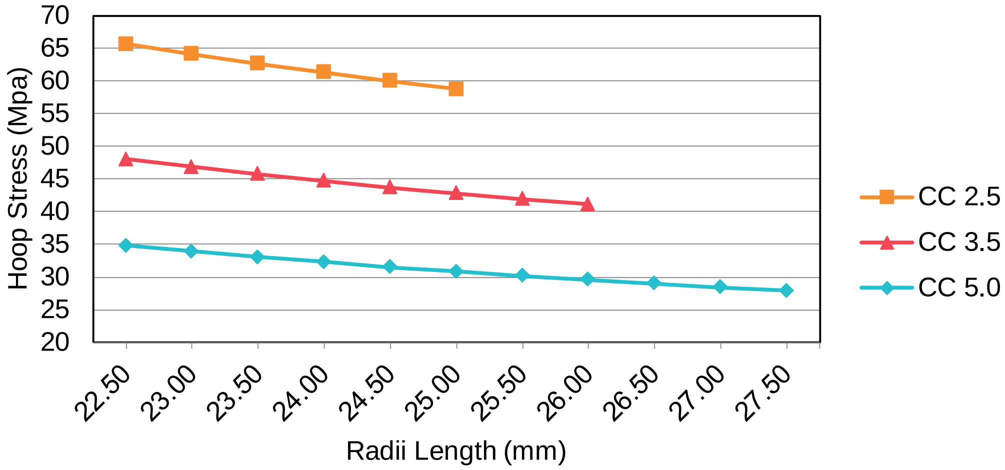

Figure 5: Hoop Stress of CC 2.5, CC 3.5 and CC 5.0

The CC 5.0 with an outer diameter of 55mm and thickness of 5mm exhibited a maximum hoop stress value of 34.8MPa and a minimum value of 27.915MPa. The difference between these two values was 6.885MPa. Evaluating all three models showed that hoop stress had the highest maximum and minimum value of the model with an outer diameter of 50mm. A larger thickness of casing decreased the value of hoop stress at the inner wall. The radii length, although different for all three models, showed that there was a similar downward trend of hoop stress regardless of the casing thickness.

This generally means that the force which is exerted circumferentially is perpendicular to the symmetry axis and radii of the cylinder. Maximum hoop stress also occurs on the inner wall of a thick wall cylinder according to Lamé's Theory. Hoop stress is also tensile stress [7]. This is observed in Figure 5 in which all three models displayed their maximum values of hoop stress at a radii length of 22.5mm on the inner wall of the case.

3.1.3 Von Mises Stress of CC 2.5, CC 3.5, and CC 5.0

Von Mises or equivalent stress is the overall stress used to predict the yielding of an isotropic and ductile material upon loads. Figure 6 shows the comparison of the three models in graphical form.

In this case of internal pressure applied on the inner wall of the model, it is observed in Figure 6 that Von Mises stress showed similar behaviour as in Figure 6 of hoop stress across the radii length. All three models showed a linear decrease in values throughout their respective thicknesses of 2.5mm, 3.5mm, and 5mm.

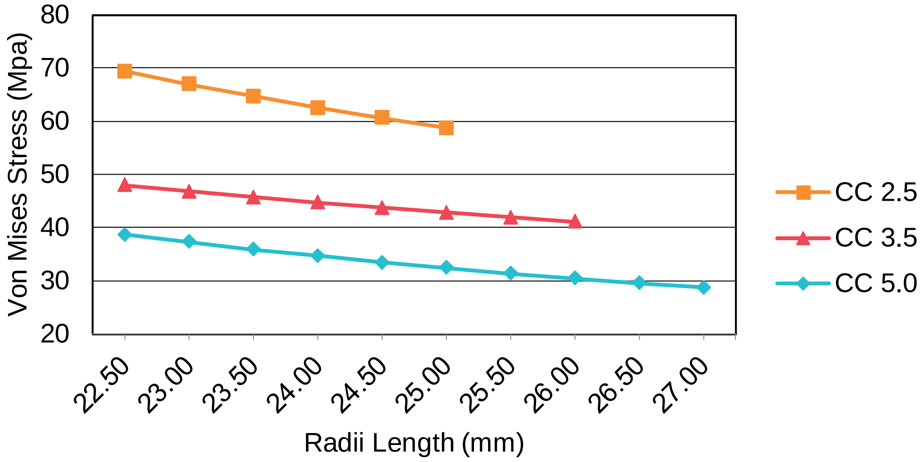

Figure 6: Von Mises Stress of CC 2.5, CC 3.5 and CC 5.0.

CC 2.5, exhibited by the red line in Figure 6, had a maximum Von Mises stress value of 69.352MPa. This value decreased to a minimum Von Mises stress value of 58.763MPa. The difference between the two values was 10.769MPa. CC 3.5, exhibited by the green line, had a maximum stress value of 51.783MPa. This value decreased steeply to a minimum value of 41.108MPa. The difference between the maximum and minimum values was 10.675MPa.

Lastly, CC 5.0 represents the model with an outer diameter of 55mm. A maximum Von Mises stress value stood at 38.699MPa and a minimum occurred at the outer wall of the case at 27.910MPa. This model also showed the highest difference in values with 10.789MPa as represented in Figure 6. Comparing all three models, when looking at Von Mises stress, the model with an outer diameter of 55mm had the least amount of maximum and minimum stress applied.

This would mean that a larger distance between the inner and outer wall of the casing would exhibit lower overall stress values. The maximum stress value will still occur on the inner wall of the casing and vice versa.

3.2 Steady Thermal Analysis

Many problems that exist in rocket motor casing today are due to severe temperature differences. These differences potentially affect the structural performance of the casing. Thermal analysis is necessary to find out the temperature distribution and its relation with the heat flux to evaluate the thermal aspects of rocket motor casing upon combustion of the propellant.

3.2.1 Temperature Distribution of CC 2.5, CC 3.5, and CC 5.0

Steady-state thermal analysis was then conducted to show the temperature distribution throughout the thickness of the models. This simulation was completed using models with outer diameters of 50mm, 52mm, and 55mm. Figure 7 shows the comparison of the three models in graphical form.

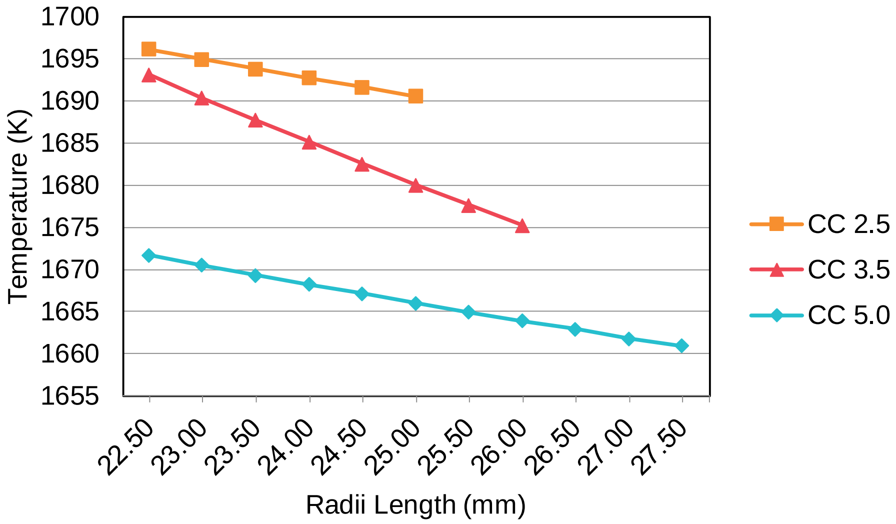

Figure 7: Temperature Distribution of CC 2.5, CC 3.5, and CC 5.0

As the heat transfer occurred from the inner wall, it is observed in Figure 7 that the maximum temperature occurred at the inner wall of the casing. This was due to the heat transfer of convection and radiation from the combustion of the propellant.

Initially, with all three models, the maximum value of temperature ranged from 1696.10K to 1671.70K. The graph showed that when an outer diameter of 50mm was used, CC 2.5 temperature dropped to about 1690.50K from 1696.10K. The temperature drop for this model was 5.60K. When an outer diameter of 52mm was used, CC 3.5 showed a linear decrease to a value of 1675.20K. This means that there was a larger temperature drop of 17.9K from 1693.10K.

Lastly, the analysis was repeated with an outer diameter of 55mm where CC 5.0 had the lowest maximum temperature among the three models at 1671.70K. The temperature drop was at 10.8K for this model. The graph trend showed a more gradual decrease of temperature across the radii length when compared with the other models. It also exhibited a less steep slope when compared to the model with an outer diameter of 52mm but was steeper than the model with an outer diameter of 50mm.

The rate at which heat was transferred was proportional to the rate of temperature change. The biggest slope amongst the three models was CC 3.5. This means that CC 3.5 had the steepest drop in terms of temperature across the radii length. Therefore, the heat was transferred at a high rate in this model. The difference in the behavior of temperature across the thickness of the radius of the casing was due to the thermal conductivity of the material. Emissivity values on all three models were the same which was somehow inaccurate to be used since emissivity depended on the thickness of the material as well as the surface finishing [8].

3.2.2 Heat Flux of CC 2.5, CC 3.5, and CC 5.0

Heat flux is the rate of heat energy transfer per unit area perpendicular to the direction of heat flow. Heat flux is however influenced by the temperature difference and the thickness of the material along with the area of contact [9].

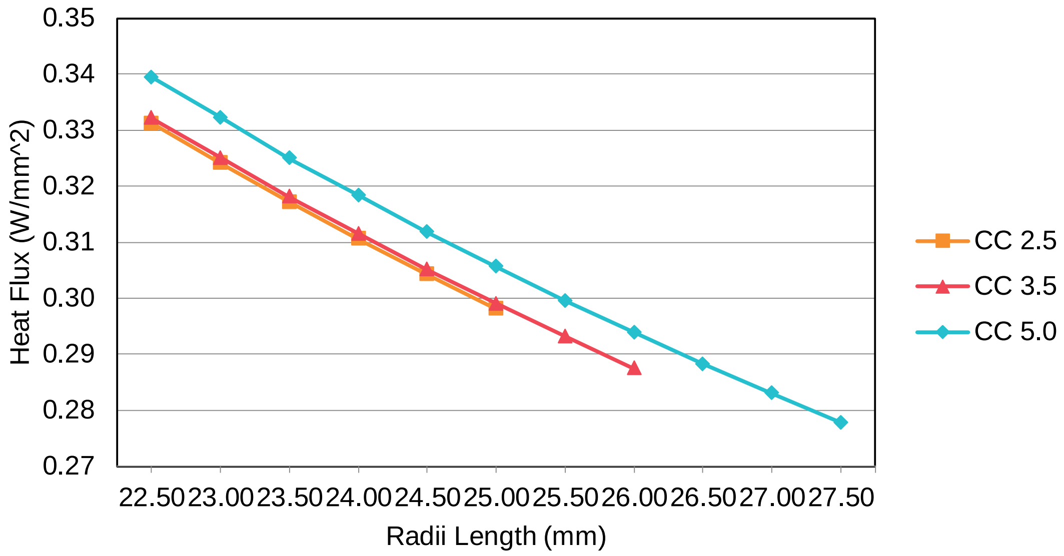

Figure 8: Heat Flux of CC 2.5, CC 3.5 and CC 5.0

Figure 8 shows the comparison of the three models in graphical form. The maximum heat flux value occurred on the inner wall of all three models as shown in Figure 8. All three models showed a gradual decrease in heat flux values across the length of thickness of the casing.

Based on Figure 8, CC 2.5 and CC 3.5 coincided in the values of heat flux per unit area. A thickness of 5mm was represented by an outer diameter of 55mm of CC 5.0 which also showed a similar downward trend of heat flux. However, the maximum value of heat flux was higher than the other models at 0.3394 W/mm^2. It also had the lowest minimum value of heat flux at 0.2778 W/mm^2.

Although the temperature of the inner wall was the lowest for the model with the thickness of 5mm, it had the highest heat flux value amongst the rest. The rate of heat transfer was higher for a larger distance of thickness. Since the rate of heat transfer was higher, the temperature, therefore, decreased faster across the radius length [10]. This showed the minimum value of heat flux on the outer wall of the case for CC 5.0.

Table 6: Overall Results

Model	CC 2.5	CC 3.5	CC 5.0
Outer Diameter (mm)	50	52	55
Thickness (mm)	2.5	3.5	5.0
Volume (mm^3)	37311.25	53335.45	78550.00
Nodes	1107	1399	1711
Element	300	398	500
Maximum Radial Stress (MPa)	-6.8715	-6.8753	-6.8757
Maximum Hoop Stress (MPa)	65.6600	48.0020	34.8000
Maximum Von Mises Stress (MPa)	69.3520	51.7830	38.6990
Final Temperature (K)	1690.50	1675.20	1660.90
Maximum Heat Flux (W/m2K)	0.3312	0.3322	0.3394
Maximum Overall Radial Stress (MPa)	-6.8874	-6.9365	-6.9021
Maximum Overall Hoop Stress (MPa)	65.3240	76.7990	42.5960
Maximum Overall Von Mises Stress (MPa)	68.5560	76.8780	42.6140
Safety Factor	1.6045	1.4308	2.5813

3.3 Summary

Varying the thickness of the casing with 2.5, 3.5 and 5.0 mm shows how thickness affects stress, thermal and overall stress analysis, see Table 6. Generally, radial thermal stress has maximum values at the center of the thickness of the casing. Hoop thermal stresses are maximum on the outer wall of the casing and thus Von Mises stress should show a graph trend similar to radial thermal stress but at higher values [6]. When large pressure and thermal load are applied, the trends of the overall radial, hoop, and Von Mises stress are similar to the static stress analysis.

4 Conclusion

A cloud seeding rocket mainly comprises the nozzle, nose cone, propellant, igniter, and casing. The first objective is achieved as the rocket motor case concept is essentially the cylindrical chamber where combustion takes place. The next objective is achieved as thermo-structural analysis on the rocket motor case starts with stress analysis, followed by thermal analysis, and lastly overall stress analysis. The analytical and method of simulation are validated initially as the verification process of this study.

Based on the three models, the overall safety factor is calculated. According to MTC Engineering, the desired safety factor is a safety factor of at least 1.5. CC 3.5 is undesirable as it has a safety factor of 1.4308 which is lower than the expectation of the company. CC 5.0 has the highest safety factor of 2.5813 and CC 2.5 has a safety factor of 1.6045.

To choose the most suitable model for the case, cost, weight, and safety factors are important parameters for consideration. Although CC 5.0 exhibits the highest safety factor, it has the largest thickness amongst the three models which means it is heavier in weight and requires more material to cast the cylinder. This would mean additional cost is necessary. CC 2.5 is therefore the most suitable as it has an adequate factor of safety of 1.6045 and has a thickness of 2.5mm. It is the lightest in terms of weight and therefore requires less material and cost to cast the rocket motor casing for fabrication.

Radiation is a parameter that influences the results, so it is better to conduct additional studies on the emissivity of a material. This also depends on the thickness and surface finishing of the casing. This will immensely help to get more accurate results to determine the safety factor of the rocket motor casing.

5 Availability of Data and Material

Data can be made available by contacting the corresponding author.

6 Acknowledgement

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