CASING DESIGN

The casing houses the grains and has a bulkhead on the forward end and a nozzle on the rear. Combustion happens inside the casing and it is necessary to ensure it can withstand the high temperatures and pressures. Aluminium 6063 T5 was selected for the casing material as it has a higher strength-to-weight ratio than steel and is also available in tubular form from local vendors.

The wall thickness was designed based on the maximum expected operating pressure (MEOP) P_c, of 5 MPa based on past data.

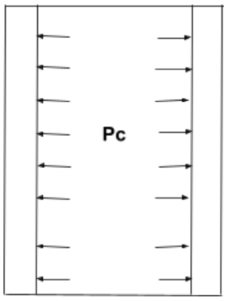


Figure 1: Casing design considerations

Problem Specifications		**Al 6063 T5 Mechanical Properties**	
Specification	**Value**	**Property**	**Value**
Length, L	725 mm	σ_{yp}	110 MPa
Inner Diameter, d	94 mm	σ_{UTS}	150 MPa
MEOP, P_c	4.26 MPa	E	70,000 MPa
Minimum S_f	2	μ	0.33

Minimum thickness

Considering the hoop stress,

$$t = \frac{P_c * d * S_f}{2\sigma_{yp}} = \frac{4.26 * 94 * 1.5}{2 * 110} = 2.7303\ mm$$

A thickness of 3 mm is selected to cater for tolerances during manufacturing.

Expected change in length

$$\Delta l = \frac{p_c * d * l}{4 * t * E}(1 - 2\vartheta) = \frac{5 * 94 * 725}{4 * 3 * 70000}(1 - 2 * 0.33) = 0.1379\ mm$$

Expected Change in diameter

$$\Delta d = \frac{p_c * d^2}{4 * t * E}(1 - \vartheta) = \frac{5 * 94^2}{4 * 3 * 70000}(1 - 0.33) = 0.03524\, mm$$

Burst Pressure

$$P_B = \frac{2 * t * \sigma_{UTS}}{d} = \frac{2 * 3 * 150}{94} = 9.5745\, MPa$$

NOZZLE DESIGN

Introduction

A de-Laval conical nozzle designed for the Nakuja N4 rocket was simulated in Ansys Fluent Software, and the throat and exit characteristics of the flow were determined. The nozzle accelerates the products of combustion, trading pressure for velocity to maximize the thrust generated.

Considerations for the expansion ratio, ἐ is the ratio of the nozzle exit area, Ae to that of the nozzle throat area, At.

Nozzle Design

The operating chamber pressure and Specific impulse were determined first using Open Motor,

Pc = 4. 26 MPa

I_{sp} = 134. 83 s

Mass Flowrate,

$$\dot{m} = \frac{I}{I_{sp} * g} = \frac{2431.36}{134.22 * 9.81} = 1.8466\, kg/s$$

Optimum throat area for sonic transition,

$$A_t = \frac{\dot{m}}{Pc} * \sqrt{\frac{R * T_c}{\gamma}} * \left(1 + \frac{\gamma - 1}{2}\right)^{\frac{\gamma+1}{2\gamma-1}}$$

The specific gas constant of the combustion mixture is determined by,

$R = \frac{R_o}{M}$ where M is the molecular weight = 35.361 g/mol (from Proprep)

R_o is the universal gas constant = 8.314 J/mol.

$$R = \frac{8.314}{35.361 * 10^{-3}} = 235.1178 \frac{J}{Kg.K}$$

Chamber static temperature during combustion,

$$T_c = 1595\ K$$

Ratio of specific heats, $\gamma = 1.1369$ (from Proprep)

Optimum throat diameter,

$$A_t = \frac{1.8466}{4.26 * 10^6} \sqrt{\frac{235.1178 * 1595}{1.1369}} * \left(1 + \frac{1.1369 - 1}{2}\right)^{\frac{1.1369+1}{2\,(1.1369-1)}} = 4.17883 * 10^{-4}\ m^2$$

Throat diameter,

$$d = \sqrt{\frac{4 * 4.17883 * 10^{-4}}{\pi}} = 23.1\ mm$$

Optimum throat-to-exit area ratio,

$$\frac{A_t}{A_e} = \left(\frac{\gamma + 1}{2}\right)^{\frac{1}{\gamma-1}} * \left(\frac{P_e}{P_c}\right)^{\frac{1}{\gamma}} * \sqrt{\left(\frac{\gamma + 1}{\gamma - 1}\right) * \left[1 - \left(\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

$$\frac{A_t}{A_e} = \left(\frac{1.1369 + 1}{2}\right)^{\frac{1}{1.1369-1}} * \left(\frac{101325}{4.26 * 10^6}\right)^{\frac{1}{1.1369}} * \sqrt{\left(\frac{1.1369 + 1}{1.1369 - 1}\right) * \left[1 - \left(\frac{101325}{4.26 * 10^6}\right)^{\frac{1.1369-1}{1.1369}}\right]}$$

$$= 0.14395$$

Optimum expansion ratio,

$$\varepsilon_{opt} = \left(\frac{A_t}{A_e}\right)^{-1} = 0.14395^{-1} = 6.947$$

Exit diameter,

$$D_e = \sqrt{\varepsilon} * d = \sqrt{6.947} * 23.1 = 60.9\, mm \cong 61\, mm$$

BOLT DESIGN

a). BOLT SHEAR STRESS

This is the failure mode that occurs when the bolts used to hold the closure into the casing break due to the force applied perpendicular to the axis of the fastener. It is most likely to occur in designs with few fasteners of relatively small diameter, and is the only failure mode not affected by casing wall thickness.

Number of Bolts Calculation

Given Data:

- Maximum yield stress of mild steel: 250MPa
- Safety factor: 2
- Shear stress according to von Mises criterion is 60% of yield stress = 150MPa
- Diameter of M6 bolt: 6mm
- Chamber pressure (Pmax):4. 26MPa
- Cross-sectional area of casing calculated based on inner diameter 94 mm
- Airframe weight: 22.5 Kg

Maximum Allowable Shear Stress,

$$\tau_{max} = \frac{150MPa}{2} = 75MPa$$

Shear stress on one bolt,

$$Area\ of\ M8\ bolt = \frac{\pi}{4} * 8^2 = 50.2655\ mm^2$$

$$Force\ per\ bolt = \tau_{max} * Area * 2 = 75MPa * 50.2655 * 2 = 7539.82\ N$$

Total Force Calculation

Force due to chamber pressure,

$$F_{chamber} = Pmax * Cross - sectional\ Area = 4.26MPa * \frac{\pi}{4} * 94^2 = 29563.46\ N$$

Force due to airframe resistance,

$$F_{airframe} = Weight\ of\ airframe * g = 22.5\ kg * 9.81 = 220.725\ N$$

Total force,

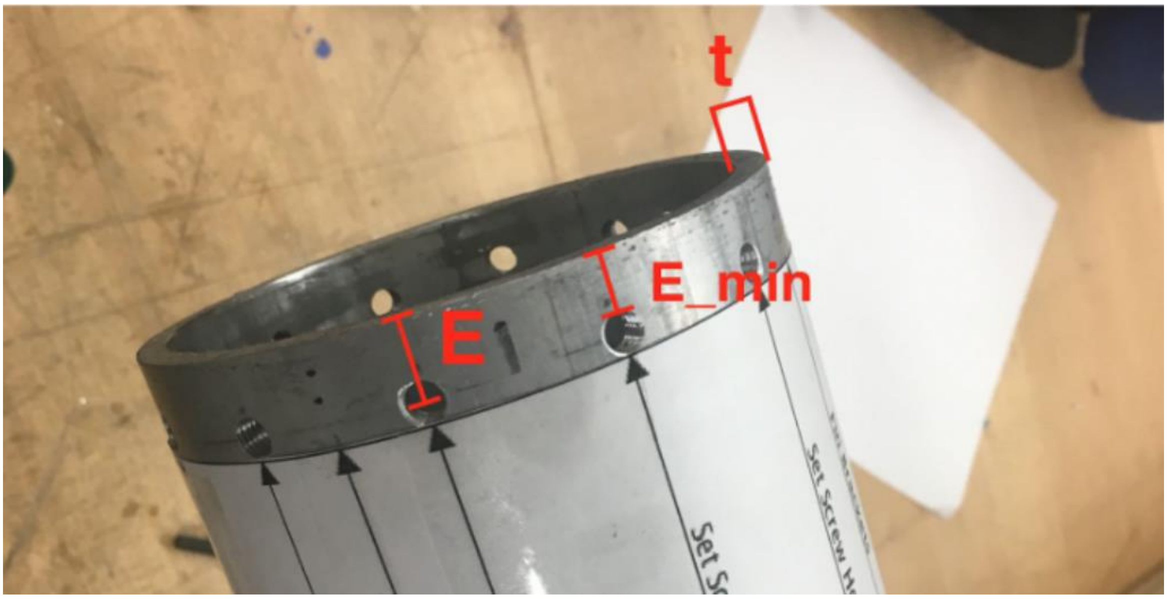
$$F_{total} = F_{chamber} + F_{airframe} = 29563.46 + 220.725 = 29784.19\ N$$

Number of bolts required,

$$Number\ of\ bolts = \frac{F_{total}}{Force\ per\ bolt} = \frac{29784.19}{7539.82} = 3.95\ \approx \boldsymbol{4\ bolts}$$

b). BOLT TEAR-OUT STRESS

Bolt tear-out is the failure in which the bolts tear through the aluminum motor casing. It is most likely to occur in designs where the fastener holes are very close to the edge of the casing, or the casing wall is relatively thin. This type of failure results from shear stresses in the aluminum casing wall.



Note that E >= 2d (bolt major diameter) is highly recommended.

And so E >= 2*8 mm = 16 mm

$$E(\min) = E - \frac{d(bolt,major)}{2} = 16 - \frac{8}{2} = 12\ mm$$

$$\sigma_{tearout} = \frac{F_{bolt}}{E_{min} * 2t} = \frac{7539.82}{12 * 2 * 3} = 104.72\ MPa$$

Shear strength is given as 115Mpa for aluminium 6063-T5.

c). BEARING STRESS

Bearing failure occurs when the force of the bolts pushing against the edges of their holes causes the casing material to fail in compression.

Bearing yield strength is given as ***276MPa*** (not true value) for Aluminium 6063-T5.

$$\sigma_{bearing} = \frac{F_{bolt}}{d_{bolt\ major} * t} = \frac{7539.82}{8 * 3} = 314.159\ MPa$$

Using a safety factor of 1.5, maximum allowable bearing pressure = 184MPa

$$\sigma_{bearing} = \frac{F_{bolt}}{d_{bolt\ major} * t} => F_{bolt} = 184 * 8 * 3 = 4416\ N$$

$$Number\ of\ bolts = \frac{F_{total}}{Force\ per\ bolt} = \frac{29784.19\ N}{4416\ N} = 6.745\ \cong 7\ bolts.$$

To prevent bearing failure, **8 bolts** are selected to ensure symmetry.

d). CASING TENSILE FAILURE

Casing tensile failure occurs when portions of the aluminium casing between the fastener holes are stretched beyond its breaking point.

$$\sigma_{tensile} = \frac{F_{due\ to\ chamber\ pressure}}{\left[\left(D_{outer\ casing} - t\right)\pi - N * d_{bolt\ major}\right] * t} = \frac{29563.46\ N}{[(100-3) * \pi - 8 * 8] * 3}$$
$$= 40.935\ MPa$$

Aluminum 6063-T5 has a yield strength of at least **110 MPa**