Research Article

Analysis and prediction of internal ballistic parameters of recoilless weapons

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Article History: Received: 5 April 2021; Accepted: 14 May 2021; Published online: 22 June 2021

Abstract: Internal ballistics examines the pressure from combustion gases. Internal ballistic analysis describes the amount of firing propellant, the amount of energy released to move the bullet, the pressure imparted to the interior of the bullet, the features of the barrel and its tolerance against pressure. The present paper uses a numerical method to predict internal ballistic parameters such as pressure, temperature, velocity and friction force along the weapon barrel. A grid was generated in the Gambit environment. Using the user-defined functions to apply the boundary conditions, the motion of the bullet inside the barrel is simulated in the FLUENT software environment, and its behavior is examined from the onset of motion due to combustion pressure until it is available. As the ultimate goal in internal ballistic analysis is range-proportional velocity, this paper describes the factors affecting the achievement of an optimal velocity. Also, the way a bullet travels down the barrel is shown using graphs and contours. The most important results include the upward and downward pressure followed by the temperature behind the bullet. Also, the maximum temperature was found to occur behind the bullet and its minimum in the bullet.

Keywords: Internal Ballistic, Recoilless weapons, Numerical methods, Internal ballistic parameters

1. Introduction

The term ballistics literary means a projectile. Internal ballistics of the bullet motion is affected by the initial force from combustion as well as various factors affecting this motion until the bullet is in the weapon barrel. Internal ballistic analysis can determine the amount of firing propellant, the amount of energy released to move the bullet, the pressure applied on the interior of the bullet, the features of the barrel and its tolerance against pressure. A background of internal ballistics suggests that most research has been carried out on bullet propellant and combustion laws. Therefore, an initial analysis of the bullet motion as affected by the initial energy from combustion can greatly contribute to the development of internal ballistics. Euler (1707-1783) was one of the first to conduct extensive research on ballistics. He analyzed the findings from experimental firing to obtain the drag applied to the cannonball [1]. In 1792, Rumford was one of the first to measure the gas pressure from an explosion of a projectile in the barrel. When the projectile propellant is ignited, it generates high-energy gases with a high temperature and pressure. This high pressure is applied to the bottom of the bullet and moves it forward inside the barrel [2]. Extensive research in the field of interior ballistics is currently underway [3-4]. Internal ballistics is of great importance due to the rapid processes and the difficulty of measurement in the barrel area. Internal ballistics researchers seek to adjust the parameters of the weapon and ammunition to meet the desired velocity in the orifice [5] in order that the weapon barrel is not damaged due to high pressure. To prevent high pressure from damaging the barrel of the weapon, researchers must calculate the pressure behind the bullet. They must also be able to predict variations of the velocity and acceleration of the bullet during ignition [6]. Using finite volume method via solving the equations governing internal ballistics, Rahimian and Talei obtained curves and compared them with their laboratory results, which was satisfactory [7]. In a behavioral study, Mehdi Nasrallah Zadeh et al. analyzed the projectile inside the barrel and demonstrated graphs of pressure, orifice velocity and maximum pressure on the projectile. In this research, the minimum shell thickness in a way the projectile structure would not fail was calculated [9]. In a numerical work, Cavalini used an unstable one-dimensional grid for prediction of an engine behavior to model combustion. He concluded that the peak pressure would immediately occur after the erosive burning and that the greatest pressure drop related to the last part of the burning [10]. In a numerical-analytical work, Martinez et al. described the fuel combustion in a projectile under variable conditions. In their research, one-dimensional numerical results were compared with the experimental data of a 155 mm launcher [11]. Hong Hu et al. used a numerical method to study the internal ballistics of rockets with solid fuel. Internal ballistic equations were calculated using the quadratic Runge–Kutta methods. They considered the main problem in practical combustion to be the erosive burning. They also maintained that the amount of spark propellant could have a significant impact on the pressure curve in the combustion chamber [12].

Internal ballistic equipment includes recoilless weapons that are open at both ends. In this equipment, from one end, the projectile ejects and from the other, the combustion gases emit. In this equipment, the forward momentum applying to the projectile equals the momentum released from the exhaust gases. In such a case, the weapon no longer moves backwards. The advantages of recoilless weapons include low weight, long life and simple structure; however, these weapons require higher propellant than other weapons. Because it is very costly and dangerous to conduct actual experiments in high-pressure internal ballistic analysis, we turn our focus to numerical methods. Combustion and its details are a complex phenomenon which is disregarded in this behavioral study. The present article somehow skips the ignition of the projectile propellant and its composition in the combustion chamber. Here, the motion of the bullet from combustion pressure until it is in the barrel is focused attention. Given that the end goal in ballistic analysis is velocity proportional to the range, this article deals with the factors affecting the optimal velocity; moreover, the bullet motion inside the weapon is also specified. Computer solution of a problem gives us complete details, yielding values of all relevant variables (such as velocity, pressure, temperature, concentration of chemical samples, and turbulence intensity). Unlike the unfavorable conditions that unfold during the test, the inaccessible positions in a computation are small and there is no current disturbance. Obviously, no laboratory study can be expected to measure the distribution of all variables across all fields. Therefore, even when a laboratory task is carried out, it would be much valuable to have a computer solution done at the same time to complete the laboratory information. A computer program does not have problems of very large or very small geometric dimensions, very low or very high temperatures, toxic or combustible substances, and following of very fast or very slow processes. In the present article, some simulations were performed for several different cases; this is while at the laboratory, we will not be able to examine all the cases found. Previous research on internal ballistic analysis focused on the motion inside the barrel, with most articles concentrating on combustion modeling. Most of the internal ballistics articles pertain to the motion inside the barrel of the weapon under certain cases while research in recoilless weapons is lacking. At present, there is no appropriate reference that deals with how the bullet travels down a recoilless weapon barrel. Therefore, in the present article, previous research in this field will be followed more comprehensively and with a different approach, and the work of others will be developed, in order to reach a tangible conclusion, because the findings are demonstrated in the form of diagrams and contours. The present article can contribute to making inferior ballistic equipment of recoilless weapons.

2- Geometry and modeling:

In this article, unorganized elements are used. An unorganized grid is best characterized by its good matching of complex boundaries and geometries, making the grid generation time in this method be much less than the organized method. However, disadvantages of an unorganized grid are the complexity of its information organization and the need for more memory and computing.

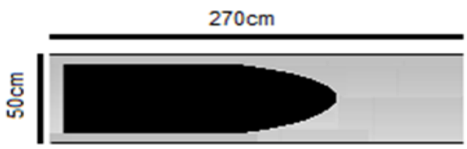

Figure 1. Projectile geometry, projectile barrel length: 270 cm, 50 cm in diameter

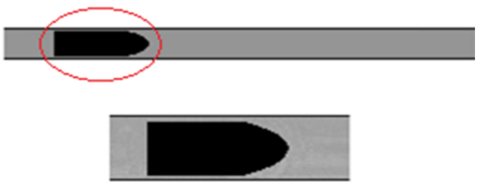

Figure 2. Computational range grid

2.1: Muzzle shape

In subsonic states, the drag on the projectile can be reduced by a suitable and smooth muzzle shape. Figure 3 illustrates the relationship between drag coefficient and velocity increase for three different muzzles in subsonic states [8].

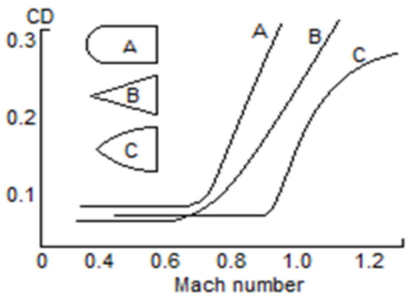

Figure 3. Rapid CD changes in the subsonic area for muzzle of different shapes [8]

Normally, the higher the muzzle, the less the drag applied. According to Figure 3, it is also clear that the drag to muzzle C is less. Therefore, in the present paper, muzzle C was used for the final analysis to yield a desirable conclusion.

3- Grid independence test

The grid with 29837 cells was selected as the final grid. The friction coefficient discrepancy between the grid with 29837 cells and the one with 53676 cells was calculated, the value of which was less than 5%. Therefore, the grid with 29837 cells was selected as it reduced the computational time and maintained adequate calculation accuracy.

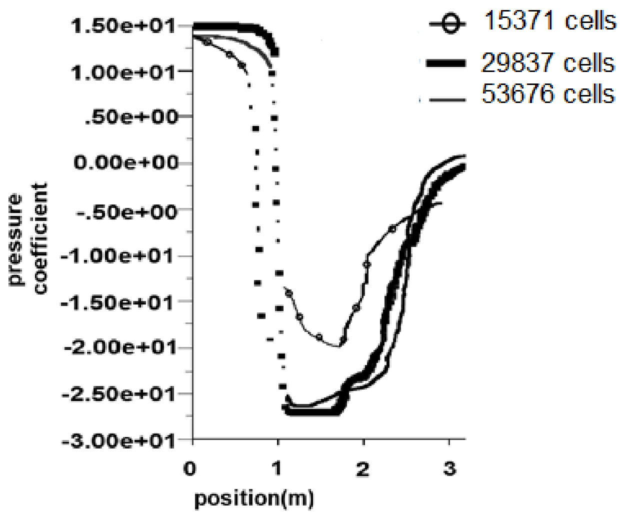

Figure 4. The discrepancy pf pressure coefficient between the grid with the number of 29837 cells and the one with 53676 cells

4: Result validation

This paper uses the motion of a bullet inside a barrel for results validation. The grid was examined on several elements and the most appropriate option was selected for the final analysis of this article. In order to ensure the validity of the calculations to use these results, the calculation findings must be matched with the practical and laboratory findings to be used if the error is insignificant. If laboratory results for comparison are lacking, the following methods should be taken to validate the results.

Previous experiments performed for similar projects

Comparison of analytical solutions of similar flows

Comparison with the results of authentic articles and books

We only validate the results for one or two functional states; however, they can also be used for various states. The results from position-velocity and friction force diagrams were validated according to " Military Ballistics: A Basic Manual Battlefield Weapons Systems & Technology" by C. L. Farrar [8]. Figures 5 and 6 illustrate the validation for the two states. Since two different states of the results were found to be consistent with credible sources, one would argue that all the states obtained were correct with a good approximation, because all graphs and contours were based on the same mesh and method.

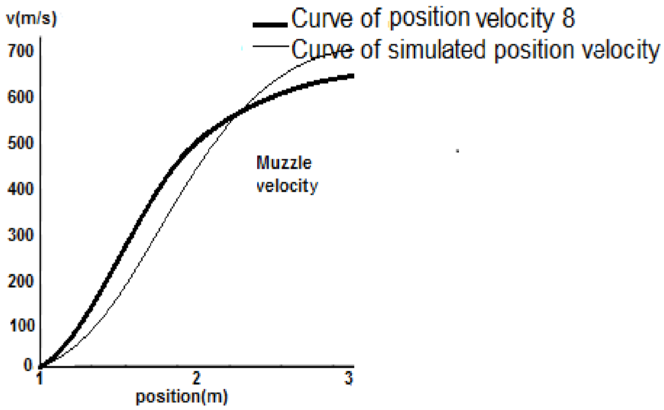

Figure 5. Validation of position velocity curves

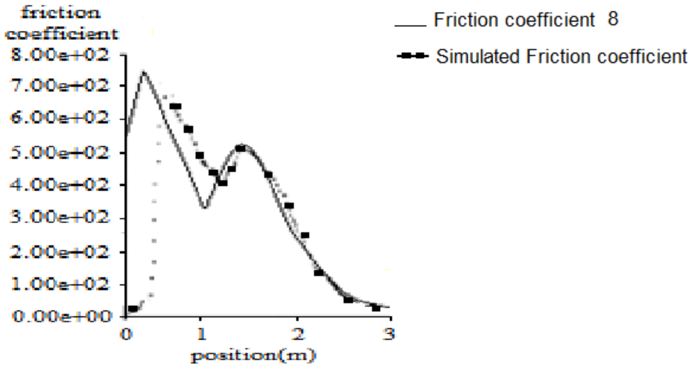

Figure 6. Validation of the friction coefficient curve

5- Results

There are many factors that affect the pressure inside the projectile barrel. The pressure behind the projectile is largely proportionate to the heat generated by the combustion chamber gases. This is seen from comparing Figures 7 and 8. When the bullet travels down the barrel at a high velocity, a pressure drop is noted along the barrel due to the friction between the combustion gases and the barrel. This pressure drop can also be due to the expanded gases inside the barrel. As shown in Figure 3, the pressure maximizes during the initial stages of combustion which is due to the rapid release of high-energy gases at the beginning of the barrel. Unlike the pressure velocity and consequently the temperature behind the bullet, it has both an upward and a downward trend.

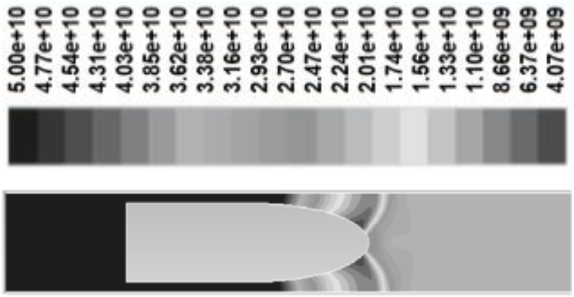

Figure 7. Static pressure distribution contour of the projectile

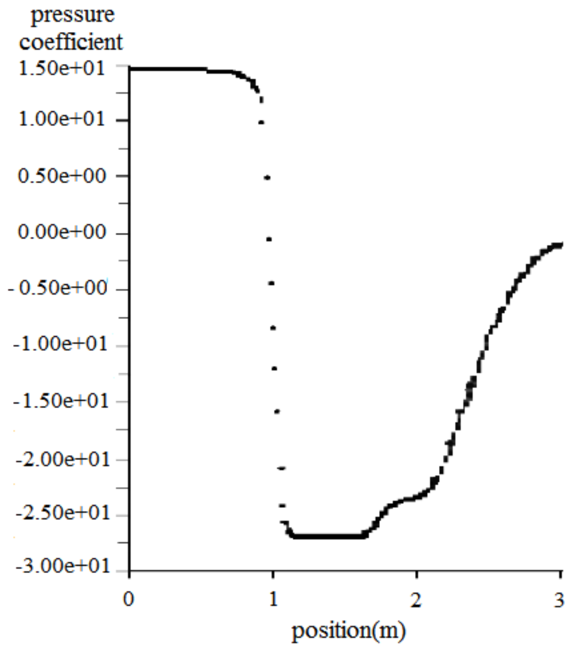

Figure 8. Pressure coefficient

Figure 8 illustrates the pressure coefficient curve based on bullet change of position. At the beginning of the chamber, the propellant is blocked by the bullet. As the energy from the pressure fuel is released and temperature rises sharply, a sudden rise in pressure in the combustion chamber follows as gas is generated at a constant volume.

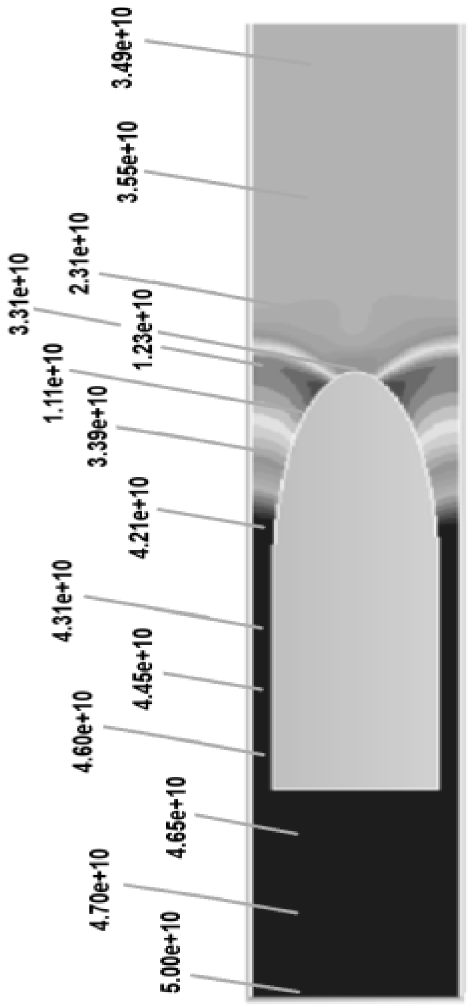

Figure 9. Static pressure distribution inside the barrel of the weapon by Pascals

When the projectile starts travelling, the space behind the projectile is small due to the low speed of the projectile (Figure 12), which cannot meet the rate of gas generated, causing pressure to rise by a large amount. At this moment, the bullet propels forwards. When the bullet propels forward at a high velocity, it leaves an increasing volume inside the barrel and behind the bullet, where this sudden change of pressure is followed by pressure coefficient. This propulsion is well defined in all diagrams within one meter of the motion. The increasing volume is then filled by high-pressure combustion gases. At this point, the propellant is still burning and high-energy gas is so generated that the velocity of the bullet cannot offset it by increasing the volume. The outcome will be a rising pressure. When the bullet reaches the end of the barrel, the pressure experiences a drop due to increased volume behind the bullet and the expanded gases inside the barrel, and when the bullet exits the barrel, the pressure and temperature decrease significantly. Exhaust gas pressure constitutes around 10 to 30% of the maximum pressure [10]. Pressure drop suggests a rate of gas production, and increased space behind the projectile increases the heat transfer, reducing the temperature and consequently the pressure. In analytical methods, the pressure of the bullet motion via increased burning rate has been compared with experimental results.

According to Figure 12 concerning the projectile velocity contour and comparing it with the static pressure contour (Figure 9), it is noted that pressure and velocity are inversely related along the barrel, and behind the bullet where we have the maximum pressure, we have the minimum velocity also. Unlike the pressure state, the velocity of the bullet does not oscillate and increases along the barrel as time passes, and this is true for every bullet inside the projectile barrel. Figure 10 illustrates the velocity position diagram, clearly indicating that the projectile velocity increases along the projectile barrel as time passes.

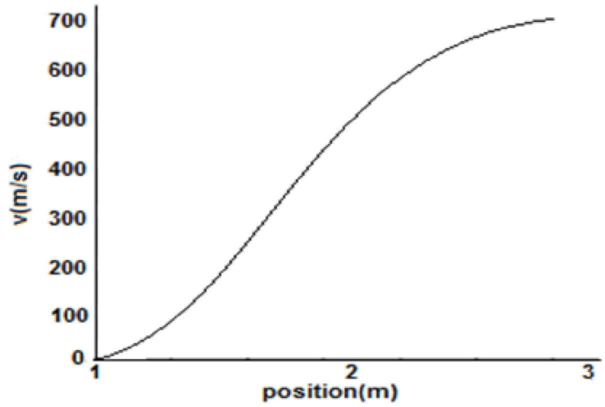

Figure 10. Velocity distribution over time inside the barrel of the weapon

Figure 12 clearly shows that the motion inside the barrel has a certain amount of velocity, which is due to the initial explosion and combustion, indicating the gas behind the bullet has not fully compacted. It is also clear that at the front edges, the bullet has a maximum velocity. The space in front of the bullet has a greater velocity than the back of the bullet as affected by the motion of the bullet.

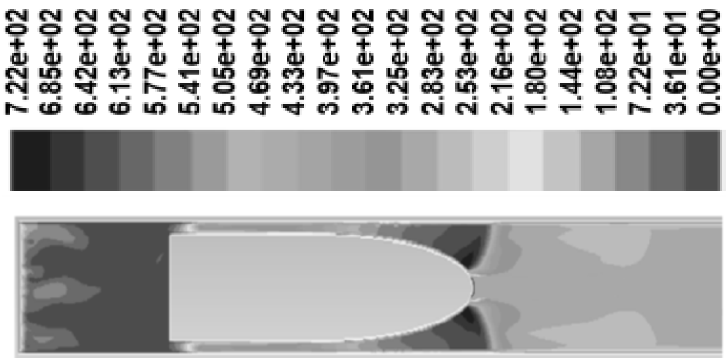

Figure 11. Projectile velocity contour

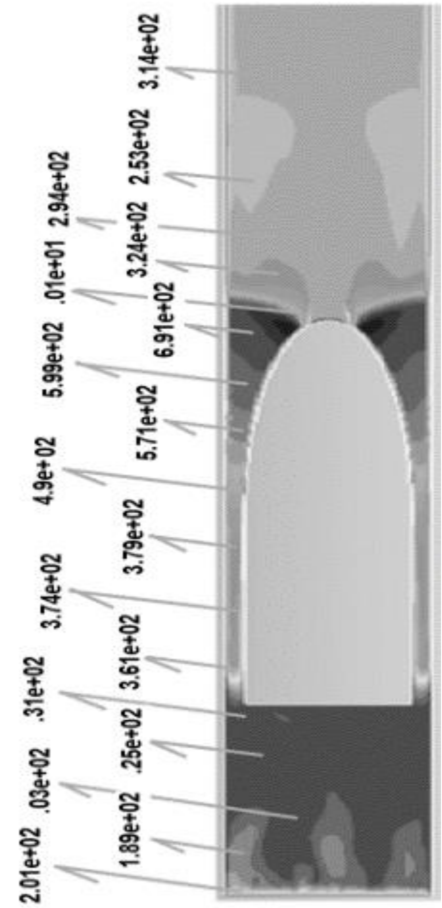

Figure 12. Velocity distribution inside the barrel of the weapon in meters per second

When the propellant is ignited and converts to gas, the temperature in the combustion chamber rises sharply. The propellant burns at one point of temperature. This temperature is obtained in a closed combustion chamber. Because the heat conduction in the projectile barrel through the walls of the combustion chamber takes places slowly, the temperature is much lower than the ignition points when the bullet travels down the projectile barrel. Understanding this temperature distribution along the barrel can help design and select the barrel material. According to the diagram in Figure 15, the energy and consequently the temperature along the barrel are on a downward trend.

Figure 13. Temperature contour

Because the energy is used for the longitudinal motion of the bullet and to heat the bullet and the barrel, and that some energy can remain in the gas in the form of hidden heat and eventually exits the barrel, the temperature along the barrel decreases.

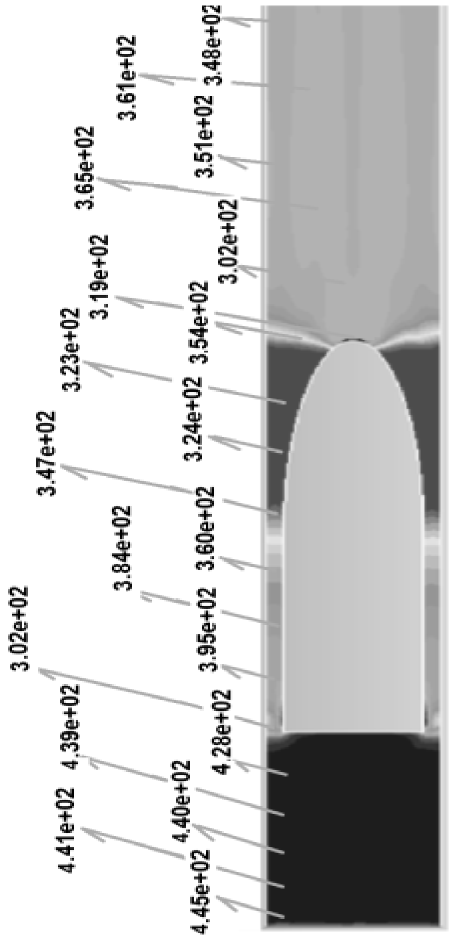

Figure 13. Temperature distribution inside the barrel of the weapon in Kelvin

As shown in Figure 13, because the velocity at the tip of the bullet is very low and the so-called "point of stagnation" occurs, the pressure and consequently temperature will be greater than the fluid in front of the bullet. Figure 14 shows very well that the minimum temperature inside the barrel occurs at the side edges in front of the bullet. The fluid in the front of the bullet has a higher temperature than the side edge of it due to its progression and compaction. Figure 15 demonstrates the temperature variations behind the bullet in the firing sequence. It is noted that in the initial positions of the bullet in the barrel, the temperature does not change as the bullet travels within a meter forwards, whereas just as the bullet travels within a meter, a drop in temperature is seen due to a sudden increase in volume behind the bullet and a sharp drop in pressure at one moment. As the bullet travels forwards and high-pressure hot gases reach the bullet, the temperature increases slightly, while dropping after some increase within a meter or nearly two meters of the barrel. In general, the temperature behind the projectile decreases as the bullet travels forward in the firing sequence, but this reduction experiences oscillations.

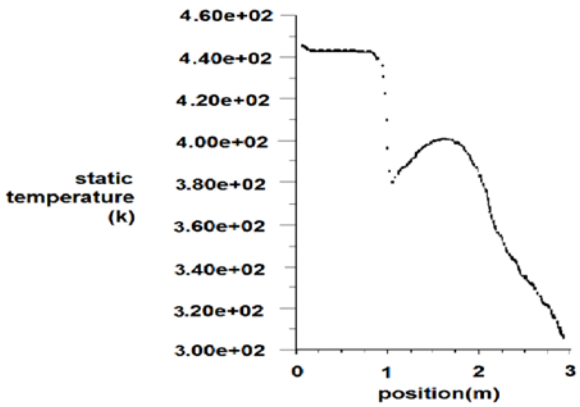

Figure 15. Temperature graph

Two types of forces are imparted to the bullet inside the barrel. One type of force arises from high pressure gases and the other from the frictional force between the bullet and the interior of the barrel, which is applied against the direction of the bullet and is proportional to the shear stress.

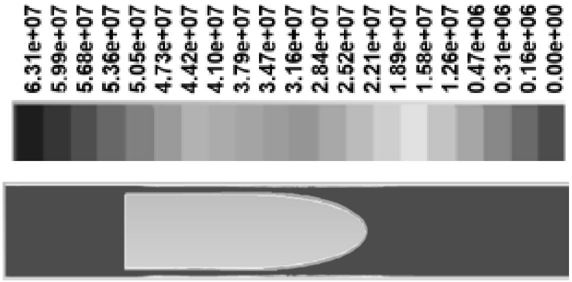

Figure 16. Shear stress contour

As shown in Figures 17, 18 and 19, the shear stress and friction coefficient have changed inversely with temperature, which is reasonable. Wherever the temperature is high along the barrel, the shear stress is proportional to the frictional force. This is due to the fact that at high temperatures, abrasion and tangential impact are less noticeable. As the friction force decreases, the shear stress also decreases as temperature increases.

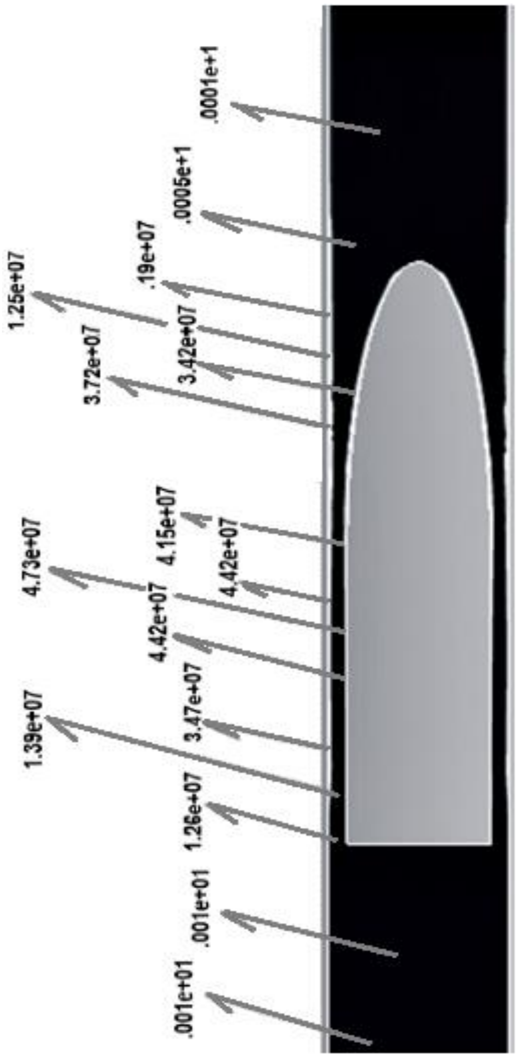

Figure 17. Distribution of shear stress inside the barrel of the weapon in Pascals

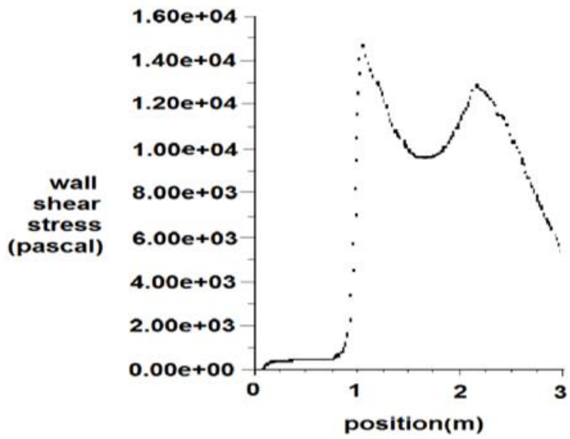

Figure 18. Shear stress diagram

At the end of the barrel, because the bullet surface is hot enough, it is less engaged with the surface and the friction force is greatly reduced. Figure 18 illustrates that there is considerable shear stress on the bullet surface and the internal surface of the barrel.

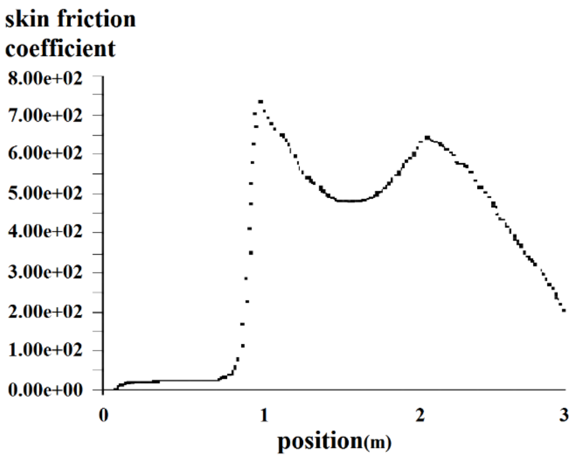

Figure 19. Friction coefficient diagram

It should be noted that along a projectile barrel, the energy released from combustion is converted to other energies. These energies include the energy used to propel the projectile forwards, with another part used for rotating projectile in rotating projectiles. The other part will be used for the friction of the barrel with some removed from the barrel. Table 1, which is the research work by Hermann Karier et al. on a medium-range caliber launcher, shows this energy distribution [13].

Table 1- Energy categorization in medium caliber launcher

Energy distribution	Value
	42.26%
Energy associated with exhaust gases	20.17%
Heat loss	3.14%
Kinetic energy of gases	0.12%
Energy imparted to the system	34.31%
Total energy imparted to the projectile	2.17%
Friction losses	.0.14%
Rotational energy of the projectile	32%
Energy imparted to the projectile	100%

6-Conclusion

The chemical potential energy in hot and high-pressure gases from combustion is what actually propels the bullet. Inside the projectile barrel, when the propellant burns, it releases a large amount of energy in the form of hot gases. The result of these hot gases is high pressure behind the projectile. Numerous factors affect the pressure inside the barrel at any given time. The gas pressure inside the barrel is largely proportional to the heat generated. As the projectile travels at high velocity at the beginning of the motion, a drop in pressure towards the rim of the bullet is noted. This drop is due to the friction between the propellant gases and a sharp rise in the volume behind the bullet. From the pressure coefficient diagram within one meter of the motion, it is clear that there is an evident turbulence behind the bullet. This is due to a low-pressure area behind the projectile, because the combustion gases cannot quickly reach the back of the bullet to fill this space. The result is a vacuum-like state with minimal pressure which can, int itself, be a kind of counter-motion. Two effective factors can highly affect the maximum pressure inside the projectile barrel. The first is the rapid release of hot gases from combustion and the second is the high mass from the projectile. The mass of the projectile tends to withstand an increase in volume, causing an increase in pressure. The energy generated by the hot and high-pressure exhaust gases along the barrel is mainly divided into the following energies. The energy that is used to propel the bullet forward along the barrel; the energy to change the position of the gases and displacing part of the possible unburned propellants; the energy that is hidden in the gases and eventually exits the projectile barrel; the energy that heats the barrel and the bullet, and the energy that is used for the friction inside the barrel. The important point is that the maximum temperature and pressure inside the barrel and the combustion chamber should not exceed the tolerance of the projectile barrel. The velocity at which the projectile exits the orifice has a great impact on the exhaustion and life of the projectile. Therefore, the life of the projectile barrel can be related to the velocity of the bullet. Understanding velocity variations along the barrel can greatly help design barrel material.

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