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Computer aided design and analysis of a tunable muzzle brake

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ABSTRACT

This research work deals with the design of a tunable muzzle brake [10] for a rifle chambered in 5.56 × 45 NATO ammunition. It proposes to solve the problem of handling differences from shooter to shooter by incorporating the feature of tunability. Beside this, it also solves the problem of requirement of optimum recoil in short recoil weapons. This innovation gives this design an edge over its already existing counterparts in the market. The product is designed using the internal ballistics calculations and the investigations been performed using solidworks flow simulation tool and ANSYS static structural to check the parameters like velocity distribution, pressure growth, and muzzle brake force along the series of ports and comparison of the so found results with those devised by the authors of the documents mentioned in references. This assures the market adaptability of the product for satisfactory performance, when brought among its already existing counterpart, though with a slight edge over them due to tunability. The results so found shall be concluded satisfactory regarding the performance of muzzle brake.

1. Introduction

A muzzle brake is a device that is attached to, or is integral with, the muzzle of a gun. Usually the brake has a series of baffles either perpendicular or nearly perpendicular to the gun tube axis. The brake is generally closed on the bottom to prevent escaping gases from endangering or annoying the gun crew. To maintain symmetrical peripheral loading and therefore balance, the top also is closed, leaving the sides open for the gases to escape after impinging on the baffles. Some standard configurations, adhering to either theoretical or empirical practice, have evolved through years of application.

Here, the inspiration of the proposed design (Fig. 1) has been taken from the Brockman's convertible muzzle brake [8] Coburn's adjustable muzzle brake [9] and which had symmetrically situated peripheral ports but only two positions, on and off. Therefore, attempts have been made to ameliorate the design by incorporating the feature of tunability [10] with enhancement in its degree or extent of variability. Although the design procedure includes consideration of so many factors, assumptions and calculations [2], but nevertheless, there always remain some traditional defects in the design of the muzzle brake. Thus, to some extent the approach remains limited and subjective. Hence, in order to verify the performance parameters through accurate algorithms, the flow simulation analysis becomes a primary necessity of the design.

For predicting the port size over the periphery, some constraints have been put on parameters and then the calculations have been done using internal ballistics equations [2]. The constraints, for instance deflecting angle, have been defined by considering geometrical and ergonomic factors. It may be noted here that the main purpose of the CFD analysis remains only to compare the maximum and minimum values of pressure decay, muzzle brake force and velocity distribution with those plotted in reference [1]. Further, some inferences regarding the formation of shock waves have been drawn from those contours.

2. Methodology and analysis

2.1. The mechanics of muzzle gas flow [2]

The quantitative analysis of the flow of propellant gases at the muzzle begins with the energy equation of internal ballistics:

$$W_c\,(RT\text{-}RT_0)/\,(\gamma\text{-}1) = v_0^2\{W_p(1+\delta)/2 + W_c/6\} \quad (1)$$

Where:

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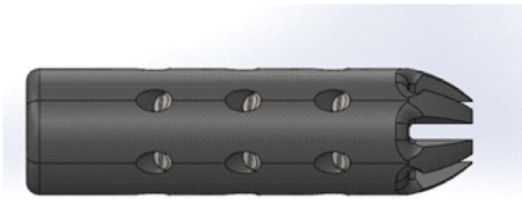

Fig. 1. Final design of tunable muzzle brake.

W_c = weight of propellant (lbs)
W_p = weight of projectile (lbs)
R = gas constant
T = temperature of propellant gas having done no external work (^{o} R)
T_0 = temperature of gas at shot ejection (^{o} R)
v_0 = muzzle velocity
γ = ratio of specific heats
δ = fractional heat loss to gun tube as function of shot energy

Weight *W* is a force, a defined term, and is expressed in pounds (lb). Mass is a computed term $M = W/g$, lb-sec2/ft (slugs) where g is the acceleration of gravity. Other dimensions may be used provided that proper conversion of factors are used Hence, substituting $\gamma = 1.26$ and $\delta = 1/7$, the equation simplifies to:-

$$RT_0 = RT - 0.26v_0^2\{(4W_p/7W_c) + 1/6\} \tag{2}$$

Appropriate values of *RT*, a characteristic of the propellant, are available in thermo chemical tables. In some ballistic operations, *RT* is called specific impetus the dimensions of which are ft-lb/lb; and $RT/(\gamma - 1)$, of the same dimensions, is the potential of the propellant. Numerically, $RT/(\gamma - 1)$ is about 6×10^6 ft-lb/lb.

2.2. Gas deflection and nozzle flow [2]

The passages in a muzzle brake are treated by the one-dimensional theory of nozzles, without allowance for friction at the walls. Furthermore, the gas is assumed to fill the nozzle completely; true only if the nozzle is so designed that there is no break away from the walls. To prevent this, the semi-angle of a conical nozzle should never exceed 30°, a rather large angle. Smaller angles result in larger nozzles, thereby increasing muzzle brake weight. If more weight can be tolerated, a smaller semi-angle of about 20° is preferred. Semi-angles below 15° offer no appreciable advantage over their immediate larger counterparts.

Here (Fig. 2),

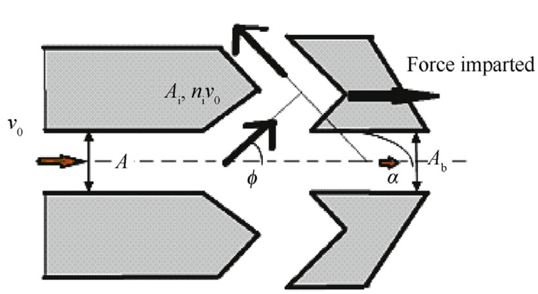

Fig. 2. Schematic diagram of muzzle brake.

A = bore area
A_b = area of projectile passage
A_e = exit area of baffle passage
A_i = inner area of baffle passage
n_e = exit speed-up factor
n_i = inner speed-up factor
v_0 = muzzle velocity
α baffle deflecting angle
ϕ semi-angle of nozzle
W_c = weight of propellant gases

Because of the projectile passage, not all of the gas will go through the baffle passage; a portion will continue straight ahead, the amount depending on the ratio of exit areas. The weight of the quantity of gas diverted through the baffles is expressed as:

$$W_i = W_c A_i / (A_i + A_b) = \Delta_i W_c \tag{3}$$

Similarly, weight of gas passing through projectile passage:-

$$W_b = W_c A_b / (A_i + A_b) = \Delta_b W_c \tag{4}$$

Therefore, thrust on the baffles: $F_b = \Delta_i\ m\ (v_i - v_e \cos\alpha)$, Where m = mass of gas impinging on the baffle. it can be written as:

$$F_b = \Delta_i m v_0 (n_i - n_e \cos\alpha) = \lambda m v_0 \tag{5}$$

Where λ = speed up factor and is dependent on Δ_i and angle of deflection.

For minimum forward thrust generated, assuming n_i and n_e be equal, and equal to *1* and $\alpha = 135^0$; we have, $\lambda = \{A_i/(A_i + A_b)\}(1-\cos 135°)$

$$\Delta_i = A_i/(A_i + A_b) = \lambda/1.707 = 0.586\ \lambda \tag{6}$$

Here, the value of deflecting angle has been randomly constrained to 135° because the design procedure intends to calculate the port size for other constraining parameters having fixed values.

2.3. Thrust calculations

Hugoniot derived the expression for rate of change of muzzle gas momentum [2].

At $t = 0$, that is when the bullet is about to leave muzzle, the rate of change of momentum *M'* is maximum and is given by the following expression:

$$M' = 12RT_0W_c\ \gamma\{1+(W_c/6W_p)\}\{2/(1+\gamma)\}^{(\gamma/\gamma--1)} \tag{7}$$

Where,

L_b = length of barrel from the breech end (inch)
g = gravitational acceleration (32.2 ft/s^2)

Including the effects of vortices and turbulence an extremely small amount of gas can be used to get favourable work, this expression is decreased by a factor of C_k which can be in order of 10^{-2}.

Therefore,

$$M' = 12C_k\ RT_0\ W_c\ \gamma\{1+(W_c/6W_p)\}\{2/(1+\gamma)\}^{(\gamma/\gamma-1)} \tag{8}$$

Now this rate of change of momentum must be equal to the thrust generated by the brake baffles. Hence, equating equations (5) and (8) we get,

$$\lambda = \frac{12C_k RT_0 W_c \gamma\{1+(W_c/6W_p)\}\{2/(1+\gamma)\}^{(\gamma/\gamma-1)}}{gL_b m v_0} \tag{9}$$

With the help of equations (6) and (9), we can obtain the value of Δ_i and hence the values of cross section area of ports.

Here it is to be noted that to simplify the calculation procedure, it has been assumed that whole of the mass of gases flows through the series of ports in one go (instead of intermittent flow through the no. of series). It is assumed due to the fact that gases rush out at very high velocities and hence there is practically negligible time difference in the gas flow through first series of baffles and the flow through the second series. Hence, the expressions mentioned in this section form the foundation of the design procedure of the muzzle brake.

2.4. Engineering data and assumptions

It is to be mentioned here that the muzzle brakes are designed for a particular type of rifle that fires a particular type of ammunition powered by a specific kind of propellant.

Here it was aimed to design a tunable muzzle brake for a rifle that fires most popular round throughout the world, *i.e.* the 5.56 × 45 NATO, for which, the required data is as follows:

RT value of IMR propellant = 1.54×10^6 (ft-lbs/lbs) [2].

W_c = 2.98 gm = 0.0066 lbs [4,5].

W_p = 4 gm (62 grain) = 0.0089 lbs [4,5].

L_b = 16.

v_0 = 2800 ft/s, which in SI is equal to 853.44 m/s [6,7].

2.5. Calculation of peripheral port diameter

Given that,

$m = W_i/g = \Delta_i \cdot W_c/g$, $A_b = \pi/4\,(5.6\text{ mm})^2$

On putting value of λ from equation (9) into (6), we get the value of A_i (for 18 ports). Thus,

$A_i = 18 \times \pi d^2/4$.

Assuming the value of C_k be around 20% of the total gas potential used to provide braking effect, the values of λ and d come to be 1.54 and 4 mm (approx).

2.6. Design specifications of muzzle brake

Type: - closed, multi-baffled type brake.

- Angle of deflection = 135°.
- Port size = 4 mm in diameter
- No. of ports = 6 × 3 (6 rows having 3 each)
- Length total = 70 mm
- Outer diameter = 20 mm
- Inner half cone angle = 30 deg.
- Threading for muzzle end = M12 × 1
- Threading for set screws = M4 × 0.5

2.7. Boundary conditions data for flow simulation

Fluid used: Although the products of the burning propellant comprise of many gases for instance, CO_2, H_2O, NO_X and some amount of CO; but the major part in constituted by CO_2 (almost 94%). Hence, for the CFD analysis, fluid used is CO_2 (real gas). This approach has been used, unlike using absolute characteristics of powder gas [3], to conduct a similar but simpler study in order to verify the results.

Pressure at inlet of brake/outlet of muzzle: From figures shown in Refs. [6,7], pressure values at the end of a 16 inch (barrel were taken as 7200 psi (50 MPa).

Temperature of propellant gas at inlet: Assuming that the propellant continues to burn even at the outlet of muzzle, the temperature was assumed to be slightly less than the burning temperature of IMR4475, *i.e.* 2000 K [7].

Volume flow rate at inlet: It is to be mentioned that due to changes in density, volume flow rate is given preference over the mass flow rate. Assuming continuous flow throughout the barrel, $Q = A_b.\ v_0 = 0.0222\text{ m}^3/\text{s}$.

Ambient conditions: The ambient conditions at the outlets of ports and the brake end were assumed to be atmospheric, *i.e.* pressure 10^5 Pa and temperature 300 K.

Strength testing for set screws: Maximum pressure acting at the bottom of the screw has been taken as 10^8 Pa, which is well more than the maximum pressure at the muzzle end of the barrel. Though it is significantly less than the maximum chamber pressure, being 3.6×10^8 Pa [4]. The body of the brake has been assumed as rigid support of structural steel as the chosen material.

3. Results

1. The simulation of a basic design (Fig. 3) expresses the pressure decrement along the length of the brake. It clearly shows the vigorous decrement in violent pressures (Pa) at first series of peripheral ports to the outlet of muzzle brake. The static pressure plot is shown in Fig. 4 while Fig. 5 is the comparison plot of static pressure (MPa) taken from Ref. [1]. It is to be clearly mentioned here that in context of Figs. 4 and 5, the independent parameters on X-axis, although being different from each other, the figures can nevertheless be used for comparing the peak values and the least values of pressures. ref [1] constitutes a transient CFD analysis to count for the time related variation of pressure, whereas the purpose to conduct this steady state CFD analysis was to check the maximum and minimum pressures, independent of time as a parameter.
2. The simulation (Fig. 6) expresses the velocity distribution of gases along the peripheral ports. The sudden increment in velocity at the outlet is a proof of the generation of shock waves. Hence, there's an abrupt change in mach no. across the length of flow.
3. The plot in Fig. 7 shows the average muzzle brake force generated. The Fig. 8 [1] shows the muzzle brake force distribution taken as reference for comparison. Again, the difference in independent parameters shown on X-axis in both the plots is due to different solver type. This work indeed utilised steady state CFD simulation to compare the minimum and maximum values and subsequent distribution of muzzle brake force with that generated by the transient analysis conducted by the authors of the mentioned reference work, which included time dependence as a parameter as well. Plots showing force (in KN) corresponding to each series of slats have been shown in Fig. 8; whereas Fig. 7 shows the mean value of force (in $N \times 10^{-3}$) generated by all the three series of the muzzle brake. Their purpose was to check the distribution of entities with respect to time (in milliseconds); whereas the purpose been served here as to just check the maximum generated muzzle brake force by the designed brake.
4. The factor of safety shown in Fig. 9 was found to be more than enough for M4 screws to be brought in use in this muzzle brake.

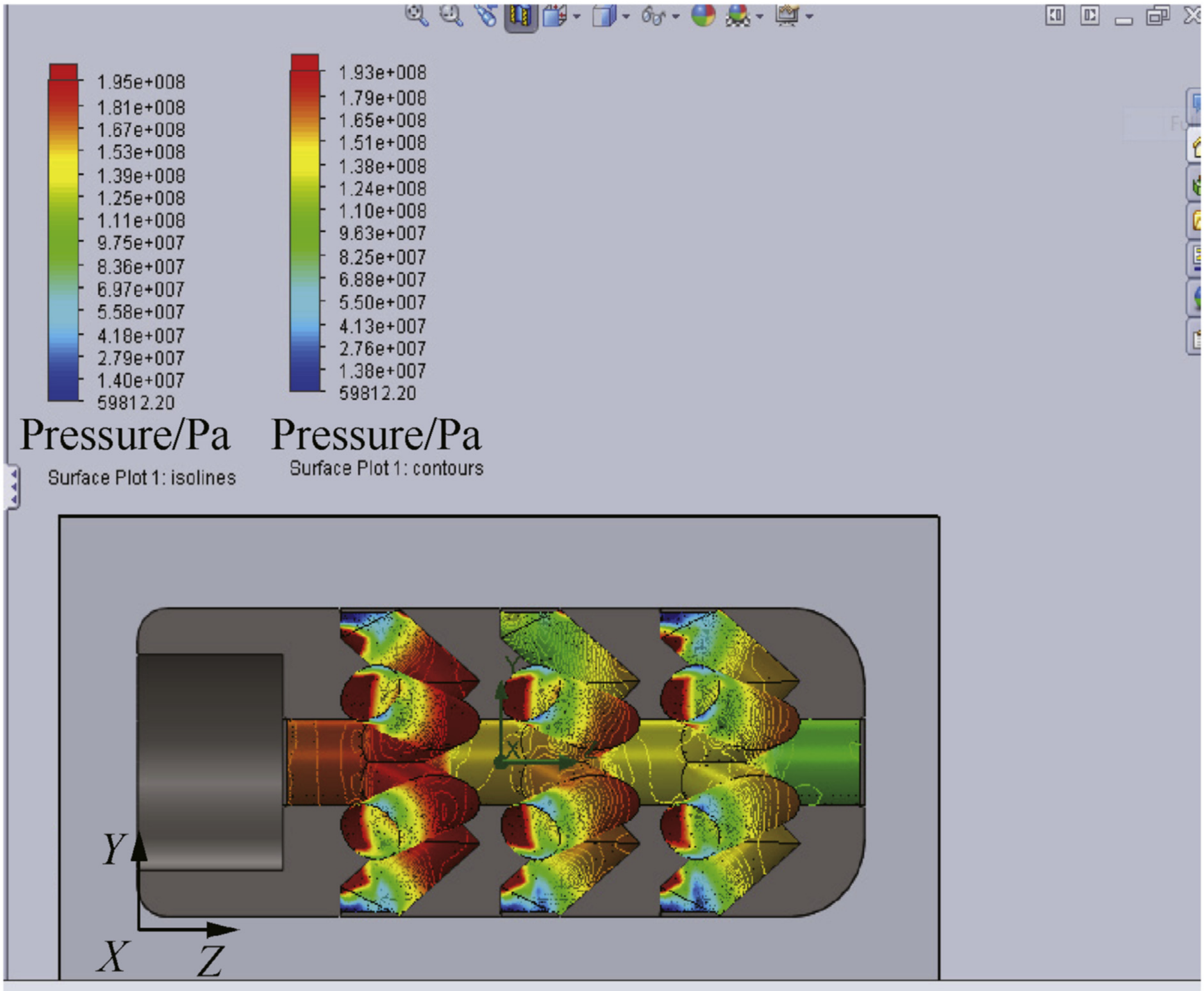

Fig. 3. Pressure decay along the length of the brake and across the peripheral ports.

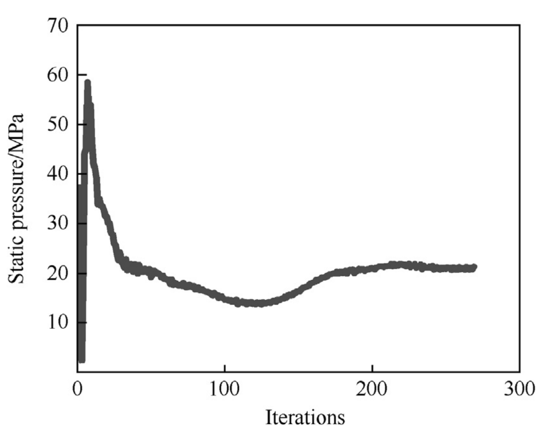

Fig. 4. Mean static pressure distribution of all the three series of ports along the length of the designed brake.

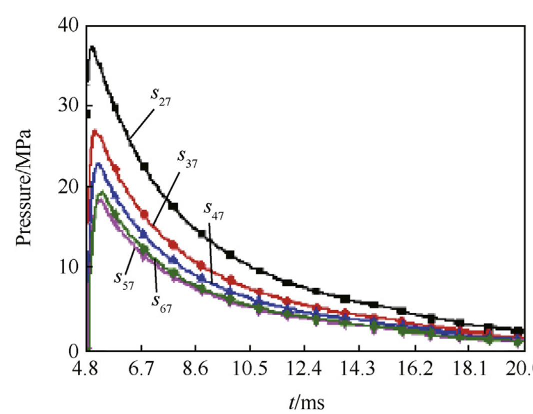

Fig. 5. Plot representing pressure decay corresponding to each series of slats in reference work [1].

4. Conclusion

1. The computed spectrums of pressure values and muzzle brake force values were found to be in good agreement with those shown in mentioned reference works. The different independent parameters on *X*-axis shown in Figs. 4 and 5 and Figs. 7 and 8 respectively, only exhibits the difference of a transient analysis been conducted in the referenced works. The purpose to check the maximum and minimum values of pressures and muzzle brake force computed by the solver (independent on time as a parameter) was thus fulfilled and the objectified results were found to be in good congruence with those of the

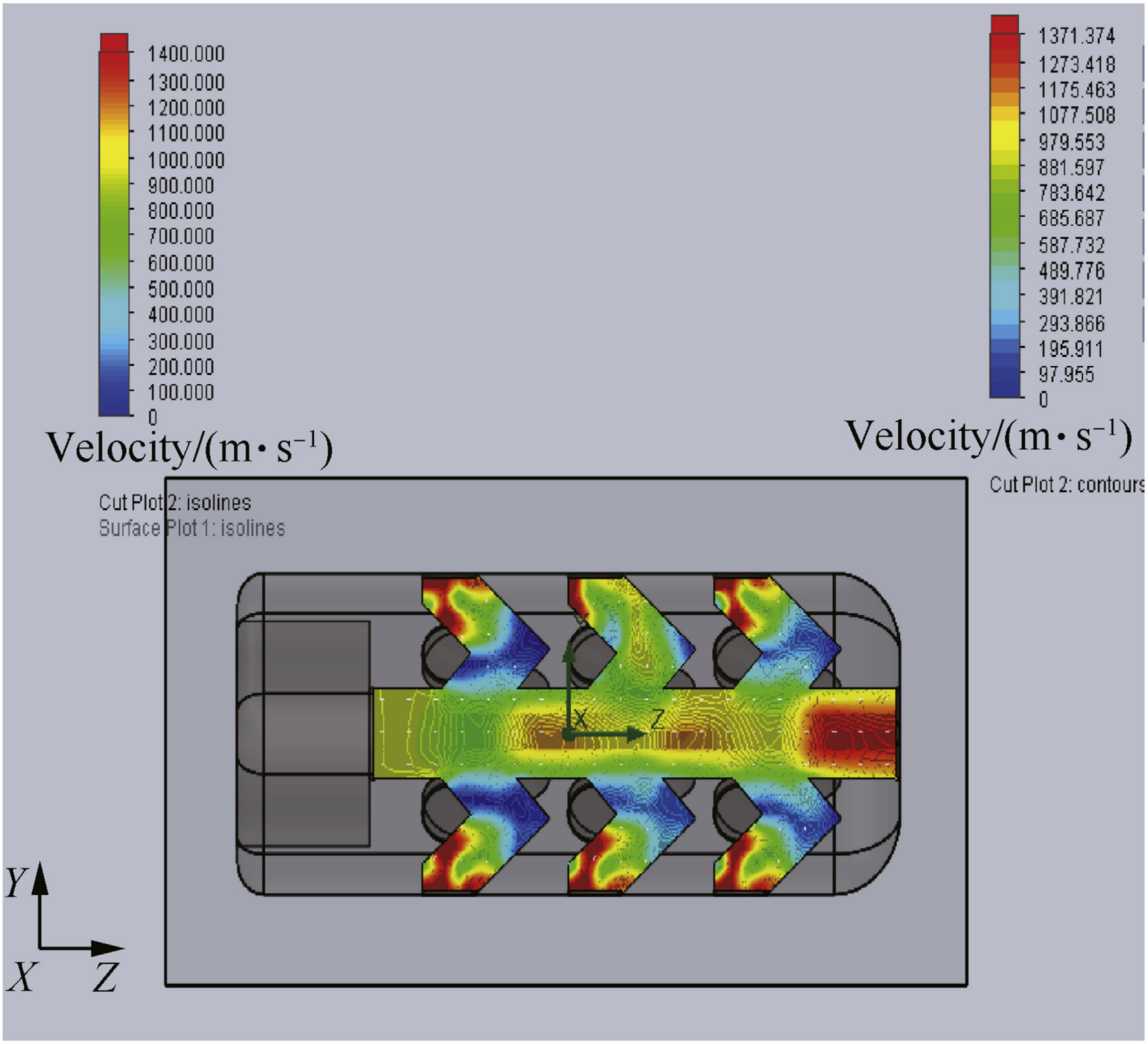

Fig. 6. Gas velocity distribution along the length of the muzzle brake.

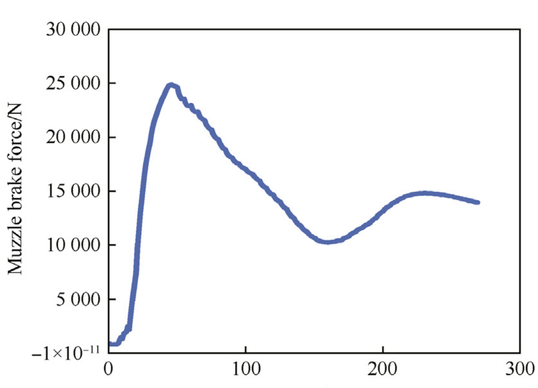

Fig. 7. Mean muzzle brake force of all the three series of ports. Peak value is 25 kN.

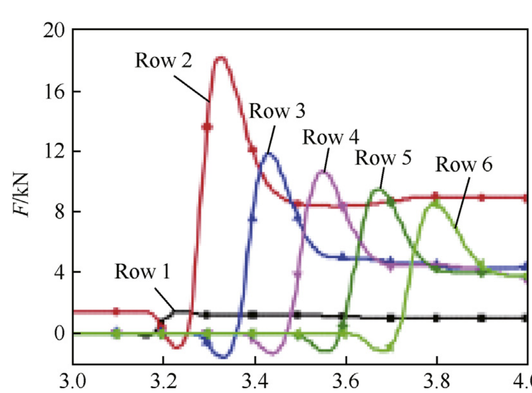

Fig. 8. Muzzle brake force distribution corresponding to each slat series. Peak value is 18 kN.

referenced works. Figs. 4 and 7 showed the mean values distribution of the respective dependent entities while Figs. 5 and 8 showed the specific time dependent distribution corresponding to each series of slats of the referenced muzzle brake design.

2. Since the performance been verified, it can be concluded that the extra feature of tunability (through combinations of open and closed peripheral ports, by unscrewing some of the set-screws) definitely gives it an edge over other existing designs.

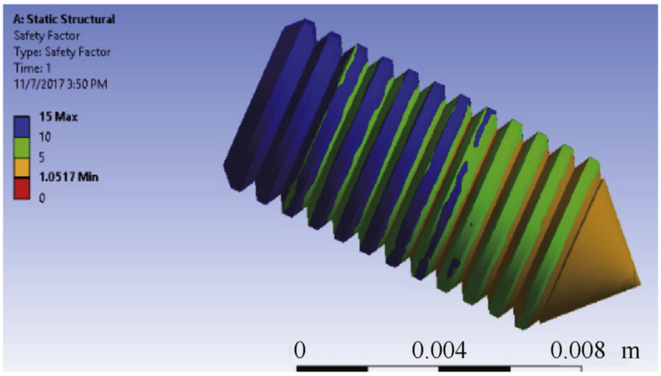

Fig. 9. Volumetric distribution of factor of safety for set screw subjected to muzzle blast pressures.

This feature not only intends to make the weapon much more operator friendly, but also can control fire rate in recoil operated weapons. In case of recoil weapons, this can work as a recoil "optimizer" as well. It means that in adverse environmental situations, for instance exceptionally cold climate or a dirty environment, where some extra recoil is required to make the weapon function reliably, this device can optimize it to a level such that the recoil generated would be enough to make it function without any failure, but wouldn't be excessive as to produce handling problems.

3. A much simpler design, with all the dimensions same as those in the detailed design, was used for conducting CFD flow simulation in order to ensure proper meshing, faster response from the system, and to facilitate the iterations in design for verifying the performance of the designed brake. Nonetheless, this study is hindered by a number of limitations. The chemical reactions between the propellant gases were not considered in the analysis. The stress test was not verified because of the limitation of experiment condition. The necessity of a time dependent analysis was not considered. In future works, the simulation results should be verified by stress tests, a time dependent transient analysis including thermal effects.

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