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Study of the Effect of Some Muzzle Device Types on the Firing Force and Firing Impulse

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Abstract: In this article, a mathematical model is used to determine the force and impulse of the weapon's firing. The force and impulse of the weapon's firing are determined during the whole firing process, which consists of two stages: the stage projectile moving inside the barrel and the stage at the final action stage of combustion gas. The input parameters of the UK-59 machine gun in the Czech Republic were selected to verify the mathematical model. The results of the article are the law of combustion gas pressure in the barrel, the law of combustion gas pressure in the gas chamber, and the law of force and impulse of the shot corresponding to different types of muzzle devices. This result is consistent with the experimental results presented in the document, and the error is less than 3%. Besides, the article also analyzes the influence of some muzzle device types on the firing force and firing impulse. The method of numerical integration has been applied to solve the problem using Matlab software. The research results of the article are a reliable theoretical basis for determining the firing forces, serving the problem of designing the mount as well as the firing stability of the weapon when firing. This is the basis for the optimal selection and design of the muzzle device used in the weapon.

Keywords: firing force, firing impulse, muzzle devices, the UK-59 machine gun

1. Introduction

When a firing is fired, in addition to the desired effect of imparting velocity to the projectile, there are also other undesirable effects. These include electromagnetic radiation, smoke, toxic fumes, as well as thermal and pressure effects. The high-pressure propellant gases impart stresses to the barrel and are the cause of forces and moments transmitted to various parts of the weapon. At the same time, a pressure wave is created at the muzzle, which acts on the surroundings [1]. Determining the force of the gas pressure acting on the barrel and proposing solutions to reduce this force has been of interest to many researchers. To limit unwanted effects, people often use muzzle devices. For weapons, the muzzle device is considered an important component in the weapon system; it is diverse, with many types with different uses such as muzzle brakes, flash hiders, muzzle deflectors, recoil intensifiers, and silencers. At the same time, some muzzle devices affect the gun's stability during firing [2–4].

In addition, some studies show that a part of the combustible gas energy is not converted into kinetic energy of the bullet but is released from the barrel, this energy usually accounts for about 40% [5]. Therefore, many studies have taken advantage of this energy source to increase the stability of the gun when shooting by using various types of muzzle devices [6–20]. The muzzle device is a component located at the mouth of the gun barrel; it operates during the final phase of the combustion gas and does not change the ballistic characteristics of the gun. They are simple in structure, easy to fabricate, assemble, and operate reliably [21].

Early studies on muzzle devices often simulated the flow field near the muzzle by computational fluid dynamics (CFD) method [13, 15]. Several studies have used experimental methods to evaluate the effectiveness of muzzle devices [8, 14, 17]. The traditional method of testing the effectiveness of a muzzle brake is to use a deformation stamp to measure the recoil of the gun, but such indirect measurement does not provide high accuracy [14]. Wang et al. [17] propose a contrast method to test the recoil efficiency of the muzzle brake; this method uses a sensor to measure the displacement of the gun, and then integration is performed to determine the working efficiency of the muzzle brake. Chen [8] proposes a method for determining the efficiency of the muzzle device using compressed air rather than the combustible gas of the propellant. An alternative approach to model the operation of the muzzle device was considered using ANSYS CEX and an example was calculated for the 152 mm2A36 gun [20]. The results obtained from this study are the parameters of the gas flow in the process of flowing through the muzzle device and the graph of the change in the recoil force of the gun. Several models of muzzle dynamics have been simulated, such as the model for calculating the recoil brake and rotational brake forces of the muzzle device for the Gatling multi-barreled gun [10]. Mathematical model of muzzle devices on non-lethal weapons with deformable warheads is mentioned in the

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literature [6]. The simulation results from this study have been compared and verified by experimental results. A simulation study determined muzzle airflow and acoustic noise for the case with and without a muzzle device and then compared the results obtained to predict the impact of noise and optimize the structure of the muzzle device [19]. To evaluate the effectiveness of the muzzle brake device, tests with different muzzle devices were carried out [12, 18]. The effect of the muzzle brake on the stability of hand-held weapons during salvo firing was studied in an experiment [16]. The results of this study are the force exerted by the combustible gas on the bottom of the barrel during the final phase of combustion of the combustible gas, the bouncing angle of the gun in the vertical and horizontal planes, and compared with the results of the case without muzzle device. A common point of the above methods is that they all use high-cost testing equipment; the results obtained do not adequately describe the causes and nature of the use of muzzle devices. Some studies have given the law of recoil force, but this law is calculated indirectly, leading to inaccurate results. Furthermore, the study of the influence of some muzzle devices on the firing force and firing impulse is still limited.

In this study, a mathematical model to determine the characteristics of the firing was established. The mathematical model applied to the Czech Republic UK-59 machine gun, see Figure 1. Besides, the article also studied the influence of some muzzle devices on the firing force and firing impulse. Two muzzle devices with opposite effects were selected, namely muzzle brakes and the flash hider or reactive recoil increaser. This is the basis for the optimal selection and design of the muzzle device used in the weapon.

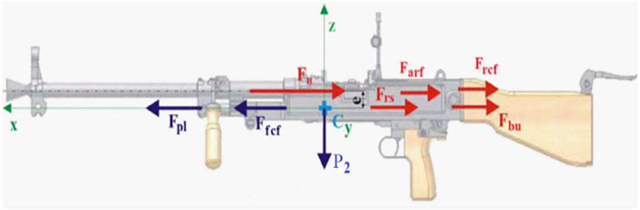
Figure 1
The UK-59 machine gun

2. The Firing Force and Firing Impulse

The main forces acting on the weapon casing and causing the motion of all weapon parts during the firing operation depend on the type of operation of automatic weapons, see Fiser and Popelinsky [1] as well as Minh [22]. They are determined based on the knowledge of the firing force acting on the barrel, the gas chamber, and the functional cycle of the weapon. For the type of gas-operated weapon system, the definition and analysis of these forces acting on the weapon casing are described in detail in Balla [23], Russell [24], and Tien [25]. Its graph is illustrated in Figure 2. The forces shown in Figure 2 are acting during one functional cycle. These forces are periodic in the case of firing in a burst.

Symbols in Figure 2 are as follows: F_H is the force of the firing; F_{pl} is the pressure force in the gas chamber; F_{bu} is the buffer spring force; F_{rs} is the return spring force; F_{rcf} is the impact force when the bolt carrier hits the rear of the weapon casing during in recoil; F_{fcf} is the colliding force when the bolt carrier hits the front of the gun casing; and F_{arf} is the auxiliary resistance force of the automatic firing system acting on the weapon casing (such as cartridge case extraction force, R_v, the friction force between the bolt carrier and the guide rail on the weapon casing, F_f).

Figure 2
Forces acting on the weapon casing



The equation for the sum of the forces acting on the gun is determined as follows:

$$F_{\sum} = F_H - F_{pl} + F_{rs} + F_{bu} + F_{\mathrm{arf}} + F_{\mathrm{rcf}} - F_{\mathrm{fcf}} \tag{1}$$

However, not always for all types of automatic weapons, it is a periodic excitation with constant frequency. Automatic weapons with external drives, especially the chain gun and Gatling guns, have a certain acceleration time from zero to a nominal rate of fire. In this case, not only the mean value of the excitation force is changed for one function cycle, but the rate of fire also changes during the system start-up, see Cech [26], Vitek [27], Balla and Mach [28], and Bien et al. [29]. Fiser and Popelinsky [1] state that the total impulse of the forces per weapon functional cycle is equal to the impulse of the force of the firing:

$$I_{\sum} = I_H - I_{pl} + I_{rs} + I_{bu} + I_{\mathrm{arf}} + I_{\mathrm{rcf}} - I_{\mathrm{fcf}} = I_H \tag{2}$$

The primary source of all the above-mentioned forces is the force of firing, F_H, [23]. This force is decisive for the loading of weapons, although it only works for a few thousandths of a second. If the barrel of the weapon is recoiled, the F_H force is absorbed by the force of the barrel spring, so it does not act directly on the weapon casing. In the main content of this article, the firing force will be analyzed in detail and focused on evaluating the influence of some muzzle devices on the force and impulse of the firing. This helps the research, design, and manufacture of all types of muzzle devices.

The formula for determining the force of the firing is as follows:

$$F_H = F_{H1} + F_{H2} \tag{3}$$

where F_{H1} is the force of the firing at the stage of the bullet moving inside the barrel, and F_{H2} is the force of the firing at the final action stage of combustion gas. These forces all depend mainly on the combustion gas pressure.

The equation for the total impulse of each firing is as follows:

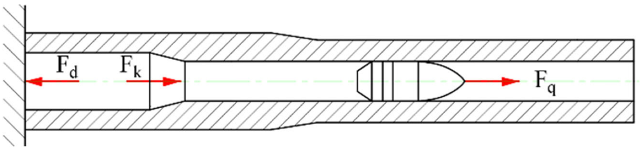
$$I_H = I_{H1} + I_{H2} = \int_0^{t_d} F_{H1}\mathrm{d}t + \int_{t_d}^{t_k} F_{H_2}\mathrm{d}t \tag{4}$$

where t_d is the time the bullet moves in the barrel, and t_k is the time the pressure at the barrel is equal to the ambient pressure.

2.1. The force of the firing at the stage of the bullet moves inside the barrel

At the stage of the bullet moves inside the barrel, the forces acting on the barrel include the force due to the pressure of the combustible gas acting on the bottom of the cartridge F_d, the pressure force of the combustion gas acting on the conical part of the barrel F_k, and the friction force between the bullet and the barrel wall F_q. These forces diagrams are shown in Figure 3.

Figure 3
Diagram of forces acting on the barrel



The formula for determining the total pressure force of the combustible gas acting on the bottom of the barrel during the bullet movement in the barrel is as follows:

$$F_{H1} = F_d - F_k - F_q \tag{5}$$

The force due to the pressure of the combustible gas acting on the bottom of the cartridge is determined by the following formula:

$$F_d = s_d \cdot p_d \tag{6}$$

where s_d is the cross-sectional area of the bottom of the cartridge case, and p_d is the pressure of the combustion gas in the combustion chamber. This value is determined by the following formula [1]:

$$p_d = \frac{1 + \frac{1}{2} k_\chi \frac{\omega}{k_\varphi m_q}}{1 + \frac{1}{3} k_\chi \frac{\omega}{k_\varphi m_q}} p \tag{7}$$

The pressure force of the combustion gas acting on the conical part of the barrel is determined as follows:

$$F_k = \int_s^{s_d} p\mathrm{d}s = p_d(s_d - s) \tag{8}$$

where s is the cross-sectional area of the barrel, and p is the average pressure in the combustion chamber.

The friction force between the bullet and the barrel wall is determined as follows [1]:

$$F_q = sp\frac{k_\varphi - 1}{\varphi} \tag{9}$$

where k_ϕ is the passive resistance coefficient, and ϕ is the friction coefficient of barrel material.

Substituting expressions (6), (8), and (9) into Equation (5), we get

$$F_{H1} = \frac{2 - k_\varphi + \frac{1}{2} k_\chi \frac{\omega}{k_\varphi m_q}}{\varphi} sp \tag{10}$$

where ω is the mass of the propellant, m_q is the mass of the bullet; and k_ϕ is the loss coefficient due to turbulent movement of the gas mixture.

2.2. The firing force at the final action stage of combustion gas

The equation for determining the force of the firing at the final action stage of combustion gas is as follows [1, 25]:

$$F_{H2} = \xi_R sp = \frac{\mathrm{d}m_\omega}{\mathrm{d}t}\mathrm{w} + s(p_v - p_{atm}) \tag{11}$$

where p_v is the gas pressure at the muzzle of the gun barrel at the final action stage of combustion gas, ξ_R is the effect coefficient of the muzzle of the barrel, p_{atm} is the ambient pressure, and w is the gas flow rate at the muzzle [1]:

$$w = \sqrt{\kappa r T \frac{2}{\kappa - 1}\left(\frac{p_{atm}}{p}\right)^{\frac{\kappa-1}{\kappa}}} \tag{12}$$

where κ is the Poisson constant of combustible gas, r is the specific gas constant of combustible gas, and T is the temperature of combustible gas in the barrel.

The differential equation to determine the change in mass of combustible gas flowing through the barrel muzzle is as follows [1]:

$$\frac{\mathrm{d}m_\omega}{\mathrm{d}t} = \varphi_{(\kappa)} s\sqrt{p\rho} \tag{13}$$

where ρ is the instantaneous density gases. $\varphi_{(\kappa)}$ is the equation of exponent of adiabatic expansion [1]:

$$\varphi_{(\kappa)} = \left(\frac{2}{\kappa + 1}\right)^{\frac{1}{\kappa-1}} \sqrt{\frac{2\kappa}{\kappa + 1}}$$

To calculate the firing force and the firing impulse, we need to solve the weapon's internal ballistics to find the propellant gas pressure in the barrel. The system of differential equations for the internal ballistics of automatic weapons is detailed in Du and Tho [30] and is given by the system of Equation (14). Symbols in the system of differential Equation (14) are explained in detail in Du and Tho [30].

$$\begin{cases} \frac{dv}{dt} = \xi_1.\xi_3.\frac{p.S}{\varphi.m} \\ \frac{dl}{dt} = \xi_1.\xi_3.v \\ \frac{dz}{dt} = \xi_2.\frac{p}{I_k} \\ \frac{d\omega_k}{dt} = \xi_2.\chi.\omega(1+2\lambda z)\frac{p}{I_k} - G_\phi - G_n \\ \frac{dW}{dt} = \xi_2.\frac{1}{\delta}\chi.\omega(1+2\lambda z)\frac{p}{I_k} + S.v.\xi_3 \\ \frac{dp}{dt} = \frac{1}{W}.\begin{bmatrix} \xi_2.f.\chi.\omega(1+2\lambda z)\frac{p}{I_k} - K_t.p - K_p.p.\frac{dW}{dt} - \\ -K_p.G_n - K_p.G_\phi \end{bmatrix} \\ \frac{d\omega_b}{dt} = G_\phi - G_\Delta - G_x \\ \frac{d\mathrm{W}_b}{dt} = S_p.\mathrm{v}_b \\ \frac{dp_b}{dt} = \frac{1}{\mathrm{W}_b}\left(G_\phi kRT - G_\Delta kRT_b - G_x kRT_b - K_{Tb}p_b - kp_bS_pv_b\right) \end{cases} \tag{14}$$

To solve the system of differential equations, internal ballistics (14) need to fully determine the input parameters. Parameters of size and mass are taken from design documents or are measured directly on the weapon. Due to the very large number of inputs, only the most important parameters are mentioned hereto, see Table 1 [25].

Table 1
Parameters of internal ballistics of UK-59 machine gun

Parameters	Value	Unit
The cross-section area of the barrel bore	$47.3{\cdot}10^{-6}$	m^2
Caliber of gun	$7.62{\cdot}10^{-3}$	m
Barrel length with helical grooves	0.609	m
The weight of the powder charge	$3.1{\cdot}10^{-3}$	kg
The specific energy of powder	$0.73{\cdot}10^{6}$	J/kg
The powder density	$0.91{\cdot}10^{-3}$	kg/m^3
The total pressure impulse	$1.702{\cdot}10^{5}$	Pa.s
The initial volume of the combustion chamber	$3.52{\cdot}10^{-6}$	m^3
The Poisson constant	1.2505	–
Initial pressure	$40{\cdot}10^{6}$	Pa
The weight of the projectile	0.0189	kg
Diameter of piston	$13.94{\cdot}10^{-3}$	m
Diameter of the inner wall of the gas cylinder	$14.02{\cdot}10^{-3}$	m
The initial volume of the gas cylinder	$12.36{\cdot}10^{-7}$	m^3
Diameter of gas hole	$1.31{\cdot}10^{-3}$	m
Mass of the bolt	0.21952	kg
Mass of the bolt carrier	0.8303	kg
Mass of the return spring	0.068	kg
The return spring pre-tension force	61	N
The stiffness of the return spring	666	N/m

Using Matlab R2022b programming software to solve, we obtain the following typical results, see Figures 4, 5, 6, and 7.

Figure 4
The propellant gas pressure

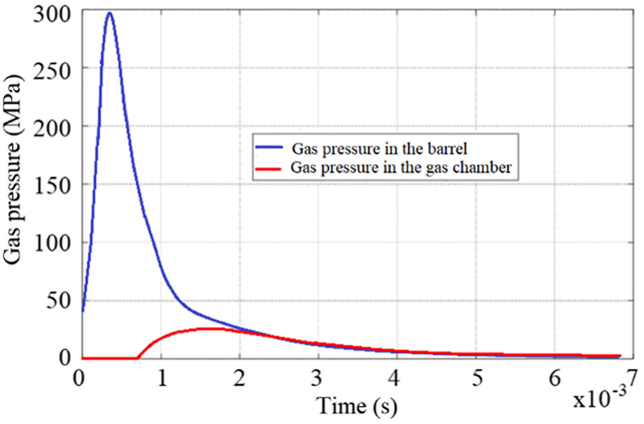


Figure 5
The velocity of the projectile

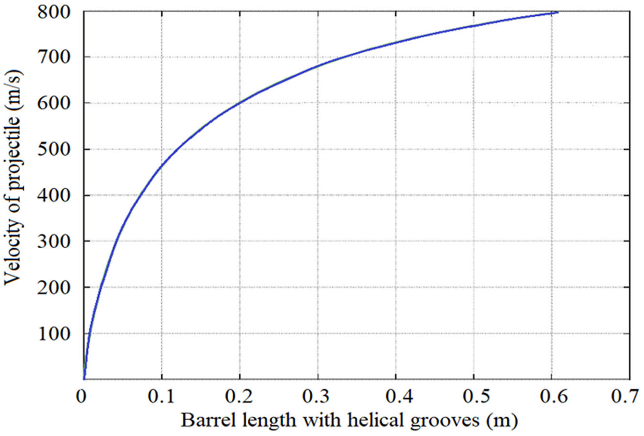
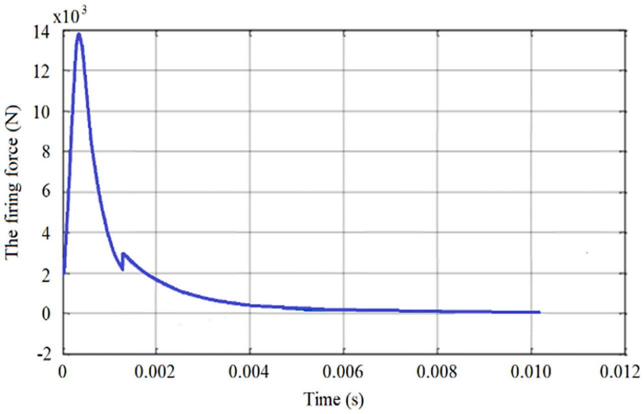
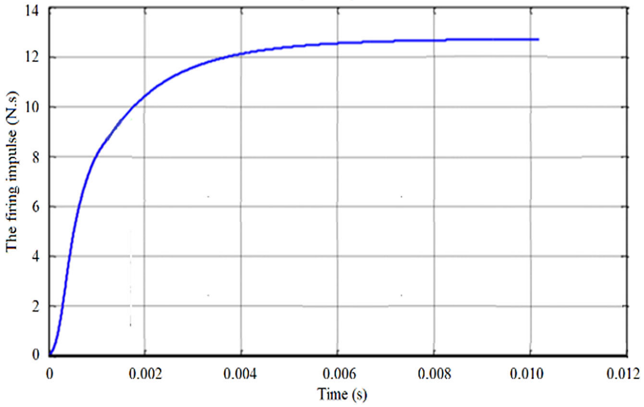


Figure 6
The firing force



The obtained simulation results are consistent with the test results and manufacturer's data presented in Tien [25]. The pressure of the maximum combustible gas in the barrel is 296.85 MPa (Figure 4), the test result is 299.72 MPa [25], and the error is 0.96%. The pressure of the maximum combustible gas in the gas chamber is 37.18 MPa (Figure 4), the test result is 38.26 MPa [25], and the error is 2.82%. The muzzle velocity of the bullet is calculated as 798.2 m/s (Figure 5), the manufacturer's announced result is 810 m/s

Figure 7
The firing impulse



[25], and the error is 1.46%. From the above comparisons, it can be shown that the established mathematical model is completely consistent and reliable. This model can be used to study further problems.

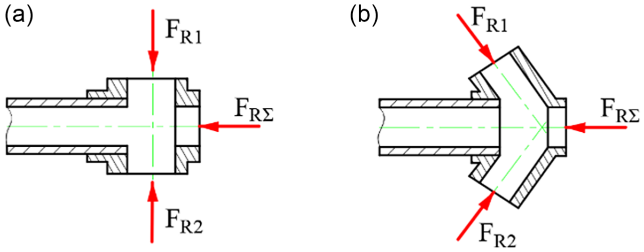
3. Effect of Some Muzzle Device Types on the Firing Force and Firing Impulse

3.1. Muzzle brakes

Muzzle brakes decrease the recoil impulse on the barrel by directing propellant gases back toward the breech as they emerge from the barrel. This creates a negative impulse, which reduces the overall recoil effect on the barrel. The efficiency of a muzzle brake increases with the number of gases discharged and with their angle of deflection and enables to diminish the recoil energy from 25% to 30% and in special cases even up to 60% to 70%. A muzzle break is essentially a mechanism for reversing the motion of the escaping gases. Use of them is of great practical importance. They enable us at the same ballistic output to carry out a lighter construction of the weapon and improve the accuracy of fire especially when firing in bursts. The working principle of this type of device is detailed in Fiser and Popelinsky [1] as well as Tien [25] (Figure 8).

Some features of the muzzle brakes are as follows:

Figure 8
Diagrammatic representation of a muzzle brake. (a) Muzzle brakes which vent sideways at 90°; and (b) Muzzle brakes which vent sideways at an angle greater than 90°



– The efficiency of the device is determined by the following formula [1]:

$$\eta_{ub} = \frac{\Delta E_{zub}}{E_z} = \frac{E_z - E_{zub}}{E_z} \tag{15}$$

where E_z is the back energy when not using a brake-type muzzle device, and ΔE_{zub} is the difference between the energy of the reverse part when not using a brake-type muzzle device and with the use of a brake-type muzzle device.

– The factor taking into account the influence of the muzzle device is determined as follows [1]:

$$\beta' = \frac{\sqrt{1-\eta_{ub}} \cdot \left(m_q + \beta \cdot \omega\right) - m_q}{\omega} \tag{16}$$

– Impulse characteristics of brake-type muzzle device [1]:

$$\chi = \frac{\beta' - 0.5}{\beta - 0.5} \tag{17}$$

The firing force during the final stage act of the combustion gas when using a brake-type muzzle device is determined by the following expression:

$$F'_{H2} = \chi \cdot F_{H2} \tag{18}$$

The variation in the firing force and its impulse with respect to time is shown in Figures 9 and 10 for muzzle brakes of different efficiencies.

Based on the results obtained in Figures 9 and 10, it shows that when using muzzle brakes, it will significantly reduce the force of shots on the gun. The performance of muzzle brakes depends on the area of the air hole and their deflection from the barrel axis.

Figure 9
The firing force

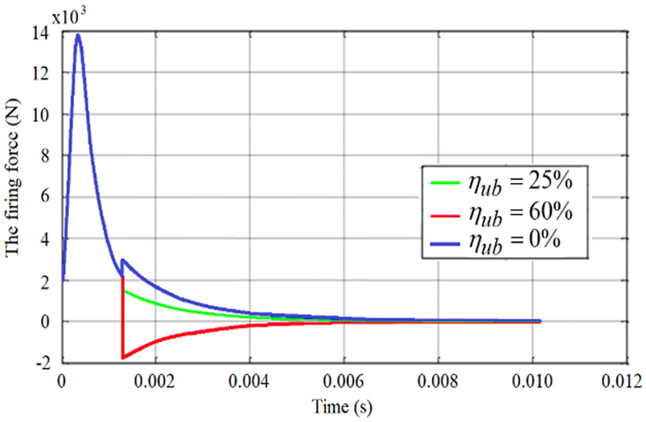
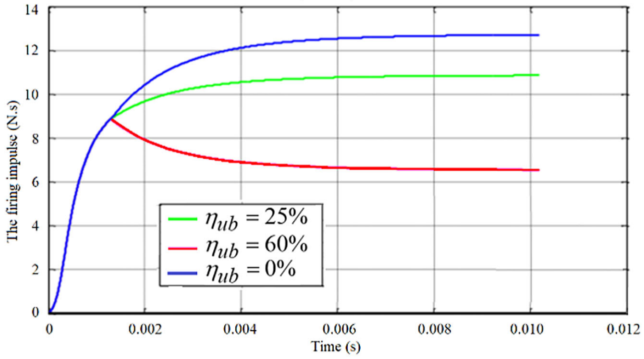


Figure 10
The firing impulse

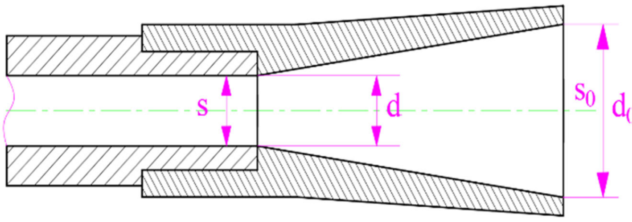


Muzzle brakes that vent sideways at 90° (Figure 8(a)) usually have an efficiency between 20% and 30% and the impulse-force characteristic is usually greater than zero. Muzzle brakes that vent sideways at an angle greater than 90° (Figure 8(b)) usually have an efficiency of between 50% and 60% and the impulse-force characteristic is usually negative. The obtained survey results are a reliable theoretical basis for researching, designing, and manufacturing muzzle brakes suitable for each type of gun. With a reduction in the force and impulse of the shot, the weight of the gun is reduced, increasing mobility and increasing shooting stability.

3.2. The flash hider or reactive recoil increaser

For small caliber weapons driven by the barrel recoil, it is often necessary to increase the firing impulse to provide sufficient energy to cycle the weapon. When a reactive recoil increaser is used as part of the flash hider, the impulse acting on the whole weapon is increased. Figure 11 shows the diagrammatic representation of the flash hider [1].

Figure 11
Diagrammatic representation of the flash hider



In this case, the firing force at the final action stage of combustion gas is determined similarly to the formula for determining the thrust of a rocket engine and is given by an expression of the following form [1]:

$$F'_{H2} = \frac{\xi_{rz}}{\xi_r} \cdot F_{H2} \tag{19}$$

where ξ_r= 1.24 are values of discharge coefficient without a muzzle device, and ξ_{rz} are values of discharge coefficient for the flash hider, determined according to Table 2.

Table 2
Values of discharge coefficient for the flash hider ξ_{rz}

d_0/d	1	2	3	4	5	6
s_0/s	1	4	9	16	25	36
ξ_{rz}	1.24	1.62	1.72	1.80	1.86	1.89

The variation in the firing force and its impulse with respect to time are shown in Figures 12 and 13 for the flash hider of different efficiencies.

Figure 12
The firing force

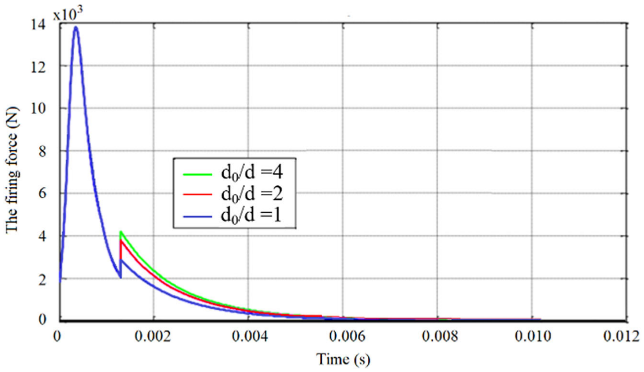
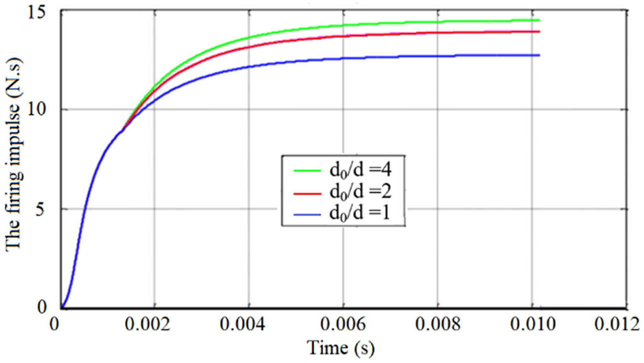


Figure 13
The firing impulse



Through numerical simulation results, it can be seen that:

1) The efficiency of the flash hider depends on the ratio between d_0/d. As the d_0/d ratio increases, the firing force and firing impulse in the final active phase of the combustible gas also increase;
2) Amplified muzzle devices are commonly used to increase the force of the combustible gas during the final phase of its effect on the barrel. This type of device is commonly used for small automatic weapons driven by the recoil energy of the barrel.

4. Conclusion

The content of the article presented a method to establish a mathematical model to determine the force and impulse of the shot of an infantry gun when using a muzzle device. With the research results achieved, some conclusions are made as follows:

1) The mathematical model has been built suitable for the general case; it is possible to determine the force and impulse during the entire process of the shot. Numerical methods have been applied to solve the problem of the problem. This model can be applied to a variety of weapons. The results of this problem are the input parameters for the next problems such as the design problem of the pedestal rack as well as the shooting stability problem of the automatic handgun;
2) The mathematical model has been verified by calculation for the Czech Republic UK-59 machine gun case. The obtained calculation results are consistent with the experimental measurement results and the results announced by the manufacturer; the error is less than 3%;
3) The content of the study also investigated the influence of some muzzle devices on the force and impulse of the shot. Several recommendations have been made for designers in optimizing the structure of the muzzle devices for types of hand-held automatic guns.

The next research direction is experimental research to verify the theoretical results that have been developed and offers several structurally optimized muzzle devices.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data available on request from the corresponding author upon reasonable request.

Author Contribution Statement

Bien Vo Van: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration; **Phon Nguyen Duy:** Software, Formal analysis, Resources, Writing – review & editing; **Phu Nguyen Minh:** Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

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