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Investigation on Structural and Thermal Analysis of Medium Calibre Cannon Gun Barrels

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ABSTRACT

With the advent of new technologies, the rapid-firing cannon is transforming from a field to a precision weapon, enhancing accuracy and reliability. The cannons are the heart of mobile weapon platforms which offer precise offensive and defensive firepower against a broad range of threats. The barrels are the integral part of cannons which are indebted to a high rate of firepower, accuracy and muzzle velocity. The maximum chamber pressure, gun design and service pressure, mechanical and thermodynamic properties, propellant mass and energy are the vital functional parameters required to design the cannon barrels. Structural and thermal analysis of barrels, using analytical and simulation studies are compared and validated. The design methodology studies to estimate maximum safe pressure, a factor of safety and thickness ratio along the length of barrels are also discussed.

Keywords: Cannon barrel; Complex stress states; Static structural analysis; Transient thermal analysis

NOMENCLATURE

σ_r	: Radial stress (MPa)
σ_h	: Hoop stress or Circumferential stress (MPa)
σ_a	: Axial or Longitudinal stress (MPa)
σ_{ev}	: Equivalent stress (MPa)
K	: Thickness Ratio
n	: No. of rounds fired per second
a	: Rifling rate (rad/m)
m_p	: Mass of propellant (g)
m_s	: Mass of the projectile (g)
V_m	: Muzzle Velocity (m/s)
κ	: Thermal conductivity of the gun barrel (W/m K)
c.v	: Calorific value of propellant (cal/g)
c	: Specific heat of gun barrel (J/kg K)
C_p	: Specific heat of gas in constant pressure (J/kg K)
T_i	: Ambient temperature (K)
T_g	: Gas temperature (K)
T_f	: Adiabatic flame temperature (K)
ρ	: Density of gun metal (kg/m^3)
u	: Dimensionless time
t_o	: Time constant (s)
P_i	: Internal pressure (MPa)
P_o	: External pressure (MPa)
P_s	: Service pressure (MPa)
r_i	: Inner radius of the barrel (mm)
r_o	: Outer radius of the barrel (mm)
r	: Radius at any point of interest (mm)
d	: Bore diameter (mm)
Y	: 0.2 % Proof stress of material (MPa)
b_1	: Empirical factor (1.11)
H	: Total heat input to gun barrel including revolving chamber (J)
H_∞	: Total heat input to gun barrel per unit area per round (J/m^2)
H_b	: Heat input per unit area in barrel (J/m^2)
A	: Total area of the barrel with revolving chamber (mm^2)
A_b	: Area of the barrel (mm^2)
b_2	: Constant (0.17)
k	: Radius of gyration of projectile (m)
Re	: Reynolds number
Pr	: Prandtl number
D	: Characteristic linear dimension (m)
V	: Flow speed of gas (m/s)
h_g	: Heat transfer coefficient of gas (W/m^2 K)
μ_g	: Viscosity of gas (kg/m s)
ρ_g	: Gas density (kg/m^3)
κ_g	: Thermal conductivity of the gas (W/m K)

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1. INTRODUCTION

Armament weapon systems are categorized based on its barrel calibre/bore diameter and effective functional range. The barrels bore diameters of 5.56 to 12.7 mm, 12.7 to 76 mm, and above 80 mm are considered as infantry weapons, medium calibre and large calibre weapons, respectively. Cannon guns are typically medium calibre weapons, mostly integrated with mobile warfare platforms like warships, helicopters and military vehicles used for defence applications. In cannons, barrel design is the critical part as the barrel bore is exposed to high pressure, thermal wear and mechanical friction. The high rate of barrel firing results in intensification of propellant combustion masses which subjected to high temperature, pressure, projectile velocity within few microseconds. The rifled barrel transfers the energy to the projectile which rotates at high speed and further collides with breech assembly repetitively. The barrel has to face design encounters of strength, stiffness, fatigue and wear problems. The barrel plays vital role in ensuring accuracy, range, velocity and reliability of the weapon.

The barrel designing plays a vital role because the prototype development is time consuming and cost-intensive process to analyze the strength and durability. In worldwide, researchers have studied on strength and modal analysis of barrels using various strength theories and yield and residual stress distribution criterion of autofrettaged and non-autofrettaged barrels. In Figure 1, the pressure-space curve generated through an internal ballistic solution is adopted to finalize the boundary conditions of the designed gun barrel analysis. Moreover, the gun barrel designers assume realistic simplification of the gun barrel to be thick-walled cylinders and consider material properties including yield strength, percentage of elongation, thermal conductivity, and specific heat capacity of the barrel steel for modelling and analysis.

Few researchers studied thick-walled cylinders formed from linear-hardening material under blast pressure, to arrive relation between radial and circumferential stresses with radial velocity of expansion using the Prandtl-Reuss flow theory and mixed boundary element method[1-3]. Li Mao-lin*, et al.* studied the effect of plastic load on thick-walled cylinders subjected to radial stresses using strain gradient plasticity theory, highlighting the strain rate sensitivity index[4]. When the material is subjected to an external load, internal resisting force (mechanical stresses) induced by the material is advanced in all directions. The distribution of stresses and deformation behaviour of the material at the maximum design pressure and internal ballistic service pressure determines the structural integrity, functional performance, fatigue life, and barrel safety. It is evaluated through radial, axial and hoop stresses subjected on the barrel due to internal combustion pressure applied on the bore. Practically, gun barrels are subjected to mechanical load, internal pressure, and fluctuated thermal loads[5]. Contrarily, only mechanical stress in the material at maximum design pressure on 2D and 3D models are considered and discussed in detail through linear static analysis in the ANSYS tool on axis-symmetric breech and muzzle segment[6,7]. If the material can resist without fracture or failure at maximum internal bore pressure during firing, then the corresponding maximum pressure denoted as maximum safe pressure (MSP) is an essential criterion in the designing of the gun barrel[8]. In cannon barrels, the pressure which causes circumferential bore strain up to 0.03-0.05 percent is considered as maximum safe pressure and it's nearly 1.2 times the design pressure.

To avoid the design intricacies during barrel development, researchers examined analytical and simulation studies on the same dimensions of 2D and 3D models through ANSYS software. Along with external loads and internal ballistic pressure, the gun barrels are subjected to high-temperature cycles due to repeated combustion of propellant gases and the maximum instantaneous temperature during combustion may be a few thousand degrees Celsius. The barrel is exposed to high temperatures during firing where the projectile traverse in few milliseconds and cools off till the next firing[9-11]. Sometimes, the cool-off time will be a few times more than the firing time in a Gatling-type cannon where multiple barrels are in the weapon. The temperature varies at outer and inner surface of the barrel, also along the length from the breech to the muzzle end is represented in Fig. 1. It is due to, the rate of heat transfer coefficients for convection and radiation of combustible gases

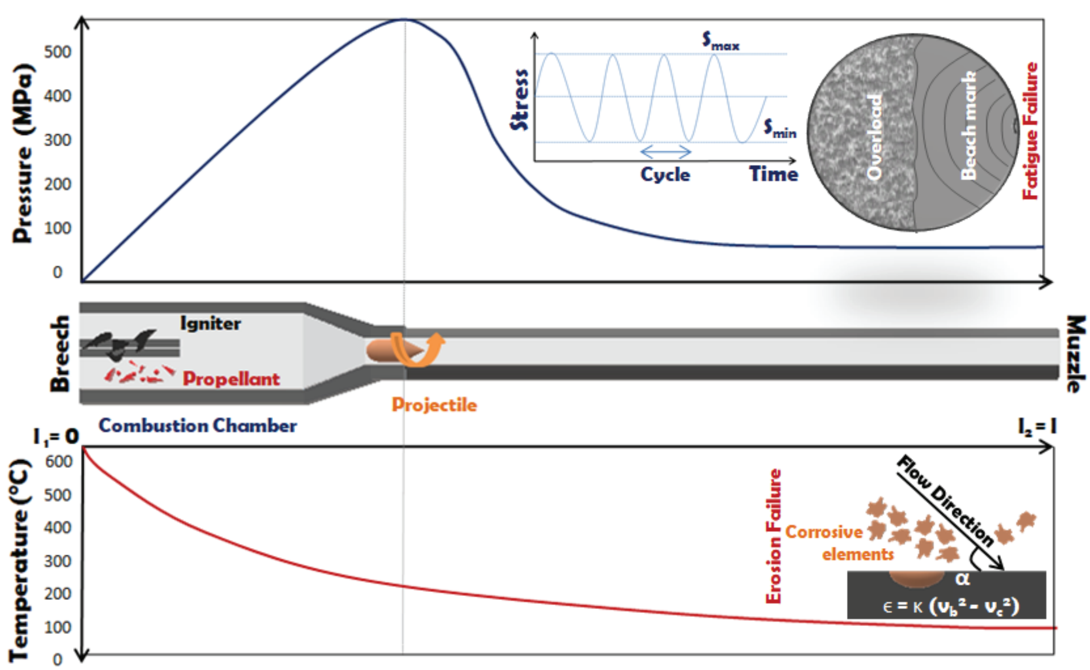

Figure 1. Schematic representation of variation in pressure and temperature along the length of a barrel.

being different and heat transfer from inner to outer surface by heat conduction[12].

Most researchers have studied thermal analysis, diagnostic and prognostic of only large calibre gun barrels[13] and not many literatures were available on medium caliber gun barrels. Herein, the evaluation of structural properties including complex stress states, maximum safe pressure, factor of safety and thermal characteristics viz. combustible gas temperature and bore surface temperature of medium caliber cannon barrel made of indigeniously developed defence standard 10-13/2 grade steel was carried out for first time as per internal ballistic data. The calculated aforementioned characteristics were validated with numerical simulation using ANSYS Workbench software (FEA) modelled in real-time using Solidworks CAD professional.

2. THEORY AND CALCULATIONS

The cannon barrel is developed with specialized indigenously developed electro-slag refined (ESR) DEF-STAN 10-13/2 grade steel tested in our lab for mechanical properties (as presented in Table 1). The geometric parameter of the barrel is tabulated in Table 2. Firstly, the structural and thermal analysis of the barrel is evaluated using simulation on ANSYS software and results are compared with analytical calculations[14].

2.1 Assumptions for Design and Simulation of Cannon Barrels

- Herein, the hollow cylinder in which the explosives are filled was considered to be homogeneous, incompressible, and perfectly plastic
- For ease of analytical calculations, the barrel's inner wall was presumed to be a smooth wall and the local dimensional properties of the inner wall of the barrel which rifling with lands and grooves was ignored whereas rifled barrel was considered for numerical simulations
- With a thorough literature survey and its comparison with the simulation, the best suitable criterion viz. von Mises criterion was implemented and so the analysis and simulation are independent of thermal deviations and stiffness strains
- It is assumed that the body of the barrel is exposed to only explosion pressure. Moreover, the barrel volume is presumed to be constant after and before the explosion
- In this work, the effects of swinging and load due to shock waves towards radial direction of the barrel are neglected
- The smooth inner wall surface was subjected to the maximum pressure in segments concerning the pressure-space curve of internal ballistic data of suitable ammunition.

3. NUMERICAL SIMULATION FOR STRUCTURAL AND THERMAL ANALYSIS

In this analysis, Solidworks CAD professional was utilized for modelling the barrel consisting of grooves with the pitch and ANSYS Finite Element Analysis (Static Structural and Transient thermal analysis) was used to simulate/solve the structural and thermal analysis of the cannon barrel[15-16].

Table 1. Properties of material used for cannon barrels

Material	DEF-STAN 10-13/2
Proof stress (MPa)	975 – 1274
Hardness (BHN)	280 – 320
Density (g/cc)	7827
Impact energy (J)	70 (minimum)
Elongation (%)	35
Thermal conductivity (W/m K)	38.07
Specific heat (J/kg K)	490

Table 2. Geometrical properties of cannon barrel

Internal diameter (mm)	30
External diameter (mm)	54
Barrel Length (mm)	1493

4. METHODOLOGY

Mises-Hencky theory is capitalized to design barrels to ensure structural integrity and prevent failure under complex loading conditions. The complex stress states, viz. 1. The stress acting in the radial direction in a pipe, perpendicular to the longitudinal axis (radial stress) 2. The stress acting tangentially around the circumference (hoop stress) 3. The stress acting along the length of the cylinder (axial stress) is build up within the barrel owing to the development of internal pressure after firing of rounds. The simulation of stress distribution offers efficiency of material, structural integrity, durability/longevity and barrel safety. The complex stress states are calculated using Lame's Eqn.[17] as given in Eqn. 1, Eqn. 2, and Eqn. 3 and the equivalent stress developed on the cylinder was derived using Mises-Hencky theory as determined in Eqn. 4.

Radial stress,

$$\sigma_r = \frac{p_i r_i^2 - p_o r_o^2}{r_o^2 - r_i^2} - \frac{p_i - p_o}{r_o^2 - r_i^2}\frac{r_o^2 r_i^2}{r^2} \tag{1}$$

Hoop stress,

$$\sigma_h = \frac{p_i r_i^2 - p_o r_o^2}{r_o^2 - r_i^2} + \frac{p_i - p_o}{r_o^2 - r_i^2}\frac{r_o^2 r_i^2}{r^2} \tag{2}$$

Longitudinal or axial stress,

$$\sigma_a = \frac{p_i r_i^2}{r_o^2 - r_i^2} \tag{3}$$

Equivalent stress Eqn. of von Mises yield criterion,

$$\sigma_{ev} = \sqrt{\tfrac{1}{2}\left[(\sigma_a - \sigma_r)^2 + (\sigma_r - \sigma_h)^2 + (\sigma_h - \sigma_a)^2 \right]} \tag{4}$$

The governing Eqn. (4) represents equivalent principal stress, and hence, the boundary conditions are assumed with the following shear stresses of respective planes (radial, circumferential, and axial) are $\sigma_{ra} = \sigma_{hr} = \sigma_{ah} = 0$.

The radial stress and hoop stress determined using Lame's Eqn. and the equivalent stress using Mises-Hencky theory were evaluated to be ~400 MPa (Compressive), ~830 MPa (Tensile), and ~997 MPa (Tensile) respectively. Herein, it can be inferred that the radial stress may be compressive and hoop stress could be tensile. Numerically, at the inner region of the cylindrical surface, the hoop stress value exist usually higher than radial stress. The *p-L* curve and the average pressure curve of the cannon barrel are accumulated from the classical internal ballistic theory.

The maximum pressure region usually extends two to three folds of the diameter along the direction of the muzzle to ensure the reliability and safety of the barrel in its service condition keeping the calculation error of the maximum pressure point and the varying load conditions into consideration.

The maximum radial stress and hoop stress (largest stress component) are discerned on cylinder inner surface where the pressure is exerted and becomes insignificant at the free surface with an increase in wall thickness in the absence of any external pressure. This diminishing radial stress can be attributed to the built-up intrinsic pressure which instantly enacts on the innermost plane and dissipates across the wall thickness of the material. Meanwhile, the declining hoop stress may be ascribed to the equilibrium of forces acting in the material and the material's adequacy to defy the internal pressure more effectively and uniformly along the cylinder wall thickness.

4.1 Research Method for Maximum Safe Pressure and Factor of Safety

The maximum safe pressure (MSP) is an important parameter in designing and determining the structural integrity of the barrel. MSP is defined as the maximum pressure that the barrel can withstand without inducing any plastic deformation to affect its accuracy[12].

Maximum safe pressure,

$$MSP = b_1 \times Y \times \frac{K^2 - 1}{K^2 + 1} \tag{5}$$

Factor of safety,

$$FOS = \frac{MSP}{P_s} \tag{6}$$

The Proof pressure (~400 MPa) and MSP (~500 MPa) vary along the length of the barrel and are calculated using service pressure (332 MPa) as per internal ballistic data from the chamber end. The MSP can be evaluated using Eqn. 5 and can be correlated with a factor of safety using Eqn.s 6. The maximum safe pressure, proof pressure, and service pressure

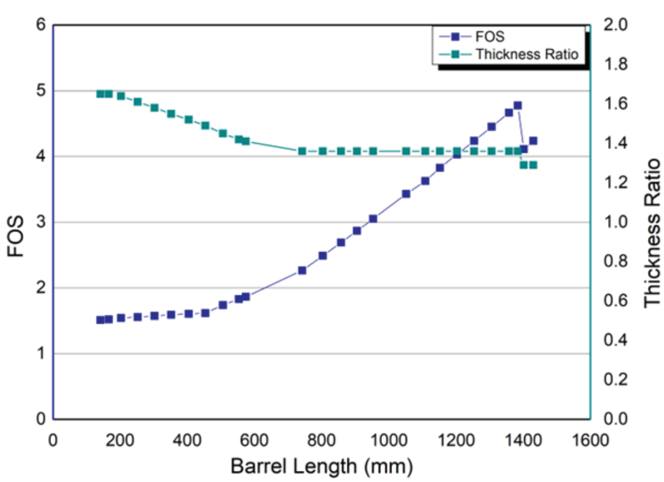

Figure 2. Factor of safety and thickness ratio vs length of the barrel.

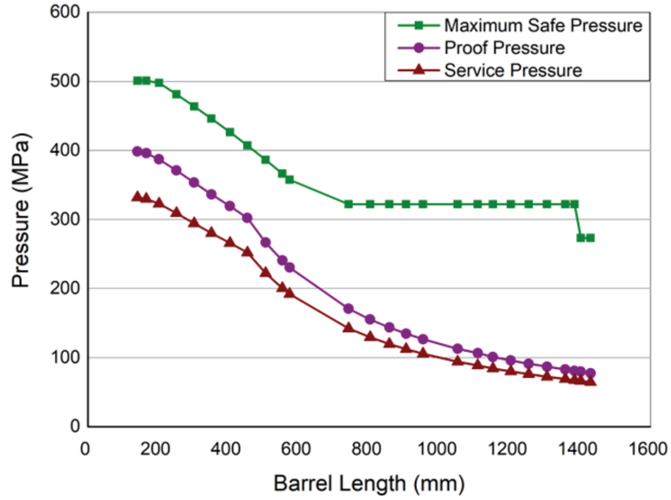

Figure 3. Pressure distribution along the length of the barrel.

along the barrel length is represented in Fig. 2 whereas the FOS and thickness ratio along the varying barrel length is represented in Fig. 3. The factor of safety is derived to be ~1.5 at maximum design pressure acting on the bore segment and reaches the maximum value near the muzzle segment.

The thickness ratio is maximum at the chamber section and minimum at muzzle end owing to the induced high temperature after the ignition of propellant and declines along the barrel

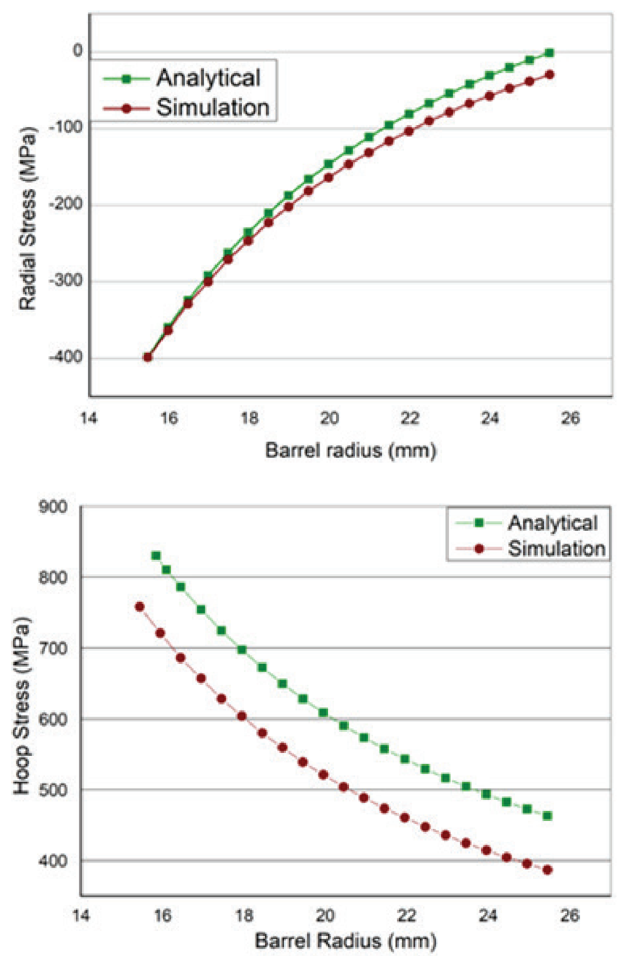

Figure 4. Typical stress distribution of cannon barrel along the radial direction.

length. The excellent thermal stability and heat dissipation due to optimised wall thickness ratio led to improved accuracy and longevity of the barrels.

4.2 Numerical Simulation for Structural Analysis

The numerical simulation of complex stress state distribution was carried out on a cannon barrel model at a peak pressure of 400 MPa. The radial stress and Hoop stress of around 398 MPa and 758 MPa are observed in the innermost surface of the barrel at a length of 200 mm from the chamber end during simulation with a 1 % and 9 % difference from that of theoretical calculation (400 MPa and 860 MPa), respectively. The 9 % variation in hoop stress can be attributed to the assumption of a thick cylinder with a smooth surface in theoretical analysis whereas a completely rifled barrel in numerical simulation. Conclusively, the radial and hoop stress distribution along the barrel radius is significantly declining as predicted in theoretical analysis and depicted in Fig. 4.

The equivalent stress distribution of analytical and simulated results along the radial direction is represented in Figure 5. The equivalent stress (997 MPa) calculated from Mises-Hencky's theory is nearly equal at the inner surface of the cannon barrel to that of simulation (1012 MPa) with an acceptable difference of less than 2 %. The slight increase in simulation results is ascribed to the effect of complex stress states when compared to that of theoretical analysis leading to a gradual increase along the wall thickness of the barrel.

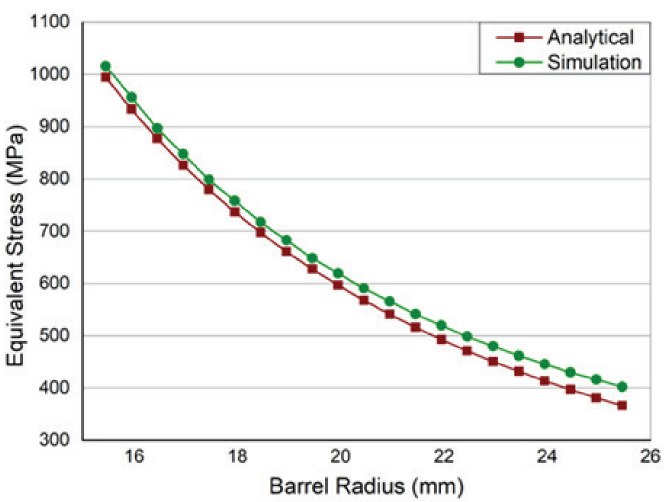

Figure 5. Equivalent stress distribution of barrel based on Mises-Hencky theory.

5. RESEARCH METHOD

In the combustion process, for instance, the generation of temperature inside the engine is high due to the compression of combustion fuel and ignition. Similarly, high temperature is generated at the combustion of propellant in firearms. This is attributed to the heat flux at the barrel's bore depending on the velocity, propellant gas density, and the bore temperature and the thermal characteristics of the gun metal. This ignition induces the maximum temperature and pressure when in synergistic effect with mechanical load elevates the kinetic energy of the projectile and directs it along the bore towards the muzzle segment[18]. Accordingly, thermal conduction in the direction of the axis is presumed to be trivial when measured up against to that of conduction along the radial direction. Also, the heat generated during the sliding between the shells's driving band and the bore area was also neglected. During firing, a maximum temperature and pressure is attained due to the ignition of propellant where the thermal energy is preliminarily intense in the chamber segment. The peak pressure gases expands and cools as the projectile progresses along the barrel, the induced thermal energy is dissipated through convective and radiative heat transfer leading to a decrease in temperature along the barrel length.

The cooling is improved due to the air stream around the barrel specifically in semi-automatic and automatic cannons with prompt firing through convective heat transfer whereas the emissivity and surface temperature of barrels influences the effectiveness of radiative heat transfer. Therefore, the radiative heat loss rate decreases with the decreasing barrel temperature. However, the barrel surface temperature gradually increases with a number of firing rounds and the convective heat transfer coefficient is maximum inside then the surface temperature of the barrel is maximum[9,19-20]. According to Thornhil Eqn. as represented in Eqn. (7), the total input to gun at one second of firing calculated and the heat generated in the chamber by burning the propellant is calculated using Eqn. 8. The kinetic energy of projectile and gases are given in Eqn. 9 and Eqn. 10, respectively. The utilized energy is subtracted from the total heat input to the gun and it is known as unaccounted power. The heat energy lost, strain energy, and the energy to overcome resistance are evaluated using the Eqn. 11, Eqn. 12 and Eqn. 13. The gas temperature and barrel inner, and outer surface temperatures are calculated using Eqn. 14 and Eqn. 15, respectively.

Total heat input to gun barrel per unit area per round,

$$H_{\infty} = \frac{2400\times \left(T_f - 1.8T_i\right)\times\sqrt{d}}{\left[1.8+\left(616\times d^{2.22}/m_p^{0.86}\right)\right]} \tag{7}$$

At elevated temperatures, the thermal properties of the gun barrel are assumed to be constant and therefore, the heat generated in the chamber by burning the propellant (E_p) can be calculated using Eqn. (8)

$$E_P = n\times m_p\times\left(c.v\right) \tag{8}$$

Kinetic energy of the projectile,

$$E_{proj} = \frac{m_s\times\left[1+\ k\times a^{2}\right]\times n\times V_m^2}{2} \tag{9}$$

Kinetic energy of the gases,

$$E_{gas} = \frac{m_p\times n\times V_m^2}{6} \tag{10}$$

Heat energy lost from gun,

$$E_h = \frac{b_2\times\left[m_s+\ m_p/3\ \right]\times n\times V_m^2}{2} \tag{11}$$

Strain energy of gun,

$$E_s = 0.005\times E_p \tag{12}$$

Energy to overcome resistance,

$$E_{res} = \frac{0.04\times m_s\times n\times V_m^2}{2} \tag{13}$$

Heat energy due to unaccounted power

$$= n \times m_p \times C_p \times \ T_g - T_i) \quad (14)$$

Temperature of bore in barrel after 1st round of firing (T_1),

$$\frac{(T_1 - T_i) \times \sqrt{\pi \times \kappa \times \rho \times c \times t_o}}{H_b} = 2 \times \sqrt{u \times e^{-u} \times \left(1 + (u/3) + (u^2/10)\right)} \quad (15)$$

Total heat input to gun barrel including revolving chamber,

$$H = H_\infty \times A \quad (16)$$

Heat input per unit area in barrel,

$$H_b = \frac{H}{A_b} \quad (17)$$

Merely, the total heat input per round (H_∞) is around 342 kJ/m^2 and time constant (t_o) is 8.4×10^{-4} s. The temperature of the combusted gases in the barrel chamber is 1340°C and the temperature of the bore in the barrel for 1s of firing is approximately 560°C. The heat flux elevated swiftly to the peak value when the shell is fired from the barrel, and then declines gradually[21-23]. Hence, the heat transfer was simplified by considering the heat flux as an exponentially degrading parameter based on which the relation between peaks bore temperature and heat transfer per firing round is established in Eqn. 17[24-26].

5.1 Numerical Simulation of Thermal Analysis

The numerical simulation of 2D axis-symmetry thermal analysis was carried out by dividing the barrel into 30 segments with 45,600 elements and 46,421 nodes for up to 30 rounds firing (t = 0 to 2.324 s). The inner ballistic time for the barrel is around 6 ms and the barrel is considered to be a gatling gun of 6 barrels. The schematic representation of the simulated inner surface temperature of the barrel for t = 0.965 s and t = 2.324 s of firing is shown in Figure 6. The time segment has been chosen where maximum temperature was observed around 13 and 30 rounds of firing. The maximum temperature of ~1378°C and ~1254 °C at the chamber segment and a minimum temperature of 23.1 °C and 22.1 °C at the muzzle end are observed after 30 rounds (t = 2.324 s) and 13 rounds (t =0.965 s) of firing, respectively. Figure 7 represents the temperature profile of the barrel during 30 rounds of firing (t = 0 to 2.324 s).

The governing Eqn. for thermal analysis are:

Gas velocity and gas density Eqn. are given in Eqn. 18 and 19, where, 'x' denotes barrel length and 'y_1' denotes velocity of gas and 'y_2' denotes gas density:

$$y_1 = 0.0000001305x^5 - 0.0000536494x^4 + 0.0085063593x^3 - 0.6777771854x^2 + 31.4978374620x + 14.6856641959 \quad (18)$$

$$y_2 = -0.071201548x^4 + 1.8579758354x^3 - 19.5579164256x^2 + 117.9804301177x + 25.0880421532 \quad (19)$$

The heat transfer coefficient is calculated using pipe flow Eqn. (Nusselt number) as in Eqn. 20.

$$Nu = 0.023 \times \mathrm{Re}^{0.8} \times \mathrm{Pr}^{0.4} \quad (20)$$

Reynolds number,

$$\mathrm{Re} = \frac{D V \rho_g}{\mu_g} \quad (21)$$

Prandtl number,

$$\mathrm{Pr} = \frac{\mu_g C_p}{\kappa_g} \quad (22)$$

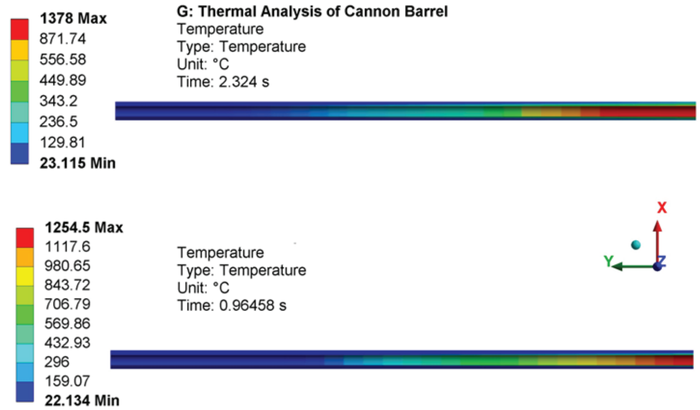

Figure 6. Internal surface image of cannon barrel during firing at t = 0.965 s and t = 2.324 s.

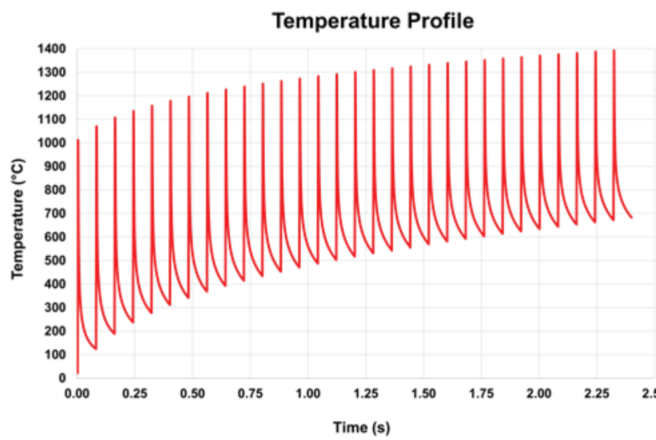

Figure 7. Temperature profile of the barrel during 30 rounds of firing (t = 0 to 2.324 s).

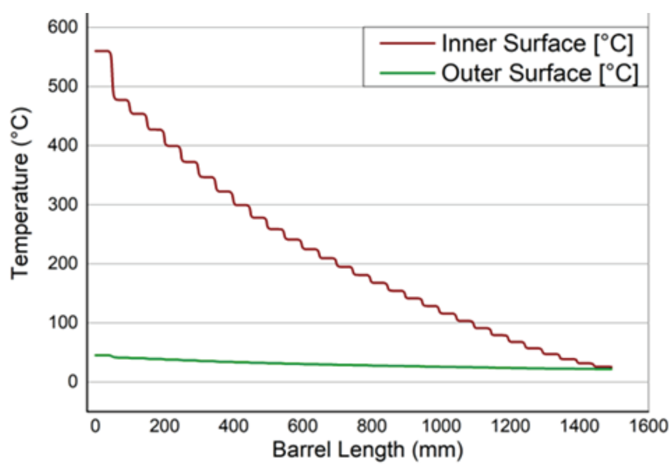

Figure 8. Simulation results on retained temperature along the barrel length at t = 1 s.

The temperature variation on the inner and outer surface of the barrel along the length at t = 1 s is shown in Fig. 8. The maximum temperature of the inner and outer surface is 558°C and 49 °C at the chamber segment, respectively. The minimum temperature of the inner and outer surface at the muzzle segment is almost equal to the atmospheric temperature. The theoretical analysis of the same has been carried out at t = 1 s, using the Eqn. 15 and the same has been discussed earlier. Thus, the simulation results are validated with theoretical analysis.

6. CONCLUSION

In the weapon system, the barrel is an important element that plays a significant role of directing the projectile through a narrow and long cylindrical area. In general, the barrel can be presumed as a pipe usually classified into three distinct zones including breech face - combustion chamber, the bore portion, and the muzzle section which is operates in variable temperature and pressure. This work theoretically evaluates the design parameters of cannon barrel developed using specialized indigenous DEF-STAN 10-13/2 grade steel subjected to 1) Complex mechanical stress states viz. radial (~400 MPa) and hoop stress (~830 MPa) at maximum design pressure and their respective factor of safety (~1.5), and thickness ratio (~1.65) for design and 2) Temperature variation along the length of the barrel (maximum 560°C) due to combustion of propellant using an igniter.

These evaluations are validated using a numerical simulation carried out in transient thermal analysis (~558 ± 2 °C) and structural analysis (σ_r ~ 398 MPa and σ_h ~ 758 MPa) of ANSYS FEA software modelled using Solidworks CAD Professional. It can be concluded that the analysis carried out from theoretical calculations are in well accordance with numerical simulations regarding the aforementioned mechanical and thermal characteristics with acceptable differences between them.

REFERENCES

1. Odintsov VA, Selivanov VV. Behavior of a rigidly plastic cylindrical shell exposed to internal pressure. Journal of Applied Mechanics and Technical Physics. 1975 May;16(3):457-60.
2. Xu H, Chen S. An analysis of an autofrettaged cylinder considering strain-hardening effect, Bauschinger effect and temperature dependence of material properties; In Volume: 1: Part 1. Analysis for open-ended cylinder; In Design & Analysis. Beijing, China; 1989 Jan 1. pp. 423-430. Available from: https://www.sciencedirect.com/science/article/abs/pii/B9781483284309500447
3. Babaei H, Malakzadeh M, Asgari H. Stress analysis of gun barrel subjected to dynamic pressure. International Journal of Mechanical Engineering and Applications. 2015 Aug;3(4):71-80.
4. Li ML, Fu MF. Limit analysis of viscoplastic thick-walled cylinder and spherical shell under internal pressure using a strain gradient plasticity theory. Applied Mathematics and Mechanics. 2008 Dec;29(12):1553-9.
5. Chevalier O, Langlet A, Fouché-Sanseigne L, Guilmard Y. Assessment of the lifetime of gun barrels under high-speed moving loads. Journal of Pressure Vessel Technology. 2015 Feb 1;137(1):015001.
6. Boukera AW, Kari AV, Jerković DD, Hristov NP. The influence of the internal ballistic pressure on the rifled barrel stress response. Scientific Technical Review. 2020;70(2):41-6.
7. Ahmad S, Kumar V. Structural integrity analysis of a battle tank gun barrel during service. Defence Science Journal. 2015 Jan 1;65(1):83-9.
8. Bhetiwal A, Kashikar S, Markale H, Gade SV. Effect of Yield Criterion on Stress Distribution and Maximum Safe Pressure for an Autofrettaged Gun Barrel. Defence Science Journal. 2017 Sep 1;67(5).
9. Susantez Ç, Caldeira AB. Heat Transfer Modelling and Simulation of a 120 mm Smoothbore Gun Barrel During Interior Ballistics. Defence Science Journal. 2022 Jan 1;72(1).
10. Longmiao C, Linfang Q, Yadong X. Numerical simulation of transient thermal response of composite material barrel during gun firing. In: 2008 Asia Simulation Conference-7th International Conference on System Simulation and Scientific Computing. Beijing, China. 2008 Oct 10, 633-637. Available from: https://ieeexplore.ieee.org/abstract/document/4675437
11. Akcay M, Yükselen MA. Unsteady thermal studies of gun barrels during the interior ballistic cycle with non-homogenous gun barrel material thermal characteristics. J. Therm. Sci. Technol. 2014 Jan 1;34(2):75-81.
12. Gu ZC, Lu HT, Wang S, Yan WM, Xu C. Numerical simulation of 3D barrel system based on thermal-structural coupling under continuous firing. In Volume: 1507, No. 8. Nanjing, China: Journal of Physics: Conference Series 2020 Mar 1; p. 082052). Available from: https://iopscience.iop.org/article/10.1088/1742-6596/1507/8/082052/meta
13. Dubey A, Sharma PK. Thermal Study of 155 mm Gun Barrel: A Review. Defence Science Journal. 2022 Mar 1;72(2).
14. Şentürk A, Işık H, Evci C. Thermo-mechanically coupled thermal and stress analysis of interior ballistics problem. International Journal of Thermal Sciences. 2016 Jun 1;104:39-53.
15. Uyanık MS, Soydan AM, Yılmaz A, Ata A. Design, analysis, manufacturing, and testing of a composite gun barrel. Polymer Composites. 2024 Sep 10;45(13):11804-15.
16. Segall AE, Carter R. Finite-Element Modeling of the Thermal/Structural Response of a Rifled Silicon-Nitride Barrel Subjected to Thermal and Pressure Transients. In Volume: 47543. Vancouver, BC, Canada; ASME Pressure Vessels and Piping Conference 2006 July 23; 847-856. Available from: https://asmedigitalcollection.asme.org/PVP/proceedings-abstract/PVP2006-ICPVT-11/847/364199
17. Hearn EJ. Mechanics of Materials 2: The mechanics of elastic and plastic deformation of solids and structural materials. Elsevier; 1997.
18. Deng S, Sun HK, Chiu CJ, Chen KC. Transient finite element for in-bore analysis of 9 mm pistols. Applied Mathematical Modelling. 2014 May 1;38(9-10):2673-88.
19. Loiola BR, Susantez Ç, Caldeira AB. Numerical modelling

of heat transfer and simulation of a 5.56 mm rifle barrel. In: Volume 2478, No. 11: Journal of Physics: Conference Series 2023 Jun 1; p. 112030. Available from: https://iopscience.iop.org/article/10.1088/1742-6596/2478/11/112030/meta

20. Gadalla M, Jasim M, Ahmad O. Heat transfer characteristics of various gun barrels under different operating conditions. In: Volume 59452: ASME International Mechanical Engineering Congress and Exposition; Salt Lake City, Utah, USA; 2019 Nov 11; p. V008T09A081; American Society of Mechanical Engineers. Available from: https://asmedigitalcollection.asme.org/IMECE/proceedings-abstract/IMECE2019/59452/1073451
21. Chen TC, Liu CC, Jang HY, Tuan PC. Inverse estimation of heat flux and temperature in multi-layer gun barrel. International Journal of Heat And Mass Transfer. 2007 Jun 1;50(11-12):2060-8.
22. Abaci WB, Hristov N, Ahmed NZ, Jerkovic D, Drakulic M. Determination of the gun barrel walls temperature distribution and its experimental validation during multiple-shots firing process. International Journal of Thermal Sciences. 2022 Sep 1;179:107667.
23. Chen S, Wang X, Shi Y, Xu C. Transient heat transfer study of small-caliber barrel in continuous fire. International Journal of Thermal Sciences. 2024 Feb 1;196:108737.
24. Li S, Wang L, Xu F, Yang G. Numerical simulations for artillery barrel temperature variation considering mechanical friction heat under continuous shots. International Communications in Heat and Mass Transfer. 2023 Mar 1;142:106663.
25. Júnior MT, Zilio G, Mortean MV, De Paiva KV, Oliveira JL. Experimental and numerical analysis of transient thermal stresses on thick-walled cylinder. International Journal of Pressure Vessels and Piping. 2023 Apr 1;202:104884.
26. Chen S, Li Y, Fu J, Chen L, Qian L. Reconstruction of transient convective heat transfer coefficients in heat transfer of gun barrels with variable coefficients. Case Studies in Thermal Engineering. 2023 Oct 1;50:103467.

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In the present work, he validated the concepts of numerical investigation and formatted the manuscript.