Design Analysis of Mild Steel Combustion Chamber for a Sugar Base Propellant of a Solid Rocket Motor

Rasheed O. DUROJAYE, Olusegun A. ADEFUYE , Nurudeen A. RAJI, Elkanah O. OYETUNJI

***Abstract*— Solid rocket motors (or SRMs) are simple devices comprising of bulk head, combustion chamber and nozzle in one unit [1]. The solid rocket motor combustion chamber is made of an extruded mild steel metal with an adjoining nozzle screwed to the end of the pipe. It was designed and fabricated at the Center for Space Transport and Propulsion an activity center of the National Space Research and Development Agency (NASRDA).The combustion chamber of a solid rocket motor is the part that houses the propellant grains. Combustion takes place inside the chamber after ignition of the propellant grains and hot combustion gases are produced and forced out through the nozzle thereby generating high thrust for rocket lift off [4]. The simplicity of SRMs makes them a very suitable and an attractive choice for many rocket propulsion applications. Because there are few structural component parts, the SRM is efficient in that the vast majority of its weight is actually usable propellant [7].**

***Index Terms*— Nozzle, Ignition, Combustion, Propellant, Thrust, Extrusion.**

I. Introduction

In the design of combustion chamber for solid rocket motors, it is very critical to have adequate knowledge of the propellant characteristics such as the density, burn rate, maximum expected temperature, maximum expected pressure, burn time etc[3]. These characteristics are very paramount as they form the critical design input for material selection and sizing of the various component parts of the solid rocket motor.The propellant contains both fuel and oxidizer; therefore these devices can operate in the vacuum of space [4]. Thrust is developed as the high thermal energy of the combustion gases is converted to kinetic energy in the exhaust. Solid Rocket Motors can be ignited in a moment's notice and don't require external tanking of liquids prior to operation. Although, their efficiency (specific impulse) is generally lower than liquid rocket engine systems, and they cannot be readily throttled. Once they are ignited, the motor will burn to extinction unless special provisions are included to terminate thrust during the middle of a firing [4].

Rasheed O. DUROJAYE, Department of Structures and Aerodynamics, National Space Research and Development Agency, Lagos, Nigeria
Olusegun A. ADEFUYE , Department of Mechanical Engineering, Lagos State University, Ojo, Nigeria
Nurudeen A. RAJI, Department of Mechanical Engineering, Lagos State University, Ojo, Nigeria
Elkanah O. OYETUNJI ,Department of Mechanical Engineering, Lagos State University, Ojo, Nigeria

II. FLIGHT TRAJECTORY ANALYSIS

The design process started with a flight trajectory analysis for a 1Km altitude rocket using Potassium nitrate as oxidizer and Sucrose as the main fuel. The table below shows the flight trajectory simulation results for a 5.06Kg KNSU Propellant.

Table 1.1 Flight trajectory parameters.

PARAMETERS	SYMBOLS	VALUES	UNITS
Gravity Acceleration	g	9.69	m/s2
Air Density	rho	1.223	kg/m3
Drag Coefficient	Cd	0.4	
Burn Time	tb	7.0	s
Specific Impulse	I_{sp}	150	s
Rocket Total Mass	mo	41.32998	kg
Propellant Mass Ratio	fp	0.122429	
Mass Of Propellant	mp	5.06	kg
Propellant Mass Flow Rate	mp-dot	1.363881	kg/s
Mass Of Final Rocket	mf	36.26998	kg
Rocket Diameter	d	0.2	m
X-Section Area	A	0.031416	m2
Drag Factor	k	0.007684	kg/m
Fineness Ratio Of Rocket	λ	12	
Length Of Rocket	L	2.4	m
Total Impulse	I	7354.71	N-s
Average Thrust	F	1982.402	N
Thrust-To-Weight Ratio	vo	4.949971	
Number Of Iterations	N	300	
Sampling Time	Δt	0.012367	s
Maximum Time	tmax	17.09553	s
Maximum Altitude	hmax	1200	m

Using ProPep Simulation software for the characterization of the sugar based propellant; the results generated can be seen in the table below.

Table 1.2 KNSU PROPELLANT GRAIN PARAMETERS

S/N	PARAMETERS	VALUES
1	Propellant outer Diameter, D (m)	0.105
2	Propellant Core Diameter, D_o (m)	0.038
3	Bate Length (m)	0.118
4	Mass of propellant (kg)	5.06
5	Number of bates, N	3
6	Throat diameter (m)	0.036
7	Total length of grain (m)	0.354659
8	Burn time, $t_b(s) = \dfrac{R_o - \sqrt{R_o^{\,2} - \dfrac{V_p}{\pi L_p}}}{r_b}$ Where $r_b = 0.00904\ m/s$	7.0
9	Propellant density (kg/m^3)	1896
10	Max. Kn	88.199
11	Average thrust, F (N)	1925.907
12	Max pressure, P_c (MPa)	1.08
13	MaxTemperature, P_c (^oC)	1376

III. NOZZLE DESIGN PARAMETERS

NozzleDesign Analysis was carried out using critical input from the ProPep simulation software.

<u>Input Data from ProPep:</u>

Max. Temperature inside chamber = 1650K
Max. Pressure inside chamber = 1.08MPa= P_1
Mass Flow Rate = 0.723Kg/s
Specific Impulse = 150s
Burn time = 7s
Air pressure at 10KM= 0.02644MPa = P2
Pressure Ratio = P_2/P_1= 0.0245MPa
The critical throat pressure for which the isentropic mass flow is maximum P_t is calculated next [1],

$$P_t = P_1\left[\frac{2}{K+1}\right]^{\left(\frac{K}{K-1}\right)} \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where k =1.3 is the specific heat ratio.

$$P_t = 0.6156\,MPa$$

The throat velocity v_t is given by:

$$v_t = \sqrt{\left(\frac{2K}{K+1}\right)RT_1} \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

$$v_t = 814.19\,m/s$$

Where, R=355.4 JKg-K is gas constant,

T_1 =1650K is the chamber temperature.

Ideal exit velocity is calculated by:

$$v_2 = \sqrt{\left(\frac{2K}{K+1}\right)RT_1\left[1-\left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}}\right]} \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

$$v_2 = 1710\,m/s$$

$$\text{Mach number, } M = \frac{v_2}{a} \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

where, a is the speed of sound = 340 m/s

$$M = 5.03$$

Specific volume (V_1) at nozzle entrance is:

$$V_1 = \frac{RT_1}{P_1} \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

$$V_1 = 0.543m^3/kg$$

Specific volume (V_t) at the throat is:

$$V_t = V_1\left(\frac{K+1}{2}\right)^{\frac{1}{K-1}} \ldots\ldots\ldots\ldots\ldots\ldots(6)$$

$$V_t = 0.865m^3/kg$$

Specific volume (V_2) at the exit is:

$$V_2 = V_1\left(\frac{P_2}{P_1}\right)^{\frac{1}{K}} \ldots\ldots\ldots\ldots\ldots\ldots(7)$$

$$V_2 = 9.42m^3/kg$$

Area (A_t) and Diameter (D_t) at the Throat Section:

$$A_t = \frac{\dot{m}\times V_t}{v_t} \ldots\ldots\ldots\ldots\ldots(8)$$

where $\dot{m}$ is the propellant mass flow rate = 0.723Kg/s

$$A_t = 7.68\times10^{-4}m^2$$

$$D_t = \sqrt{\frac{4A_t}{\pi}} \ldots\ldots\ldots\ldots\ldots\ldots(9)$$

$$D_t = 0.03m$$

Area (Ae) and Diameter (De) at the Exit Section:

$$A_e = \frac{\dot{m} \times V_2}{v_2} \quad \dots\dots\dots\dots\dots\dots (10)$$

$$A_e = 7.68 \times 10^{-4} m^2$$

$$D_e = \sqrt{\frac{4A_e}{\pi}} \quad \dots\dots\dots\dots\dots\dots (11)$$

$$D_e = 0.07m$$

Length of Convergent (Lconv) Nozzle Section

$$L_{conv} = \frac{D_{ch} - D_t}{2\tan\alpha} \quad \dots\dots\dots\dots\dots\dots (12)$$

Where: $\alpha = 40^o$, D_{ch} is chamber diameter $= 0.24m$

$$L_{conv} = 0.058m$$

Length of Divergent (Ldiv) Nozzle Section

$$L_{div} = \frac{D_e - D_t}{2\tan\beta} \quad \dots\dots\dots\dots\dots\dots (13)$$

Where : $\beta = 15^o$

$$L_{div} = 0.075m$$

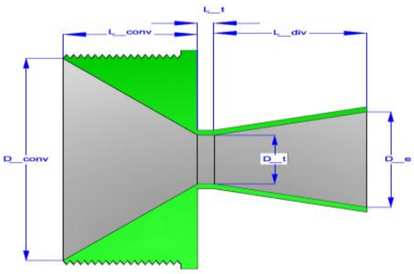

Fig 1.0: Sectioned-View of Designed Nozzle

IV. COMBUSTION CHAMBER WALL THICKNESS

The minimum wall thickness is calculated by [2], [6].

Where: $$t_{ch} = \frac{f \times P_{max} \times D_{ch}}{2 \times \delta_b} \quad \dots\dots\dots\dots\dots\dots (14)$$

Pmax = 2.0 MPa is maximum expected operating pressure.

Dch =122mm is internal chamber diameter.

δb = 400MPa is Ultimate tensile Strength of mild steel.

f = 8 is factor of safety.

The calculated chamber thickness is:

$$t_{ch} = \frac{8 \times 2.0 \times 122}{2 \times 400}$$

$$t_{ch} = 2.44mm$$

t_{ch} of 3mm was selected

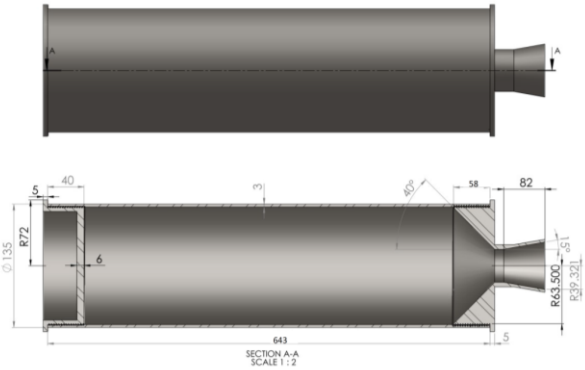

Fig 2.0 2D Sectioned view of combustion chamber with nozzle

Fig 3.0: 3D view of combustion chamber with nozzle.

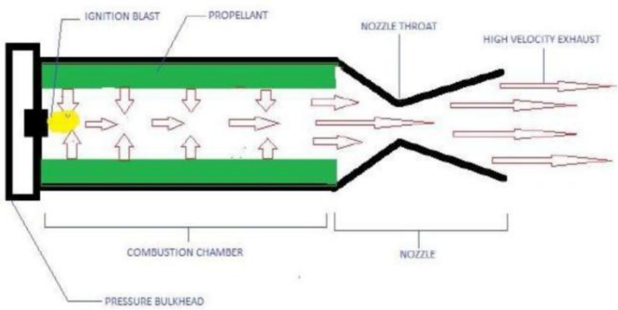

Figure 4.0: Behavior of Gases after Ignition inside the Combustion Chamber [8]

Total Length of Combustion Chamber

$$L_{ch} = L_{conv} + L_{grain} + L_{free\_volume}$$

$$L_{ch} = 58 + 354 + 231 = 643mm$$

VI. MATERIAL SELECTION

Material selection is also a key factor in the construction of rocket motors [7]. The following factors were considered before the final selection of the material used to fabricate the designed rocket motor.

- Weight of material
- Strength
- Availability of material
- Affordability/Cost effectiveness
- Ease of Fabrication
- Versatility of attachment options
- Fracture Toughness
- Thermal Conductivity
- Resistance to wear
- Melting point of material

Having exhaustively considered the above factors, mild steel was selected for the construction of the rocket motor.

REFERENCES

[1] Sutton GP, Biblarz O (2001) Rocket propulsion elements. (7th edition), John Wiley and Sons New York.

[2] Dennis Moss, Pressure vessel design manual (3rdedn), Gulf professional Publishing Burlington USA.

[3] Clergen, J.B., "Solid Rocket Motor Conceptual Design – The Development of a Design Optimization Expert System with a Hypertext User Interface," AIAA 93-2318, 1993.

[4] Singh S (2013) Solid rocket motor for experimental sounding rockets advance in aerospace science and applications 3: 1992.

[5] Davanas GE, Jensen DW, Netzer (1996) (eds.) “Solid rocket motor design chapter 4 of tactical missile propulsion progress in aeronautics and astronautics” AIAA 170: 323-379.

[6] Ahmed Ibrahim, YeongRyu, Mir Saidpour, “Stress Analysis of Thin-Walled Pressure Vessels”, Mechanical Engineering Technology, Farmingdale State College, Farmingdale, New York, USA, February 2015.

[7] J. H, Bultrzlkonis. “A survey of structural dynamics of solid propellant rocket motors” National Aeronautics and space administration, Washington D.C., December 1996.

[8] MdAkhtar khan1, B.K chaitanya, Eshwar Reddy cholleti, “Conceptual Design and Structural Analysis of Solid Rocket Motor Casing” ISSN (e): 2250-3005, Volume 07, issue 02, February 2017.

Engr. Rasheed .O Durojaye

I am a Chief Engineer at the National Space Research and Development Agency in Nigeria. A doctoral student at the Lagos State University Ojo in Nigeria.Currently working on failure analysis of mild steel combustion chamber of a solid rocket motor. My research interest includes rocket structural component design, Aerodynamics and engineering failure analysis. I possess a master’s degree in mechanical engineering from the university of Lagos Nigeria, and a second master’s degree in Aerospace engineering from the University of Alabama in Huntsville USA. I have attended several local and international conferences. Member Nigeria society of Engineers (MNSE), Member Council for the Regulation of Engineering in Nigeria (COREN).

Dr. Olusegun .AAdefuye

I have a PhD in metallurgy and material engineering from the University of Birmingham (UK). I am currently a senior lecturer at the Lagos state university Ojo, Lagos,Nigeria. I specialize in aluminum sand casting (characterization, gating systems). Research interest is in non-ferrous sand castings and the lost foam process. I have attended numerous national and international conferences.

Dr. Nurudeen.A Raji

I am currently an associate professor in the department of mechanical engineering at the Lagos state UniverityOjo, Lagos Nigeria. My area of specialty is in Design and Production. Research interest includes machine design, equipment design, process design, material development /process for engineering products, modeling, optimization and control of dynamic systems and processes. I have published extensively in prestigious local and international journals. I am a Registered Engineer (COREN) and a Member of the Nigerian society of Engineers.

Prof. Elkanah .O Oyetunji

He is currently a Professor of Industrial and Production Engineering in the Department of Mechanical Engineering, Faculty of Engineering, Lagos State University, EpeCampus, Lagos, Nigeria. He graduated with a BSc (Hons) in Electrical Engineering from the University of Ilorin, Ilorin, Nigeria. He has an MSc and PhD in Industrial Engineering from the University of Ibadan, Ibadan, Nigeria. He has attended numerous national and international conferences. His research interest includes production scheduling/operations management (optimization), and algorithm design amongst others. He has published extensively in prestigious local and international journals. He is a Registered Engineer (COREN) and a Member of the following professional bodies: Nigeria Society of Engineers (NSE), Nigeria Institute of Industrial Engineering (NIIE), South African Institute of Industrial Engineering (SAIIE).