Interior Ballistic Simulation for 9 mm Gun for Bullet and Blank Shot Applying Spalart-Allmars Turbulence Model

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Abstract: Internal ballistic for a bullet shot and a blank shot in a 9 mm gun were simulated. The length and the thickness of the barrel of the gun were 125 mm and 3 mm, respectively. In this simulation viscous Spalart-Allmars turbulence model was applied and the movement of the bullet was modeled with six degrees of freedom. Four different initial conditions for the bullet were considered that involved the initial position of the bullet in the barrel, pressure of gas behind the bullet, and speed of the bullet in that position. The simulated muzzle speed for each initial condition was compared to experimental data and the error (in %) for each initial condition was calculated. Also, the Mach number, gas pressure, flow field, and sound pressure level were simulated in the area outside of the gun barrel. The sound level was reduced in both axial and radial directions but the reduction of sound in the radial direction was more than in the axial direction. In the case of the blank shot, also, it was observed that the reduction of sound in the radial direction was more than the sound reduction in the axial direction. The sound pressure level for the bullet shot at the muzzle was 239.7 dB and for the blank shot, it was 220.5 dB at the muzzle. In both bullet and blank shots, it is observed from simulations that at the muzzle of the gun pressure of gas dropped and speed increased significantly. The Mach number outside of the barrel was more than 1, which means the flow of gas was supersonic, and in some regions, the Mach number reached 6. The shock wave produced from the supersonic flow of gas is detectable in the simulations.

Keywords: - Interior ballistics, Numerical simulation, Finite volume, Fluent, Spalart-Allmars method Sound pressure level, 9 mm gun

1. INTRODUCTION

Ballistics is one of the most complicated subjects in fluid mechanics that can be studied in various aspects. Combustion of propellants produces high-energy gases with high pressure and temperature. These high-pressure gases push the bullet inside the gun barrel. Considering that the speed of reactions is high and doing evaluation and measurements inside of the barrel is very difficult, interior ballistics simulation is very important.

The aim of interior ballistics simulation is the modification of gun and ammunition parameters to achieve a specific muzzle speed without damaging the barrel of the gun.

It also helps to study the gunshot sound. Gunshot makes a shock wave that is produced by exposure of hot, high-pressure combusted gases to the ambient atmosphere. Propagation of that wave leads to a gunshot sound. The sound pressure level for 0.22 and 0.3 caliber guns and pistols reaches 140 dB and 175 dB, respectively [1].

For sake of human ear safety, the peak sound pressure of pulse noises such as explosions or gunshots should not exceed 140 dB. Otherwise, it could permanently harm hearing [2].

Rahimian and Talei applied the finite volume method to solve the governing equation of interior ballistics and compared the results with experimental

data. The simulation data was in good proximity to experimental results [3].
Zhao et al. investigated the effect of a muzzle brake on certain aeroacoustics noise characteristics. They used computational fluid dynamics and computational aeroacoustics to calculate the muzzle brake flow field and jet noises, in the presence and absence of the muzzle brake. They also compared the simulation results with experimental data.
The highest SPL was 136.5 dB at a distance of 0.5 m from the muzzle [4].

Interaction between internal ballistic parameters could be completely understood by using mathematical models. Governing equations of internal ballistics are the propellant gas equation of state, mass equation, momentum equation, energy equation, and the equation of propellant combustion rate. Governing equations for two-phase flow are the mass balance equation, momentum equation, and energy equation in both phases

To solve the energy equation, it is critical to determine the sources of energy losses. In internal ballistic, the main sources of energy loss are [5]:

I) The energy lost in engraving the rotating band and in overcoming friction down the bore
II) Resistance of compressed air ahead of the bullet
III) The kinetic energy of propellant gases and unburned propellant
IV) Heat lost from the internal ballistic system to ambient
V) The kinetic energy of recoiling parts of the gun
VI) The strain energy of the gun barrel
VII) The rotational energy of the bullet

Exposure to high-pressure gases behind the bullet and the movement of the bullet in the air at speeds higher or near the speed of sound leads to shock waves. Several acoustic studies were done for gunshots. Jiang et al. studied the shock wave and its effects on projectile acceleration at the muzzle [6]. Kapil, investigated the effect of projectile shape on the characteristics of flow surrounding it by numerical simulation [7]. In another study, the simulation of the flow field surrounding the moving bullet was simulated by Mehmedagic et al [8].

Rohrbach et al. investigated the heat transfer of high-pressure gas in the chamber, the effect of backpressure, and the length of the barrel on bullet speed at the muzzle of the gun [9]. Rohrbach et al. in another study, applied a compressed air cannon utilized with a diaphragm valve to predict exit velocity [10].

Carlucci et al. surveyed the movement of the bullet in the gun with a flash suppressor [11]. Wang analytically studied ballistic phenomena in high-caliber canons [12]. Hristov applied computational fluid dynamics to study pressure changes caused by the blast wave in small-caliber guns [13].

In a study that was done by Cler et al. behavior of gases in the muzzle of the gun was simulated. In that study, simultaneously Fluent and Galerkin codes were used and simulation results were compared with experimental data [14]. Dayan used the finite element method to study gas behavior in the muzzle, before and after the exit of the bullet. The simulation was done in two steps using IBHVG2 and FASTRAN [15].

Stiavnický and Lisý used LS-Dyna to simulate internal ballistic and sound effects at the muzzle of the gun [16]. Luo and Zhang simulated an automatic gun by applying a UDF [17].

Xavier by simulation in Fluent investigated the internal ballistics of a cylindrical bullet. He predicted the sound at the muzzle [18].

In another study, CFD was applied to investigate the muzzle blast overpressure and the phenomena following it. Unsteady Reynolds-averaged Navier-Stokes with a suitable turbulence model were used for numerical simulation of released gases from the barrel. Simulation results compared to experimental data that were gathered. The muzzle blast has a high amplitude and short duration. For guns with higher caliber, the positive impulse duration is in the range of a few milliseconds, while a small caliber gun's impulse lasts for less than 0.5 milliseconds. Gas expansion at the muzzle caused a muzzle blast wave that is counted as the main acoustic source of the gun fired [19].
A three-dimensional transient model was used to simulate an impulsive flow with a Mach number of 1.6. Raynolds-averaged Navier-Stokes equations were solved by using the k-ω model for the determination of shear stress transport. Also, experimental data were obtained from 2-D and 3-D particle image velocimetry and high-resolution smoke flow visualization [20].

Sahu used a numerical method for the simulation of external ballistic and bullet paths using the Rand/Les turbulence model [21]. Bin et al. used an Eulerian-Lagrangian method to simulate the movement of the bullet in the air. In that study, the AUSMDV approach was used for solving the eulerian equation [22]. Mäkinen et al. presented an analytical model for the acoustic behavior of bullets [23]. Yu and Zhang applied organized and unorganized mesh for the simulation of internal ballistic and studied changes in parameters like pressure and Mach number at the muzzle of a gun [24].

Taylor and Lin numerically simulated the flow field outside of the gun barrel [25]. Sardival et al. numerically investigated the flow field around the bullet in its path in the air [26]. Ding et al. reviewed the strategies for the definition and meshing of bullet geometry in finite element software such as Abaqus [27]. The sound created from shots had been investigated in some studies, and different sources of sound were detected. For instance, Maher reviewed and identified the acoustic parameters of the shot [28]. Peterson and Schomer studied the acoustic effects of a small gun [29].

2. METHOD

2.1. Geometry of problem

Geometry was produced by the design modeler in ANSYS. An axi-symmetrical two-dimensional geometry was applied and measures were set similarly to a 9 mm gun. The length was 125 mm, the radius of the barrel was 4.5 mm, the thickness of the barrel wall was 3 mm and the length of the bullet was 15mm. The same gun was modeled for the blank shot. The model geometry for the bullet shot and the blank shot is presented in Figure 1 and Figure 2, respectively.

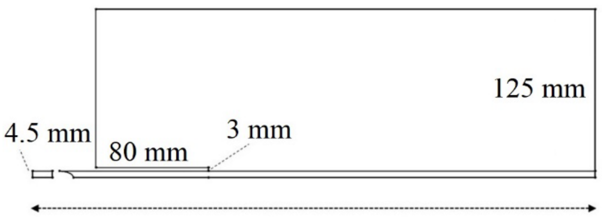

Figure 1. The geometry of simulation for the bullet shot

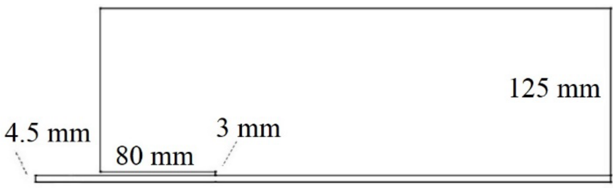

Figure 2. The geometry of simulation for the blank shot

2.2. Mesh

Mesh network was made by Mesh module in Ansys. In the area adjacent to the bullet, hybrid mesh and in other areas rectangular mesh were used. Due to the high speed of flow and severe changes in the flow of the barrel mesh size was 0.1mm and near the bullet, it was 0.05mm. The characteristics of the mesh network are presented in Table 1.

Table 1. Mesh characteristics for the bullet shot

Nodes	564828
Average Aspect ratio	3.5866
Average Skewness	9.6E-4

In the simulation for the blank shot, in all areas mesh size was 0.05mm (Table 2).

Table 2. Mesh characteristics for the blank shot

Nodes	401131
Average Aspect ratio	4.089
Average Skewness	1.31E-10

2.3. Numerical Simulation

The simulation was done in Ansys Fluent 2019R3 and was considered to be axi-symmetrical two-dimensional. A density-based solver was applied and the effect of gravity was ignored. All gases are considered to be ideal gases [30]. The viscous Spalart-Allmaras turbulence model was used to simulate the effect of eddies [18]. This model is very useful for aerodynamic problems in enclosed spaces. To validate the simulation, the problem was once simulated with the K-ω SST model, and the results were compared with the viscous Spalart-Allmaras model [13].

The movement of the bullet was modeled with six degrees of freedom (six DOF) settings. In new versions of Ansys Fluent definition of a moving body does not need a user-defined file (UDF). Also, for the regeneration of mesh networks that changed the layering setting was applied. Discretization of governing equations was done by using methods presented in Table 3.

Table 3. Settings used for simulation

Formulation	Implicit
Flux type	Roe-FDS
Gradient	The least squares Cell-based
Flow	Third order MUSCL
Modified Turbulent Viscosity	First order upwind
Transient formulation	First order implicit

Initial conditions of the problem were defined by Hybrid initialization. The Time step was 10^{-7}s and the maximum iteration in each step was 20 steps

2.4. Boundary and Initial conditions

Combustion of gunpowder was simulated as an initial condition in the simulation. It was presented as an initial pressure. Initial conditions are entered into the simulation by the patch command.

In the simulation with the bullet, the maximum pressure was 241 Mpa, and the mass of the bullet was 8 gr [31]. In the blank shot maximum pressure was 40 Mpa and the length of the combustion chamber was 22 mm [32].

The combustion of propellant is a continuous process. It occurs in all the lengths of the gun barrel, alongside the movement of the bullet in the barrel. This means that the maximum pressure does not achieve at the beginning of the barrel. A suitable initial condition (position, pressure, and speed) in this study was a challenge. Four different initial conditions were considered and the precision of each assumed initial condition was surveyed.

a) The shot was fired, the bullet did not move yet, the speed of the bullet was zero and the pressure behind the bullet was the maximum pressure
b) The shot was fired, the bullet was moving from the shell, the speed is very low (approximately zero) and the pressure behind the bullet is maximum
c) Based on data gathered from Quick-loader software the pressure behind the bullet is maximum, it has moved 4 mm from the beginning of the barrel and the speed of the bullet is 100 m/s.
d) Based on data published by weapon companies, when a 9 mm bullet has been shot, the main part of the propellant has been combusted when the bullet has moved 8 mm in the barrel [33]. In this study, it was assumed that all propellant was combusted when the bullet is 20 mm in the barrel (×2.5 distance reported by weapon companies).

Table 4. Different initial conditions for bullet simulation

Initial condition	Location from the base (mm)	Initial speed (m/s)	Initial pressure (MPa)
A	14	0	241
B	19	0	241
C	18	100	241
D	34	235	120

Using Quick-loader software pressure behind the bullet was 120 Mpa and the speed of the bullet was 235 m/s.

The initial conditions that were used in this study are summarized in Table 4 and boundary conditions are presented in Figure 3. The same boundary conditions were applied for the blank shot, except that the moving wall did not apply.

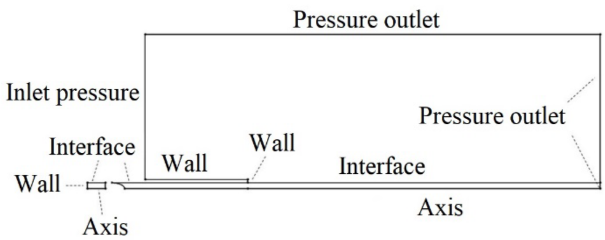

Figure 3. Boundary conditions for the bullet shot

3. RESULTS

The problem was solved for two scenarios (for the bullet and the blank shot). Simulation in presence of a bullet was solved, considering four different initial conditions (A to D), and the precision of simulation with each initial condition for estimation of the speed of a bullet in the muzzle of the barrel was investigated.

3.1. Selection of suitable initial condition

The speed of a 9 mm bullet in the muzzle of the gun is 350 m/s. The simulated speed of the bullet at the muzzle of the gun with different initial conditions is presented in Table 4. Initial condition (D) was shown to have the least error from real experimented speed, so it was applied in the simulation.

3.2. Simulation of bullet shot

The speed of the bullet, pressure and Mach number, and sound pressure were simulated. Bullet backpressure is shown in Fig 4. The movement of bullets in the barrel and consequently increasing gas volume led to a reduction of back pressure. As can be seen in Figure 4, backpressure is reduced exponentially.

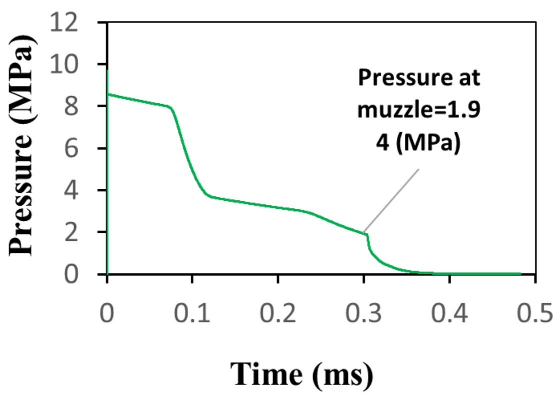

Figure 4. The pressure of gas behind the bullet

At the moment the bullet exited from the barrel, the pressure dropped significantly. The reason for this drop was releasing combustion gases into the air and a sudden increase in the volume of combustion gases.

The difference between the initial condition of pressure and pressure gained from software was because of the initial high speed of the bullet and its movement and so increment in the volume of gases. In a few time steps pressure dropped to values presented in Figure 4.

The force on the bullet was always in the direction of movement, so the motion was accelerating. As can be seen in Figure 5, the slope of the velocity diagram was positive.

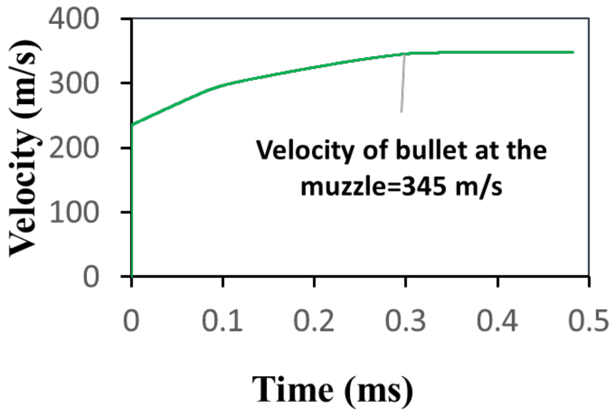

Figure 5. Velocity of bullet

But with the increase in the volume of gases the slope of the diagram reduced. After the exit of the bullet from the barrel, the force of gas on the bullet could be ignored, so the speed of the bullet approached a constant value.

In the barrel, positive acceleration led to an increase in the slope of the displacement-time diagram. Outside of the barrel, the slope is constant (Figure 6).

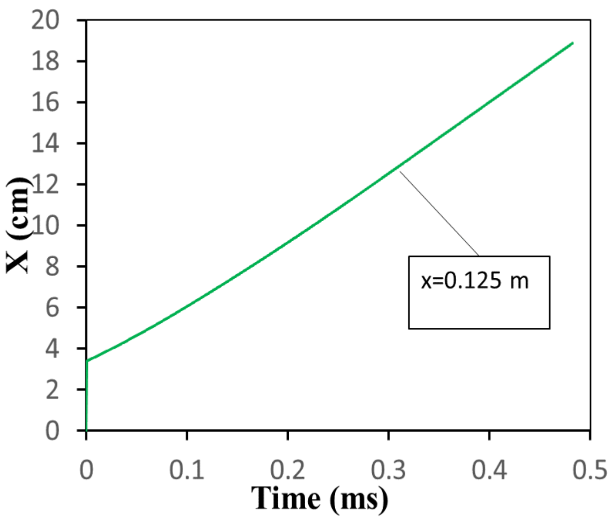

Figure 6. Movement of bullet

Mach number, speed of the bullet, speed of sound, and pressure contours were depicted when the bullet is 190 mm far from the base of the barrel.

As can be seen in Figure 7, the exit of the bullet from the gun led to the sudden expansion of gases and a pressure drop. The change of the pressure head to the kinetic head caused an increase in flow speed and consequently an increase in Mach number.

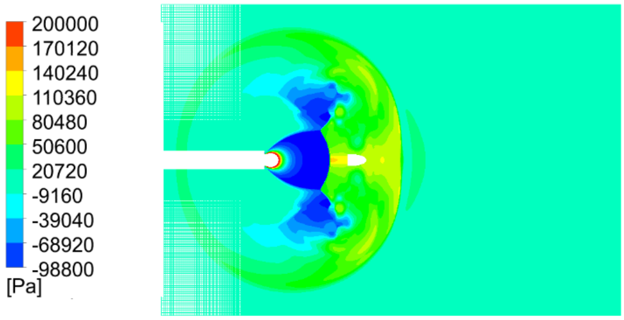

Figure 7. Gas pressure outside of the gun

According to Figure 8, the Mach number outside of the barrel was higher than 1, and in some regions, it was near 6. The flow outside of the barrel is supersonic and compressible.

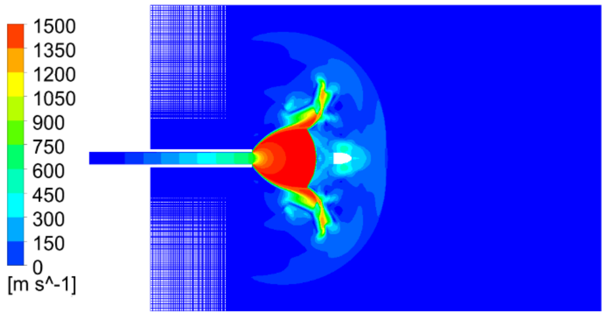

Figure 8. The velocity of gases outside of the gun

As can be seen in Figure 8, outside of the area enclosed by the dotted line the Mach number reduced considerably and the flow became subsonic.

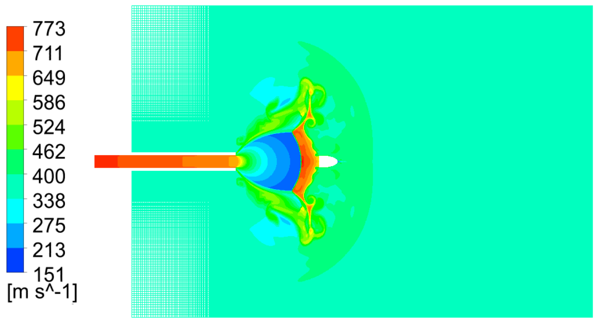

Figure 9. Sound speed outside of the gun

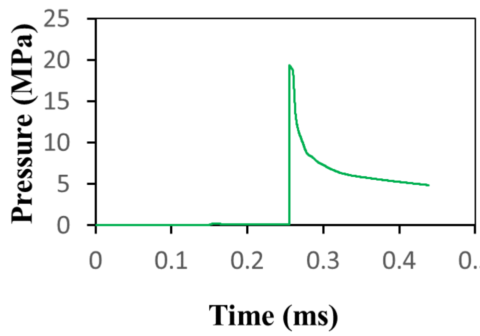

Figure 10. The pressure of the gas at the muzzle

This was the boundary of the shock wave. Shock reduced speed, Mach number, and stagnation pressure and increased pressure, temperature, sound speed, entropy, and density of flow. The shock wave is moving progressively. The contour of changes in flow speed and sound speed is presented in Fig 8 and Fig 9, respectively and in both figures the shock wave is detectable.

The pressure shock wave is the main source of the gun's sound. In Fig 10, changes in pressure at the muzzle of the gun are presented, and by using the maximum pressure at that point sound pressure level (SPL) was calculated.

In Fig 11 changes in pressure in time at 10 and 20 mm from the muzzle of the gun are presented. The method for the definition of SPL in those points was the same. SPL at the muzzle was 239.73 dB and as was expected the farther the point of measurement, the less the SPL (Table 5).

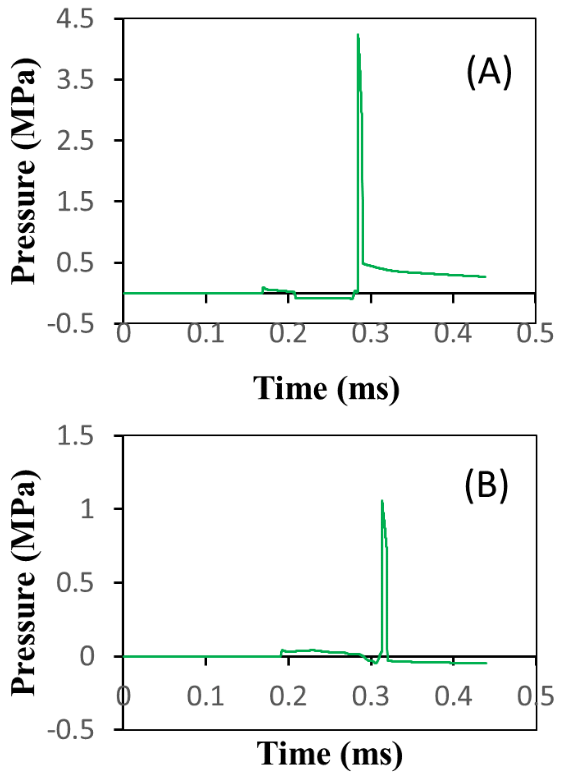

Figure 11. The pressure of gases in the axial direction (A) at 10 mm and (B) at 20 mm from the muzzle

Table 5 SPL in different axial distances from the muzzle

Axial distance (mm)	Radial distance (mm)	Sound pressure level (dB)
0	0	239.73
10	0	226.5
20	0	214.45

In Table 6, SPL in different radial distances from the muzzle (10,20, and 30 mm) was shown.

Table 6. SPL in different radial distances from the muzzle

Axial distance (mm)	Radial distance (mm)	Sound pressure level (dB)
0	0	239.73
0	10	205.58
0	20	201.61
0	30	197.49

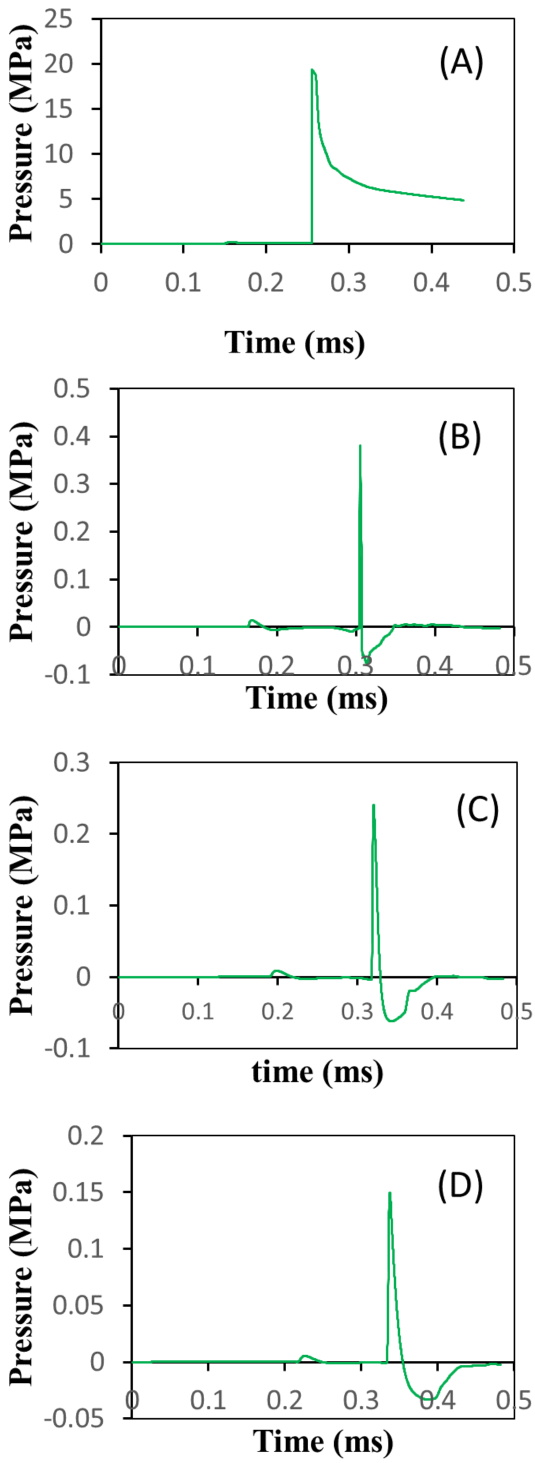

Figure 12. The pressure of gases in the radial direction at (A) the muzzle, (B) 10 mm, (C) 20 mm, and (D) 30 mm from the muzzle

Fig 13 is represented to compare sound propagation in axial and radial distances. As can be seen, the level of sound at the same distance from the muzzle was higher for axial points than radial ones. Although results for SPL in the axial direction seem to be linear, from the comparison between to direction of propagation of sound it could be seen that changes in the level of sound in both directions are exponential, and if simulation for points very far from muzzle was done, it would be seen that change in the axial direction is also exponential.

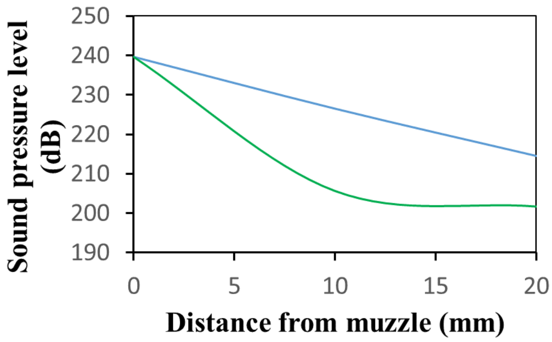

Figure 13. The sound pressure level in axial (blue line) and radial direction (green line)

3.3. Simulation in blank shot

A bullet in the barrel makes a disturbance in the flow of combustion gases that causes high pressures for combustion gases. The maximum pressure in absence of a bullet is 40 Mpa.

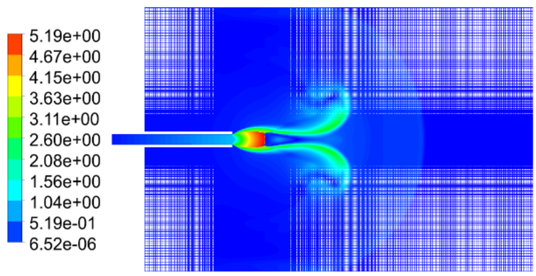

Figure 14. Changes in Mach number for the blank shot

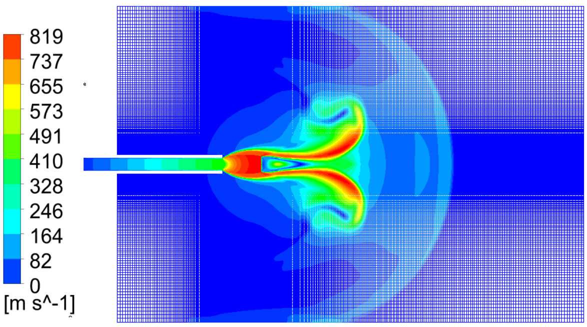

Figure 15. The velocity of gases for the blank shot

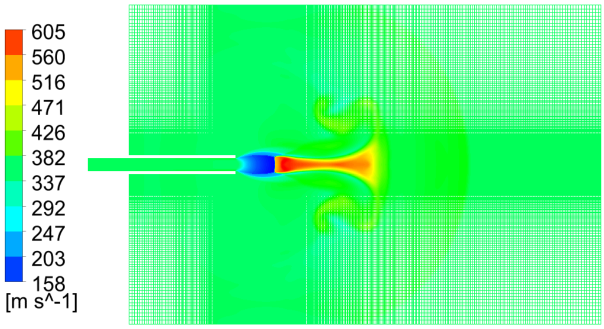

Figure 16. Sound speed for the blank shot

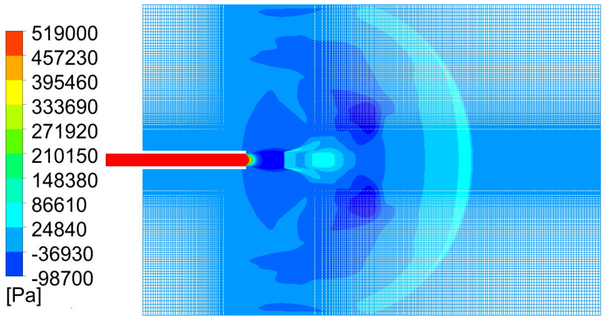

Figure 17. Gas pressure for the blank shot

The contour of Mach number, flow speed, sound level, and pressure in different points in 3.5 ms after the shot is depicted in Figures 14 to Figure 17.

Same as the shot with a bullet, exhausted combustion gases at the muzzle suddenly expanded and produced a shock wave. In Figure 18, pressure at the muzzle of the gun after the shot was represented.

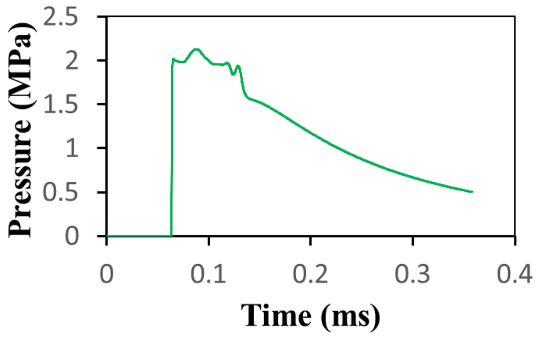

Figure 18. The pressure of gases at the muzzle

In Figure 19 same diagrams for 10 and 20 mm from the muzzle in the axial direction are presented. SPL at the muzzle was 220.53 dB and in points, farther from the muzzle was lower (Table 7).

Table 7. SPL in the axial direction for the blank shot

Axial distance (mm)	Radial distance (mm)	Sound pressure level (dB)
0	0	220.53
10	0	220.05
20	0	209.82

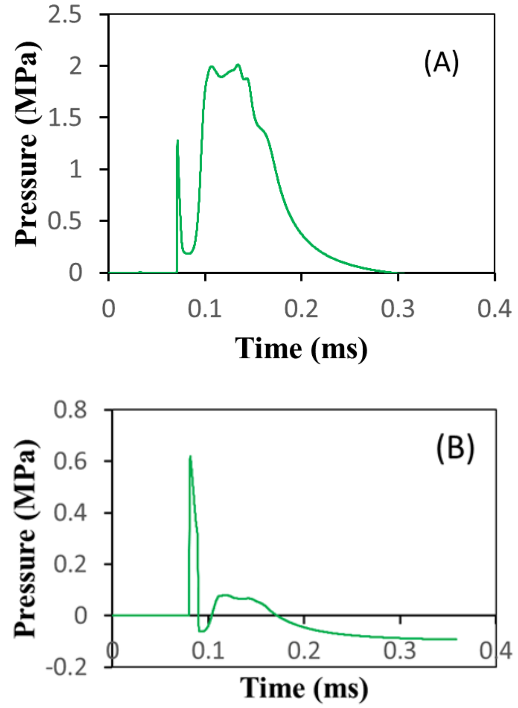

Figure 19. The pressure of gases in the axial direction for the blank shot in (A) 10 mm and (B) 20 mm from the muzzle

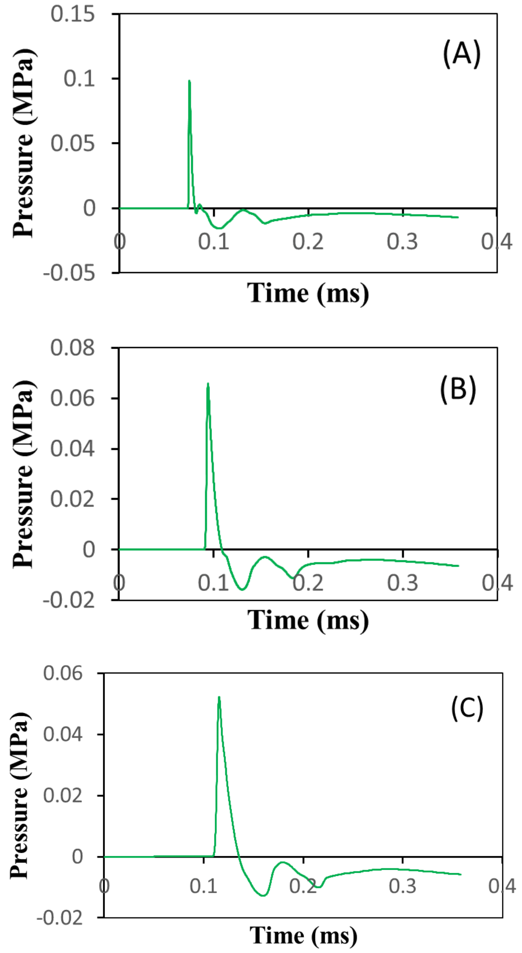

Figure 20. The pressure of gases in the radial direction in (A) 10 mm, (B) 20 mm, and (C) 30 mm from the muzzle for the blank shot

The pressure of sound in the radial direction, 10, 20, and 30 mm from the muzzle was drawn in Fig 20. SPL in those locations is presented in Table 8.

The level of sound at different distances from the muzzle in axial and radial directions is presented in Figure 21. The reduction of sound level in the radial direction is higher than in the axial direction. The same result was observed for the shot with a bullet.

Table 8. SPL in the radial direction for the blank shot

Axial distance (mm)	Radial distance (mm)	Sound pressure level (dB)
0	0	220.53
0	10	193.82
0	20	190.34
0	30	188.33

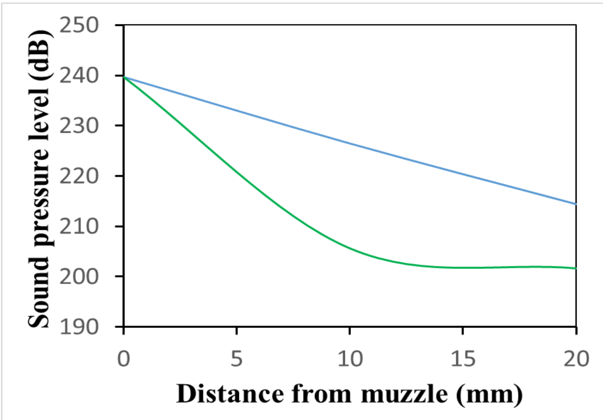

Figure 21. SPL in different distances from the muzzle in axial (blue line) and radial direction (green line) for the blank shot

In another simulation, it was assumed that the maximum gas pressure in the blank shot was the same as the bullet shot (241 Mpa) by changing the mass or kind of propellant. The velocity of the gas in this condition is depicted in Figure 22.

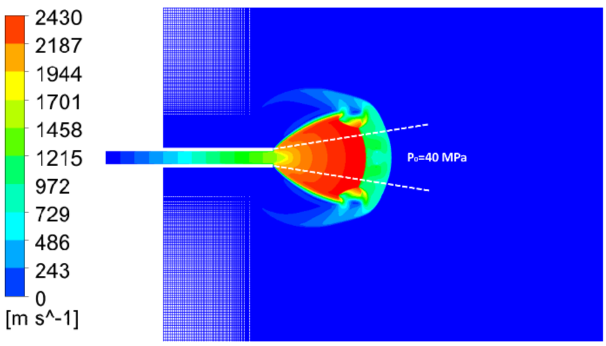

Figure 22. the velocity of gases for the blank shot if the initial pressure was 240 MPa

3.4. Level of sound comparison between the shot with and without bullet

In bullet shot and blank shot, the sound pressure level was lower in points farther from the muzzle in both axial and radial directions. In both shots (bullet and blank), the sound of the shot in direction of the gun (axial direction) is higher than in the perpendicular direction (radial direction) SPL in the muzzle for the bullet shot is higher than the blank shot by 20 dB.

The difference between SPLs reduces with distance from the muzzle. The difference between SPLs is higher in the axial direction than in the radial direction (Figure 23).

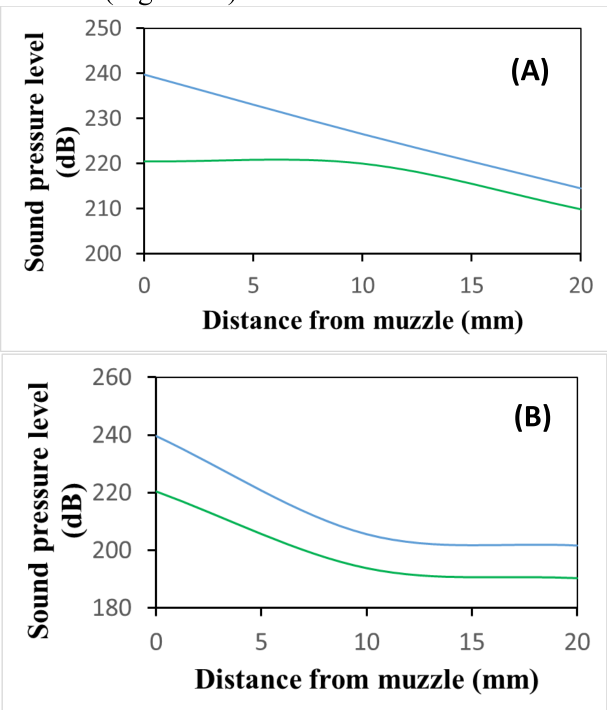

Figure 23. Comparison between SPL in (A) axial and (B) radial direction for bullet shot (blue lines) and blank shot (green lines)

3.5. Independence from the mesh

The size of the mesh has a significant effect on the precision of the simulation. The finer the mesh the more precise the model. But finer mesh means higher computational cost. So it is necessary to measure the sensitivity of the problem to mesh size and determine the size of mesh that results from simulation (speed, pressure, temperature). For any finer mesh that didn't change noticeably.

The size of the mesh in this study in all areas of geometry changed from 0.1 mm to 0.05 mm. The new mesh is presented in Fig 24 and the characteristics of the new mesh are shown in Table 9.

Table 9. Characteristics of new mesh

Nodes	1186503
Average Aspect ratio	5.2866
Average Skewness	5.04E-4

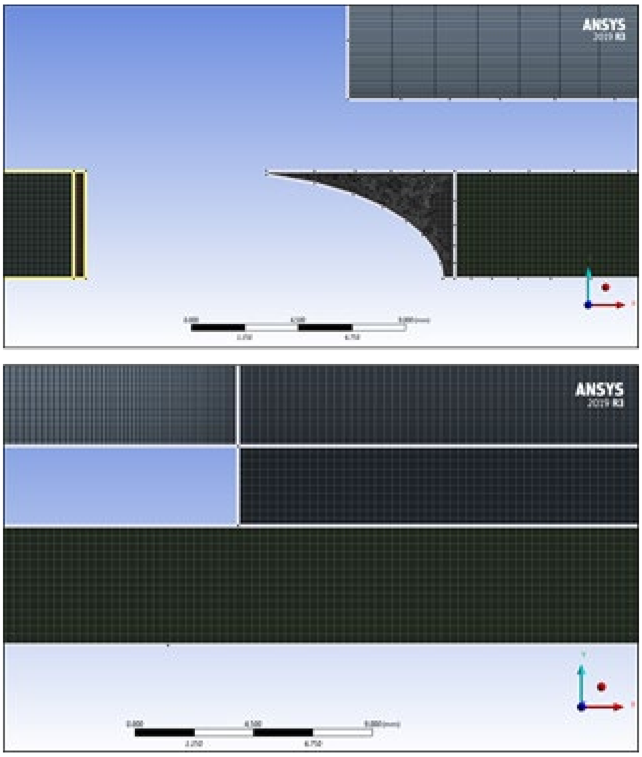

Figure 24. New mesh for simulation

The speed of the bullet at the muzzle and SPL at different distances from the muzzle, for the original mesh and new mesh were calculated and compared to each other. The difference between the two simulations in percent is presented in Table 10.

Table 10. Difference between simulations in original and new mesh

Variables	Original mesh	New mesh	Difference (%)
V_{muzzle}	345.2066	345.6027	0.115
SPL (0,0)	239.7350049	239.8223498	0.036
SPL(10,0)	226.5213012	226.6776975	0.069
SPL (20,0)	214.4530404	214.6161863	0.076
SPL(0,10)	205.5799873	205.976732	0.193
SPL (0,20)	201.6102065	201.569575	0.020
SPL (0,30)	197.4894218	197.5046353	0.008

3.6. Turbulence model check

Fluent uses different turbulence models to study eddies, such as K-ε, K-ω, and Spalart Allmaras. Spalart Allmaras is a single equation method that in addition to the reduction of simulation cost, it is capable of study of viscous eddies, especially in internal flows. In aerodynamic studies application of this method has advantages. K-ε method is a two-equation model for areas far from the wall and K-ω is a two-equation model for eddies near the wall.

application of the K-ω SST model is its capability for modeling areas near and far from the wall. In this study, the Sparlart-Allmaras model was used, and to validate the simulation, the K-ω SST model was applied.

Results for the Sparlart-Allmaras model and the K-ω SST model are presented in Table 11.

Table 11. Difference between simulations for two different turbulence models

Variables	Spalart-Allmaras	K-omega	Difference (%)
V_{muzzle}	345.2066	345.211	0.002
SPL (0,0)	239.7350049	239.7301857	0.002
SPL(10,0)	226.5213012	226.5154449	0.003
SPL (20,0)	214.4530404	214.4322805	0.01
SPL(0,10)	205.5799873	205.6594489	0.039
SPL (0,20)	201.6102065	201.7226318	0.058
SPL (0,30)	197.4894218	197.4728572	0.008

4. CONCLUSIONS

In this study, using Ansys Fluent, the internal ballistic of the shot from a 9 mm gun was simulated. A transient axisymmetrical two-dimensional model with moving mesh was applied. The combustion process was simulated as the initial condition at the moment that the main part of the propellant was combusted. The pressure and speed of gases that were used were obtained from Quickloader which had a 1% error for the speed of the bullet in the muzzle.

In some studies, for ballistic problems, the Sparlart Allmaras model was used and in some other problems, the K-ω SST model was used. The reason for the

Diagrams of speed, backpressure, and Mach number per time past from the shot were presented. The pressure was reduced exponentially and in the moment of passing the bullet from the muzzle, a sudden reduction in pressure occurred. However, speed had a positive slope, but the slope reduced over time and after that, the bullet passed the muzzle, and speed became constant. The Diagram of displacement has an increasing slope but when the bullet passes the muzzle, the diagram becomes linear.

The contour of Mach number, flow speed, speed of sound, and pressure when the bullet is 190 mm far from the barrel base were drawn. It was seen that exhaustion of combustion gases to ambient and in consequence of that, the sudden expansion of gases, causes a progressive shock wave. Shock reduces the Mach number and flow speed and increases the pressure and speed of sound.

The diagram of pressure at different distances from the muzzle in axial and radial directions was presented and SPL at that point was calculated. SPL at the muzzle was 240 dB which reduced with distance from the muzzle. SPL in the same distances from the muzzle for points in the axial direction was higher than points of radial distance.

Internal ballistic once simulated for blank shot and contours for Mach number, sound speed, pressure, and speed of flow drawn. SPL at the muzzle and other points determined. SPL at the muzzle was 220 dB and at other points, it was less.

The difference between SPL for the bullet shot and the blank shot is the most at the muzzle. For points farther from the muzzle, the difference between SPLs was less.

Also, increasing initial pressure for the blank shot led to higher flow speed and wider angle of the jet in the muzzle of the gun.

In this problem, for the simulation of eddies Spalart Allmaras model was used. To check the results K-ω SST method was applied and it was observed that the difference between the two models for the simulated speed of the bullet and SPL in the muzzle was less than 0.1%.

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