FACTA UNIVERSITATIS
Series: **Mechanical Engineering**
https://doi.org/10.22190/FUME220418028A

Original scientific paper

ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF THE MUZZLE BRAKE EFFICIENCY

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Abstract. *The muzzle brake efficiency was investigated both analytically and experimentally in this paper. An experimental test system was developed to measure the recoil force of a 12.7 mm anti-material rifle. Two types of the muzzle brake were used. The recoil force with and without muzzle brake and the muzzle velocity of the projectile were recorded. Then the muzzle brake efficiency was calculated. Besides, an analytical model based on the Orlov method for calculating muzzle brake efficiency was adopted. The obtained results were discussed. The maximum of the muzzle brake force, projectile velocity and muzzle brake efficiency obtained experimentally and analytically were compared. The analytical results were in a good agreement with the experimental ones.*

Key Words: *Muzzle Brake, Recoil, Muzzle Brake Efficiency, Muzzle Brake Force, Orlov Method, Experiment*

1. INTRODUCTION

When a firearm is fired, the burning propellant generates a blast of pressurized gases, which apply an enormous force on the projectile, resulting in accelerating the projectile forward. The same effect is applied to the breech, which induces the backward movement of the recoiling parts. After the projectile exits the barrel, the exhausted gases generate a backward impulse that increases the recoil energy. The firing event has a very short duration but it has a significant impact on the gun structure. According to Newton's third law, the recoil momentum is equal to the momentum of the projectile, and the powder gasses ejected from the barrel. In order to reduce the recoil momentum, a muzzle brake can be introduced to reduce the momentum of the exhausted gasses, thus reducing the recoil momentum.

****Received:** April 18, 2022 / Accepted June 06, 2022
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Muzzle brakes are the devices attached to the muzzle of the firearm and intended to trap and divert expanding gasses upwards or sideways, [1-6]. There are several designs of the muzzle brake, but they usually are tubular devices that utilize chambers and holes or vents. As the propellant gases impinge on the muzzle brake baffle, a portion of the gasses is deflected from the axial direction, which generates a forward impulse on the muzzle brake, hence decreasing the recoil energy.

Based on the 2D Euler equation, Zhang Huan-haw et al used a high resolution Roe scheme and the structured mesh technique to simulate the flying away of a high speed projectile from the bores through different muzzle brakes, [7]. Hong-xia Lei et al studied and analyzed the stress of the muzzle brake by using the finite element analysis based on the fluid-solid coupled method to evaluate the muzzle brake's reliability. First, a 3D numerical simulation of a muzzle brake flow based on CFD technology was conducted, and the muzzle brake force produced by side holes and baffles of each row was analyzed. Then, by loading the gas force on the corresponding surface of the muzzle brake using the fluid-solid coupled method, the stress distribution of the muzzle brake was analyzed. This study is helpful to the design and optimization of the muzzle brake, [8]. Based on internal ballistics calculation, solid works flow simulation tool and Ansys static structural, Ekanch Chaturvedi et al designed a new perforated muzzle brake and investigated its performance such as velocity distribution, pressure growth and muzzle brake force [9]. In order to reduce the recoil energy of the chain gun, Xiao et al studied the modeling and simulation of the low recoil firing of the chain gun by adopting a high efficiency recoil reduction way with new style high efficiency muzzle brake and buffer parameter combined. They studied the variation rules of gun recoil movement and recoil force of muzzle brake on three states: chain gun with the original buffer, chain gun with new high efficiency muzzle brake and original buffer, and chain gun with new high efficiency muzzle brake and new designed buffer combined. The results show that only a high efficiency muzzle brake combined with high efficiency damping buffer matching with reasonable parameters can reduce the recoil significantly [10]. Based on the interior ballistics calculations and the numerical simulation of the flow inside the muzzle brake, Czyżewska et al. developed a method for predicting the gas-dynamic efficiency coefficient for a perforated muzzle brake. A simple 1D single phase model of interior ballistics was used to determine the parameters of the flow at the inlet of the muzzle brake. Then, a 2D axisymmetric simulation of the flow inside the muzzle brake was performed. The mass flux at the inlet and outlet of the muzzle brake were determined and the gas-dynamic efficiency coefficient was calculated, [11]. A test firing of a small caliber gun with a muzzle brake was conducted in order to measure the muzzle brake force based on the strain measurement principle. Four strain gauges were pasted symmetrically on the outer surface of the barrel near the muzzle brake. After firing the axial strain of the barrel caused by the muzzle brake was determined and the muzzle brake force was calculated, [12]. Kung Jiang et al conducted a numerical simulation and experimental test to evaluate the muzzle brake performance with gauge pressure and muzzle brake efficiency. Two numerical simulations were carried out to calculate the pressure of the muzzle blast wave and the muzzle brake efficiency. The first was set up with three dimensional unsteady Euler equations ignoring the initial flow field and the second was set up with three dimensional unsteady Navier-Stokes equations with k-ω turbulence model and initial flow field with sliding projectile. For the experimental test, a howitzer was fired to measure the pressure inside the muzzle brake, recoil displacement, projectile velocity and gauge pressure at the given position. The muzzle brake efficiency was calculated experimentally using the recoil resistance work method. The numerical and the experimental results of the pressure and the muzzle brake efficiency were compared and they were in a good agreement, [13]. An experimental apparatus to measure recoil forces of sporting rifles and shotguns experienced by a typical shooter was developed, [14]. The gun movement during firing was reproduced by the apparatus through both inertial and spring type damping mechanisms. At different shooting conditions and with different ammunition, the horizontal and the vertical components of the recoil force were measured using two load cells. The gun movement was measured using high speed digital camera. The apparatus should prove useful for quantifying differences in the felt recoil as affected by different factors such as recoil reduction devices, ammunition type, gun weight, etc.

The force that occurs during the shooting process and depending on the use of the weapon must be adequately absorbed in order to reduce the load and the impact of the wave on the shooter (in the case of sniper rifle). In the case of integration of weapons on the combat platform (light combat vehicle, tank, vessel), the impact of the recoil force is smaller and can be absorbed by a suitable absorber built into the carrier, to reduce platform load and impact on firing conditions. The use of muzzle brakes depends on the recoil force, the type of weapon and the manner of use or carriage of the weapon.

The main contribution of the present work is development of an experimental setup in order to measure the recoil force and determine the muzzle brake efficiency. Two types of muzzle brake (MB) will be investigated (Fig. 1) and the obtained experimental results will be presented. Besides, an analytical model for determining the muzzle brake efficiency based on the Orlov method is adopted to the case of the investigated muzzle brakes. The experimental results would be used to validate the predictions of the analytical model.

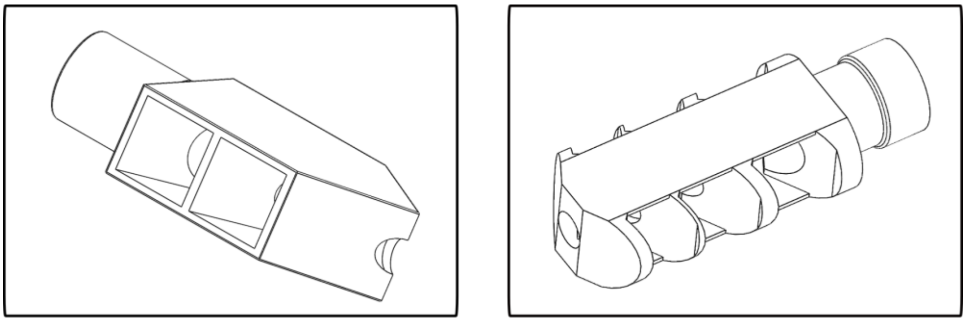

Fig. 1 Muzzle brake types: (left) Type 1, (right) Type 2

2. Mathematical models

In this study, the Orlov method as an analytical model is used to calculate the muzzle brake efficiency and muzzle brake force [15-18]. The method is based on the geometric parameters of the muzzle brake and the internal ballistic results of the release of gunpowder gases.

2.1 Muzzle brake efficiency

The main characteristic of the method is the muzzle brake efficiency (η), described as:

$$\eta = 1 - \left(\frac{1 + \alpha\beta \cdot \frac{\omega}{q}}{1 + \beta \cdot \frac{\omega}{q}} \right)^2 \tag{1}$$

where ω is the mass of propellant, q is the mass of projectile, β is the after-effect coefficient and α is the structural characteristic of the muzzle brake.

After-effect coefficient β is calculated as:

$$\beta = \frac{1300}{v_0}, \text{ if } v_0 < 700\ m/s \tag{2}$$

else,

$$\beta = 1.59 \frac{\sqrt{k \cdot p_M \left(W_{pc} + S \cdot L\right) / \omega}}{v_0} \tag{3}$$

where v_0 is the muzzle velocity, p_M is the muzzle pressure, L is the travel length of the projectile, W_{pc} the volume of the powder chamber, S is the area of bore cross section and k is the specific heat ratio of gases.

Structural characteristic α of the muzzle brake is determined by equation:

$$\alpha = K_0\sigma_1\sigma_0 \ldots \sigma_m + \sum_1^m K_{\sigma i}\xi_i\sigma_1\sigma_2 \ldots\ldots \sigma_{i-1}\left(1-\sigma_i\right) \cdot cos\psi_i \tag{4}$$

where K_0 is the coefficient of the muzzle brake cavity reactivity, σ is the relative amount of unused propellant gas in the muzzle brake chamber, K_σ is the coefficient of side-channel reactivity and ξ is the coefficient that takes into account the effect of gas expansion in the oblique cut.

The coefficient of muzzle brake cavity reactivity K_0 is expressed as:

$$K_0 = \chi_1\left[1 + \chi_2 \cdot \chi_3\left(K_H - 1\right)\right] \tag{5}$$

where,

$$\chi_1 = 0.98 \tag{5-a}$$

$$\chi_2 = \frac{\ln(\sec\theta)^2}{(\tan\theta)^2} \tag{5-b}$$

$$\chi_3 = 0.9 \tag{5-c}$$

Parameter χ_1 is the coefficient that takes into account the dissipative forces, χ_2 is the ratio that takes into account the expansion of the gases in the conic entrance of an angle θ

and χ_3 is the coefficient that takes into account the non-stationary expiration of gases from the barrel channel. Parameter K_H is the ideal nozzle reactivity coefficient and it is determined by equation:

$$K_H = \frac{\lambda_0 - \lambda_0^{-1}}{2} \tag{6}$$

where λ_0 is the ideal dimensionless speed and it depends only on the shape of the entrance to the muzzle brake cavity. This relation is expressed as:

$$\frac{S_s}{S} = \frac{\left(\frac{2}{k+1}\right)^{\frac{1}{k-1}}}{\lambda_0 \left(1 - \frac{k-1}{k+1}\lambda_0^2\right)^{\frac{1}{k-1}}} \tag{7}$$

where S_s is the cross-sectional area of the chamber at the beginning of the side channels.

The coefficient of side-channel reactivity K_σ is calculated in the same way as K_0.

The relative amount of unused powder gases σ is calculated according to the expression:

$$\sigma = \frac{1}{1 + \delta \frac{S_\sigma}{S_0}} \tag{8}$$

where S_σ is the small area of the side opening, S_0 is the surface of the outlet hole from the muzzle brake chamber and δ is the ratio of specific losses of the propellant gases through the side and central shaft of muzzle brake, and it is calculated as:

$$\delta = 0.95 \cdot \frac{\lambda_{01}^{-2} \cos\psi + 1}{\lambda_{01}^{-2} + 1} \cdot \left(1 - \frac{\frac{k-1}{k+1}\lambda_{01}^{-2} \cos^2\psi}{1 - \frac{k-1}{k+1}\lambda_{01}^{-2}}\right)^{0.5} \quad \text{for } \psi < \frac{\pi}{2} \tag{9}$$

$$\delta = 0.95 \cdot \frac{\left(1 - \frac{k-1}{k+1}\lambda_{01}^{-2}\right)^{0.5}}{1 + \lambda_{01}^{-2}} \cdot \left(1 - \frac{k-1}{k+1}\lambda_{01}^{-2} \cos^2\psi\right)^{\frac{k+3}{2(k-1)}} \quad \text{for } \psi > \frac{\pi}{2} \tag{10}$$

where ψ is the inclination angle of side openings, and λ_{01} is the real dimensionless speed in the muzzle brake cavity, which is calculated from the following equation:

$$\lambda_{01} = K_\sigma + \sqrt{K_\sigma^{\,2} - 1} \tag{11}$$

Coefficient ξ is determined by the following equation:

$$\xi = 1 + \tan\psi_{kp} \tan\Delta\psi \tag{12}$$

where, $\Delta\psi$ is the additional angle of deviation of the lateral gas flow at the exit of the side opening and ψ_{kp} is the angle of the oblique cross-section of the side opening.

The relation between $\Delta\psi$, ψ and K_σ is expressed in the Eq. (13):

$$\frac{\sin(\psi+\Delta\psi)}{\sin\psi} = \frac{K_\sigma+\sqrt{K_\sigma^{\,2}-1}}{\dfrac{K_\sigma}{\cos\Delta\psi}+\sqrt{\dfrac{K_\sigma^{\,2}}{\cos^2\Delta\psi}-1}}\left(\frac{k-(k-1)K_\sigma\left(K_\sigma+\sqrt{K_\sigma^{\,2}-1}\right)}{k-(k-1)\dfrac{K_\sigma}{\cos\Delta\psi}\left(\dfrac{K_\sigma}{\cos\Delta\psi}+\sqrt{\dfrac{K_\sigma^{\,2}}{\cos^2\Delta\psi}-1}\right)}\right)^{-\frac{1}{k-1}} \tag{13}$$

2.2 Muzzle brake force

During the after-effect period without using muzzle brake, the weapon recoil force is equal to the force of propellant gases pressure, which is calculated with the following equation:

$$F = S\cdot p_M\cdot exp\left(-\frac{t}{b}\right)\cdot\frac{1+\dfrac{\omega}{2q}}{1+\dfrac{\omega}{3q}} \tag{14}$$

Parameter t is the time variable during the after-effect period. Parameter g is the gravitational acceleration and b is the Bravin’s exponent of the after-effect period, and it can be calculated as follows:

$$b=\frac{(\beta-0.5)\omega v_0}{S\cdot p_M} \tag{15}$$

During the after-effect period when using muzzle brake, weapon recoil force (F) is given by:

$$F = \chi\cdot S\cdot p_M\cdot exp\left(-\frac{t}{b}\right)\cdot\frac{1+\dfrac{\omega}{2q}}{1+\dfrac{\omega}{3q}} \tag{16}$$

Parameter χ represents the impulse characteristic of the muzzle brake. It can be expressed, as:

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

Muzzle brake force F_{MB} during the after-effect period is given by:

$$F_{MB} = (1-\chi)\cdot S\cdot p_M \cdot exp\left(-\frac{t}{b}\right)\frac{1+\frac{\omega}{2q}}{1+\frac{\omega}{3q}} \tag{18}$$

The pressure in the barrel and the projectile velocity were obtained from the internal ballistic calculation, [19].

The structural parameters of the two types of muzzle brakes used during experimental research are shown in Table 1.

Table 1 Structural parameters of the muzzle brakes

Parameter	Unit	Value	
		MB type 1	MB type 2
Inclination angle of the side opening	degrees	120	130
Number of chambers	-	2	3
Area of the side opening	10^{-4} m^2	9	first: 7.5 second: 6 third: 4.5
Maximum cross-sectional area of chambers	10^{-4} m^2	9	9
Surface of the outlet hole from the MB	10^{-4} m^2	1.54	1.54

The parameters of gun and ammunition, used during experimental research are shown in Table 2.

Table 2 Specific parameters of gun and ammunition

Parameter	Unit	Value
Barrel length	m	1.007
Travel length of the projectile	m	0.923
Caliber	m	0.0127
Volume of the powder chamber	10^{-5} m^3	1.8
Mass of the projectile	10^{-3} kg	51.3
Mass of the propellant powder	10^{-3} kg	15.4

Based on the above equations, the calculation of the muzzle brake efficiency and muzzle brake force is conducted.

Based on the internal ballistic calculation, the muzzle velocity of the projectile is calculated, and its value is 818 m/s.

Table 3 summarizes the muzzle brake efficiency obtained by the analytical model for the two types of muzzle brake.

Table 3 Muzzle Brake Efficiency

Parameter	MB type 1	MB type 2
Muzzle brake efficiency [%]	48.41	48.72

The muzzle brake force of both muzzle brakes type 1 and type 2 as a function of time are calculated and presented in Fig. 2.

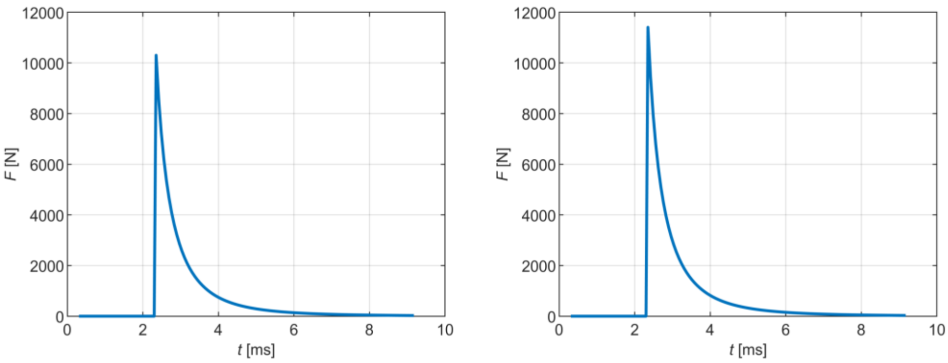

Fig. 2 Muzzle brake forces: (left) MB type 1, (right) MB type 2

3. Experiment

The standard anti-material rifle 12.7 mm was fired without and with two types of muzzle brake type 1 and type 2 (shown in Fig. 1) in order to measure recoil force, muzzle brake efficiency and the muzzle velocity of the projectile. The tests were conducted in the test center of Zastava Arms, Kragujevac.

Measuring system was based on rifle 12.7 mm, force measurement sensor, data acquisition system HBM Quantum MX410B (4-channel) and ballistic measuring system for projectile velocity measurement. A schematic diagram of the experimental apparatus is shown in Fig. 3, and its picture is shown in Fig. 4. The measuring shooting equipment consisted of Zastava Arms Fixed Firing Rest M2 (mass 400 kg, dimensions 1300 x 420 x 830 mm, elevation angle 3° with drift setting device) and Universal Receiver (mass 14 kg, dimensions 300 x 215 x 86 mm with manual and electromechanical triggering).

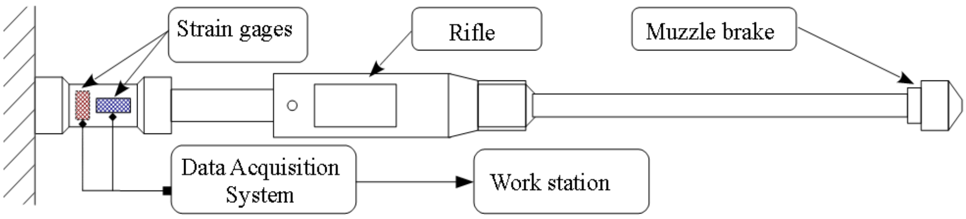

Fig. 3 Schematic of experiment setup

The ammunition used in the test is 12.7x108 mm type Ball, where the projectile mass and the propellant mass are given in Table 2.

Fig. 4 Recoil measurement apparatus

The rifle was fixed on a rigid position to restrain it from moving. The recoil force is measured using a force measurement sensor which consists of four strain gages 350 Ω connected in a full Wheatstone bridge configuration. The strain gages have to be fixed on the locations corresponding to the biggest stress level. So, a dog bone shaped specimen was created on a cylindrical rod which was fixed at the end of the rifle to allow the concentration of the stress on this area, Fig. 5. In order to measure the recoil force which is the axial force, the two pairs of gages were fixed as the following: one pair is in the principal direction of the barrel axis and the other one is in transversal direction used in temperature compensation and bending cancellation [20-23], as shown in Fig. 5.

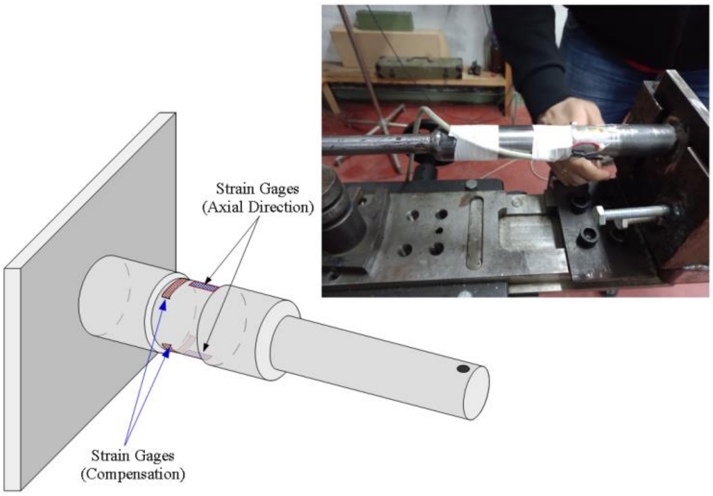

Fig. 5 Force measurement sensor: (left) schematic, (right) picture

The calibration of the force sensor was conducted in force range of 100 kN, with maximal nonlinearity of 0.3 %.

The sampling frequency in the data acquisition channel was set for 96 kHz. The initial velocity of the projectile was measured using a ballistic chronograph placed 10 m from the muzzle.

The measuring tests of recoil force and projectile velocity were carried out for three different cases: rifle without muzzle brake, rifle with MB type 1, and rifle with MB type 2. The firing test with a series of five shots was conducted to establish the baseline data. To ensure the accuracy of the data, a series of ten shots was rendered for each case, and the recoil forces, as well as projectile velocity were recorded. Thereby, the average recoil force and velocity for the three different series were calculated.

The coefficient of variation (CV) for the maximal recorded recoil forces (Max RF) and velocity was calculated to measure the data dispersion. The results are shown in Table 4.

Table 4 Coefficient of variation of the obtained results

	without MB		with MB type 1		with MB type 2	
	Max RF	Velocity	Max RF	Velocity	Max RF	Velocity
CV [%]	2.3716	0.0652	3.3602	0.1265	2.4881	0.2119

The coefficient of variation does not exceed 4 %, which signifies that the recorded data were consistent and had a low dispersion.

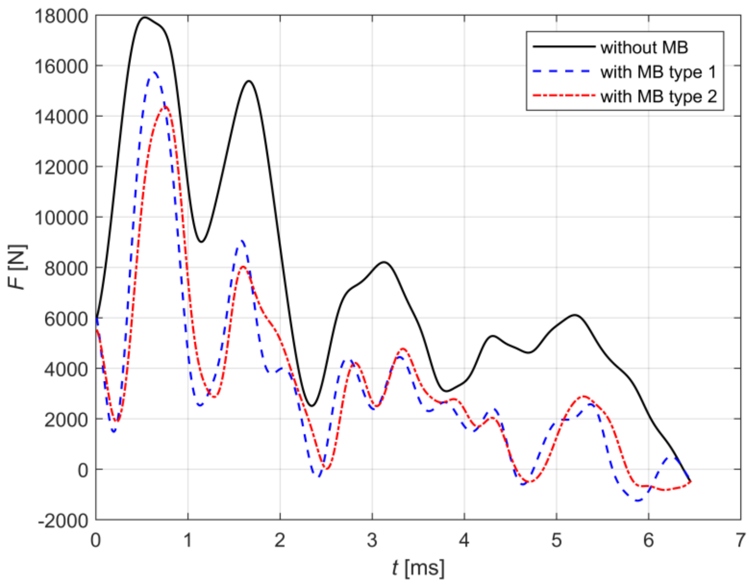

Fig. 6 Experimental averaged recoil forces

The experimental raw data were filtered using a low pass filter in order to eliminate the high frequency noise.

Fig. 6 represents the average measured recoil forces as a function of time for the three above mentioned cases.

It is noticed that without using a muzzle brake, the average maximum of measured recoil force was 17904 N. In the presence of the muzzle brake, the maximum of recoil force is significantly reduced. In the case of using the MB type 1, the average maximum of recoil force is 15729 N, which corresponds to a reduction of 12.9 % compared to the case without muzzle brake. Meanwhile, in the case of using the MB type 2, the average maximum of recoil force is equal to 14367 N, with a reduction of 19.8 % compared to the case without muzzle brake.

The recoil force described in Fig. 6 represents the force in after-effect period. The maximum force recorded during the measurement, while the projectile is in the barrel, is less than the maximum measured force when the projectile leaves the barrel.

The average measured muzzle velocity for the three cases is 815.0313 ± 2.23 m/s.

4. Results and Discussion

The experimental muzzle brake efficiency can be calculated as [24]:

$$\eta = 1 - \left(\frac{1 + \beta_m \cdot \frac{\omega}{q}}{1 + \beta \cdot \frac{\omega}{q}} \right)^2 \tag{19}$$

With the use of the muzzle brake, after-effect coefficient β_m is given by:

$$\beta_m = 1 + \frac{I_m}{\omega \cdot q} \tag{20}$$

where I_m is the impulse of the recoil force with muzzle brake.

Without using the muzzle brake, after-effect coefficient β can be calculated as:

$$\beta = 1 + \frac{I}{\omega \cdot q} \tag{21}$$

where I is the impulse of the recoil force without a muzzle brake.

Based on the experiment results, the efficiency of the two muzzle brakes is calculated. Experimental and analytical velocities, maximum of muzzle brake forces and muzzle brakes efficiency were compared as shown in Table 5.

The muzzle brake efficiency of MB type 1 is 47.6 %, which corresponds to a relative difference of 1.67 % compared to the one obtained analytically, while the muzzle brake efficiency of MB type 2 is 46.51 % with a relative difference of 4.53 % to the one obtained analytically.

For the muzzle brake type 1, the analytical peak value is around 10303 N, while the obtained experimental value is 10507 N, which corresponds to a relative difference of

1.94 %. As for the muzzle brake type 2, the observed analytical peak value is 11405 N, with a corresponding experimental value of 11644 N, which amounts to a relative difference of 2.05%.

Regarding the muzzle velocity, the analytically calculated velocity is 818 m/s while the measured value is 815.03 m/s with a relative difference of 0.36 %.

Table 5 Comparison between experimental and calculated results

	Max. muzzle brake force [N]		Muzzle brake efficiency [%]		Muzzle Velocity [m/s]
	MB type 1	MB type 2	MB type 1	MB type 2	
Experiment	10507	11644	47.60	46.51	815.03±2.23
Analytical	10303	11405	48.41	48.72	818
Relative difference [%]	1.94	2.05	1.67	4.53	0.36

The relative differences are less than 5 %, which means that the analytical results are in a good agreement with the experimental ones.

In this paper, the impulse of the recoil force in the period when the projectile leaves the barrel was used to determine the efficiency of the muzzle brake. If the total period was observed (from firing), the difference in the force impulses acting on the weapon with and without the muzzle brake would be higher due to a longer time, which would lead to a higher value of the muzzle brake efficiency. In the period when the projectile is inside the barrel, the measurement results show a small difference of the impulse of the recoil forces with the muzzle brake in relation to the weapon without the muzzle brake, which is conditioned by a higher total mass of the weapon and muzzle brake, and does not objectively affect the determination of efficiency.

The measurement results, for the period in the barrel, very well coincide with the results obtained on the basis of internal ballistic calculation, [19] in terms of maximum force (14 kN) and time (2.2 ms). Considering that the aim of the research is to determine the muzzle brake efficiency, that part of the curve of the force, i.e. the impulse of the pressure force of the gunpowder gases was not taken into account, because then it does not act on the muzzle brake. The moment of appearance of a specific shape on the curve of the measured force (saddle shape part of function) in all results of force measurement coincides with the analytically determined duration of the firing process (until the projectile comes out of the barrel). The results of internal ballistics calculations, [19] were used in this paper for analytical determination of muzzle brake efficiency.

The difference in the maximum forces of the muzzle brakes type 1 and type 2 according to the analytical and experimental model is about 10 %, that is, the muzzle brake type 2 generates a higher force of the muzzle brake by about 10 %. These differences can be deduced from the recoil forces diagrams shown in Fig. 6. However, according to the experiment, the muzzle brake force impulse is 1.1 % higher in type 1, and according to the analytical model, the muzzle brake type 2 has a higher impulse by about 8.9 %.

On the basis of correctly measured values of the maximum force and impulses, other devices for the absorption of the recoil force (spring absorber, rubber lining, etc.) can be dimensioned adequately and precisely.

The design of the muzzle brake type 2 is more complex in technological and constructive terms. Therefore, the price-quality ratio is on the side of the muzzle brake 1. Perforated muzzle brakes are often used for the purpose of absorbing recoil force and represent the simplest muzzle devices, but their efficiency is lower compared to the types of the muzzle brakes presented in this paper.

5. Conclusion

In the presented study, the muzzle brake efficiency was investigated experimentally and analytically. Two muzzle brakes model fitted on a 12.7 mm anti-material rifle were used in this work. An experimental test apparatus to measure the recoil force and the muzzle velocity of the projectile with and without a muzzle brake was developed and applied. Then, the muzzle brakes efficiency was calculated. In addition, the Orlov method for calculating muzzle brake efficiency combined with the internal ballistics' calculation was used as an analytical model.

The analytical model is validated by comparison with the experiment results. The difference in relation to the maximum of forces is around 2 %. The differences between the analytical and experimental results are less than 5 %, which reveals the feasibility and the accuracy of the analytical model.

The results of the measured recoil forces, during three sets of series, were accomplished in the same environmental and experimental conditions. An observed and described very good agreement of the values and the trend of the measured recoil force function in relation to the analytical results, and between three sets of measuring, also can verify the proposed experimental methodology. The reliability of the presented experimental procedure and results can be evaluated, also through the described coefficient of variation, which is small, bellow 4 %, especially according to the impulse nature of the observed force.

The direct approach and reliable procedure of the experimental tests, regardless of the developed analytical and numerical investigation, in order to determine the muzzle brake efficiency, is significant.

The presented research can be helpful for future studies of the design and optimization of muzzle brakes.

Acknowledgements: *The paper is a part of the research done within the project No. VA-TT/2/16-18 titled "The research of dynamical behavior of the vehicle under the influence of the firing force of integrated weapon" supported by the University of Defence in Belgrade. The authors would like to thank to Zastava Arms, Kragujevac, Republic of Serbia, for providing experimental facilities.*

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