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Preliminary communication

# Possibility of Reducing the Overpressure of Shock Wave of Powder Gases around the Mortar

Miodrag LISOV, Slobodan JARAMAZ, Mirko KOZIĆ, Ivana IVANOVIĆ

**Abstract:** This paper resulted from the research of the overpressure of the shock wave of the powder gases, which occurs during firing of the mortar. Work encompasses modeling and computation of the overpressure field. Increasing overpressure around the mortar is analyzed in the case of using the largest powder charges. In order to reduce the overpressure a corresponding technical solution has been proposed. The solution in the form of divergent nozzle has been proposed and it is placed at the barrel muzzle. The paper also analyzes the impact of this solution to reduce the overpressure intensity at the crew position.Computation results of the overpressure of the powder gases, which were obtained by the realization of numerical calculation, based on the application of the finite volume method, were confirmed by the experimental results, achieved in the firing experiments.

**Keywords**: experimental ballistics; gas dynamics; interior ballistics; intermediate ballistic; mortar; powder gases; shock wave

## 1 INTRODUCTION

The need for the increase of the maximum range, which is mostly achieved by better aerodynamic characteristics of the missile and by the construction changes at the weapon, also requires the use of greater, actually more powerful powder charges. As a consequence, the more powerful powder gases have an increase of the operation pressure in the weapon barrel and a greater production of the powder gases, which leads to the increasing overpressure around the weapon. Besides, the greater firing power is achieved by increasing the rate of fire and leads to increasing the number of impulse strains which the mortar personnel is exposed to. As a consequence there is the occurrence of the greater overpressure around the weapon and the greater number of the shockwaves during the interval of firing action, which is particularly emphasized at the mortar, where the firing operator (gunner) is in the vicinity of the barrel during the procedure of loading and firing of the weapon [1]. These loads are particularly emphasized in the regime of a fast and rapid rate of fire.

The mentioned problems impose the need of solving the increased overpressure of the powder gases [2] and reducing its intensity to the acceptable level.

Out of the mentioned reasons it is necessary to know the mechanism of emerging of the side effects which are manifested during the firing process, so as to perform their mathematical modeling and computation of characteristic gas dynamic values [3]. For the verification of the applied numerical model [4] the experimental measuring method was used.

This paper describes a solution to reduce the level of overpressure that is similar to the blast diffuser attenuator which is applied to the M252 81mm Mortar [5].

## 2 MATHEMATICAL MODEL

Mathematical model is described with conservation of mass, momentum and energy tensor form:

$$\frac{\partial \rho}{\partial t} + (\rho v_i)_{,i} = 0, \tag{1}$$

$$\rho \frac{\partial v_j}{\partial t} + \rho v_{j,i} v_i + p_{,j} - \tau_{ij,i} - \rho F_j = 0, \tag{2}$$

$$\rho \frac{\partial e}{\partial t} + \rho e_{,i} v_i + p v_{i,i} - \tau_{ij} v_{j,i} + q_{i,i} - \rho r = 0, \tag{3}$$

where: $\rho$ is the fluid density, $v_i$ – components of the velocity vector components, $e$ - internal energy per unit mass, $F_i$ – components of volume forces vector, $p$ – pressure, $\tau_{ij}$ – viscous stress tensor, $T$ – temperature, $q_i$ – heat flux and $r$ – heat supply per unit mass.

The above conservation equations may be put in the so-called conservation form of the Navier-Stokes system of equations [6, 7]:

$$\frac{\partial U}{\partial t} + \frac{\partial F_i}{\partial x_i} + \frac{\partial G_i}{\partial x_i} = B, \tag{4}$$

where: $U$ is conservative flow variables vector per unit volume, $F$ is convective flux variables vector, $G$ is diffusion flux variables vector and $B$ is source terms (mass, momentum and energy).

Pressure change with time on the barrel muzzle is defined by the Eq. (5):

$$p = p_{\mathrm{p}} \mathrm{e}^{-Kt}, \tag{5}$$

where $K$ is empiric coefficient for barrel ($K_{\mathrm{b}}$ = 0,75) or coefficient for nozzle ($K_{\mathrm{n}}$ = 0,50), $p$ is pressure, $p_{\mathrm{p}}$ is the initial pressure and $t$ is time.

From the energy equation defined as:

$$\frac{p}{RT} \frac{D}{Dt}\left(c_{\mathrm{p}} T_0\right) = \frac{\partial p}{\partial t}. \tag{6}$$

Respectively:

$$\frac{c_{\mathrm{p}}}{RT} \frac{DT_0}{Dt} = \frac{1}{p} \frac{\partial p}{\partial t}. \tag{7}$$

If we put, $\frac{c_{\mathrm{p}}}{R} = \frac{\gamma}{\gamma - 1} = m$, Eq. (7) becomes:

$$m\frac{1}{T}\frac{DT_0}{Dt}=\frac{1}{p}\frac{\partial p}{\partial t}. \tag{8}$$

The dependence between total and static temperature is given at the Eq. (9):

$$T_0=T\left(1+\frac{\gamma-1}{2}M^2\right). \tag{9}$$

Assuming that the Mach number at the barrel muzzle during the release of powder gases is approximately equal to 1, Eq. (8) becomes:

$$mr\frac{1}{T}\frac{\partial T}{\partial t}=\frac{1}{p}\frac{\partial p}{\partial t}, \tag{10}$$

wherein: $r=1+\frac{\gamma-1}{2}$.

After the integration of Eq. (10) it is obtained:

$$\ln\frac{T}{T_{\mathrm{p}}}=\frac{1}{K}\ln\frac{p}{p_{\mathrm{p}}}, \tag{11}$$

wherein: $k=mr=\frac{\gamma(\gamma+1)}{2(\gamma-1)}$.

The final expression for the change of temperature at the pressure inlet is obtained as:

$$T=T_{\mathrm{p}}\left(\frac{p}{p_{\mathrm{p}}}\right)^{\frac{1}{k}}, \tag{12}$$

where $T$ is temperature of the powder gases, $T_{\mathrm{p}}$ is initial temperature of the powder gases and the $\gamma$ is ratio of specific heat powder gases $C_{\mathrm{p}}/C_{\mathrm{v}}$.

The temperature at the pressure inlet is a function of time because of the pressure dependence on time.

## 3 PROPOSAL OF THE CONSTRUCTION SOLUTION

The initial assumption was that the integration of the divergent nozzle at the barrel muzzle shall provide significant reducing of the overpressure of powder gases at the exit of the nozzle, by which the reducing of the overpressure level of the powder gases in the area around the weapon shall be accomplished. The measuring point for measuring the pressure MP1 is at the input cross section of the divergent nozzle, and the measuring point MP2 is at the exit cross section (Fig. 1). Divergent cone has 15° semi-angle and length 110 mm.

Described solution is made and used, during the 120 mm mortar firing testing.

During firing the mortar shell had sealing ring, therefore the instantaneous flow of powder gases before exiting the mortar shell from barrel was ignored.

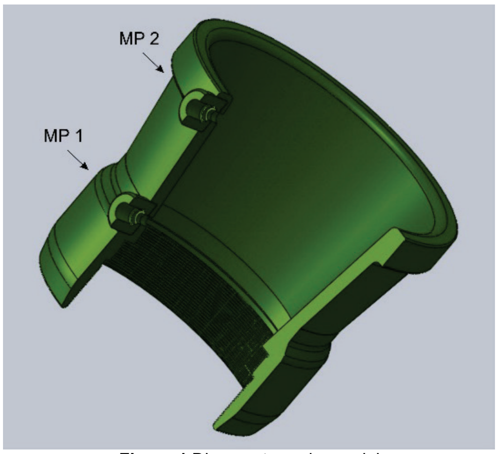

**Figure 1** Divergent nozzle, model

## 4 NUMERICAL MODEL

Computational fluid dynamics (CFD) for this kind of problems, based on the finite volume method (FVM) [8] was used in obtaining the complex flow phenomena. FVM is especially flexible for unstructured grids that enable adaptation based on the numerical solution.

Numerical computations were conducted on the basis of the proposed mathematical model adding also the ideal gas equation of state both for air and propellant. Basically, the procedure is divided into two parts. In the first part the geometry and the numerical mesh are generated. In the second part a preparation is performed of the data necessary for the ANSYS FLUENT software where the averaged Navier-Stokes equations are solved.

In order to better resolve the shock wave over time adaptive mash is used [9] based on the pressure gradient [10], because of its very high value near the shock. Dynamic adaption works very efficiently in this case, because the mesh is refined near the shock and coarsened after the shock passage [11, 12]. The basic mesh in numeric domain consists of 50000 triangular elements.

In the process of numerical simulation, the exit cross section, on the muzzle barrel, which corresponds to the measuring point MP2 on the nozzle is a boundary of the numerical domain defined as pressure inlet, with pressure change with time defined as in Eq. (5).

The presumption is accepted that at the critical section (at barrel muzzle) the Mach number is equal to the 1, this fact is used in calculating powder gases flow velocity and mass flux.

In this way the shock wave front, which moves through the space [13], causing the change of the condition in the undisturbed environment, is clearly noticed. The disturbance is manifested as a sudden change of the characteristic parameters of the environment: pressure, temperature and density of the gas.

Only the results from two-dimensional (2D) simulations are given because of two reasons. First, measuring points MM1, MM2 and MM3 lie in the same plane in which flow simulations were performed. But more important is that 3D computations [14] with used software were not able to properly resolve neither the strength nor the position of the shock wave. The unsteady explicit solver with explicit local time-stepping specially designed for the shockwave tracking was used. The CFL was limited to 0.8 corresponding to time step $2\times10^{-8}$ seconds. In order to simulate the propellant flow species model was used where material properties were taken into consideration, including the gas constant and specific heat at constant pressure. The far-field of the numerical domain is 100 calibers from the muzzle. It was defined as pressure outlet with zero static gauge pressure, velocity and propellant mass fraction, whereas density and temperature are equal to the values of the ambient air. The same values of the corresponding quantities were set as the initial conditions in the whole domain.

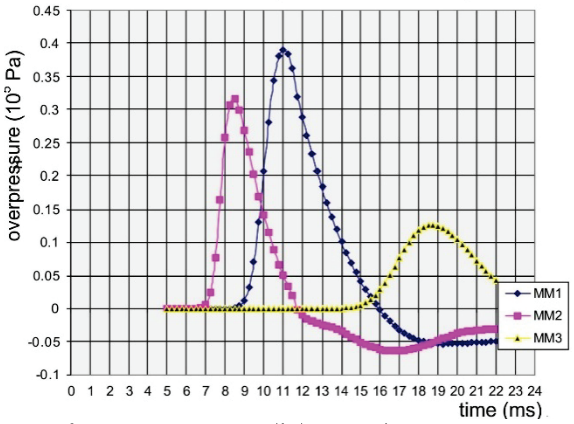


**Figure 2** Gas dynamic computation (2D), results of the overpressure, mortar barrel without divergent nozzle

The results of the overpressure of the powder gases, given in the time function and computed for the characteristic measuring points (MM): 1, 2 and 3, for the case of the firing from the 120 mm mortar are shown in Fig. 2 and Fig. 3. The numerical results presented in Figs. 2 and 3 correspond with powder charge (O+7).

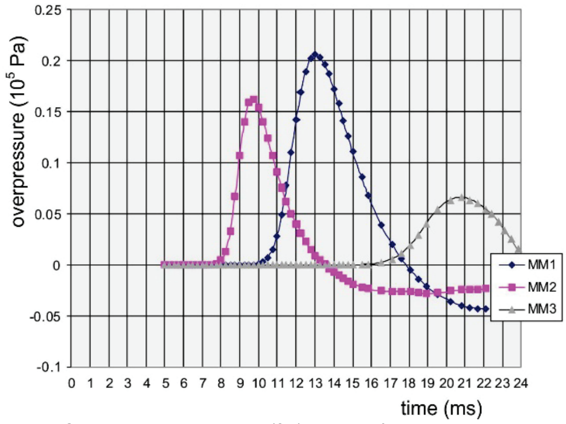


**Figure 3** Gas dynamic computation (2D), results of the overpressure, mortar barrel with divergent nozzle

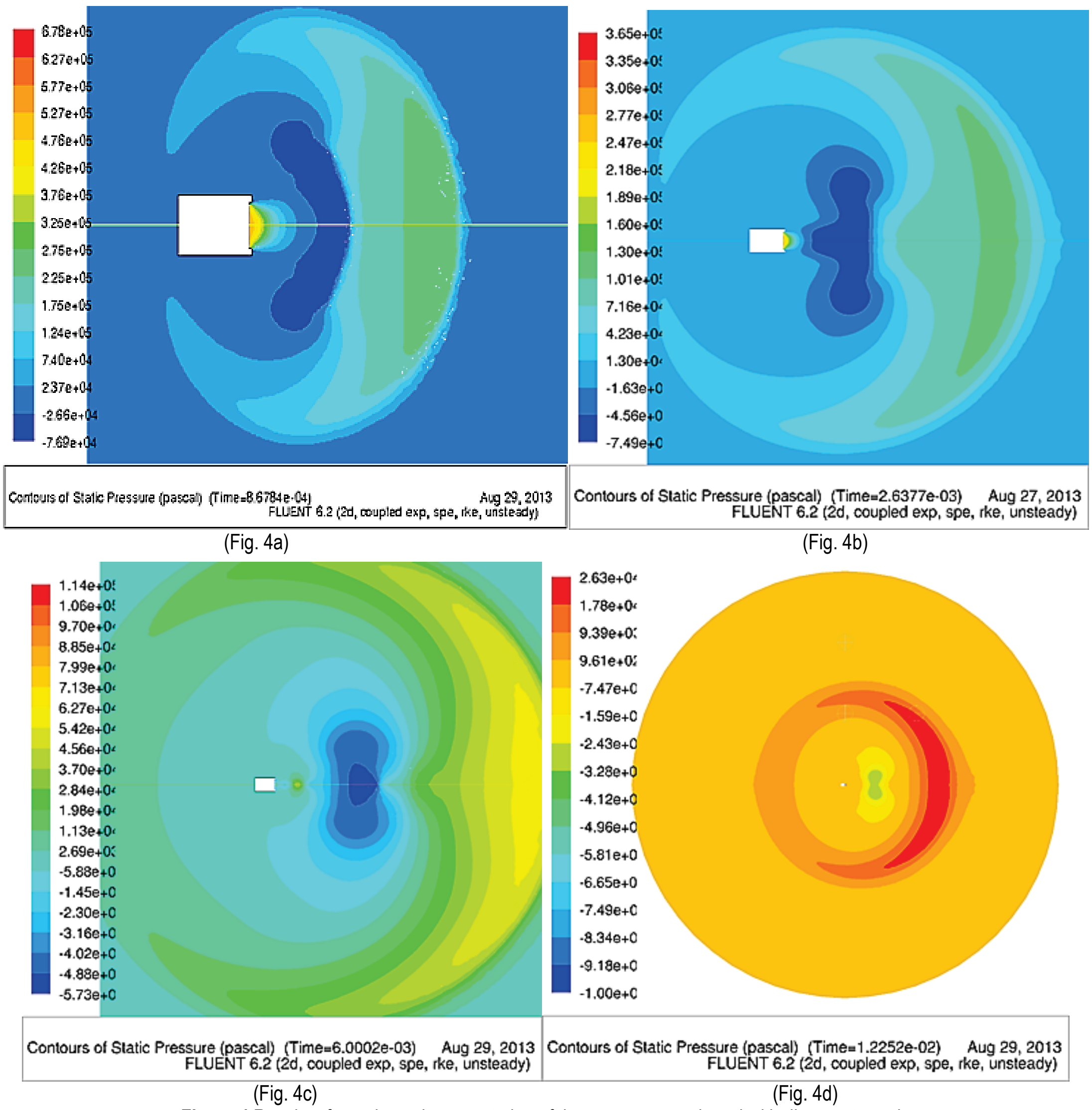


**Figure 4** Results of gas dynamic computation of the overpressure, barrel with divergent nozzle

The calculation was made in two cases, barrel without divergent nozzle and barrel with divergent nozzle. Calculations show a reduction of overpressure when the divergent nozzle is placed on a mortar barrel (Fig. 3).

Graphical representation of results of gas dynamic calculation is shown in Fig. 4. In the pictures we see the spreading of the shock wave through the surrounding air. Beside that we can see the shape and spatial distribution of the overpressure field around mortars.

Measuring points MM1, MM2 and MM3 are located in the plane at a height of 1.6 m and measuring point MM4 in the second plane at the height of 0.8 m. The height of the mortar muzzle is 1,4 m and elevation in conducted experiments is 45°.

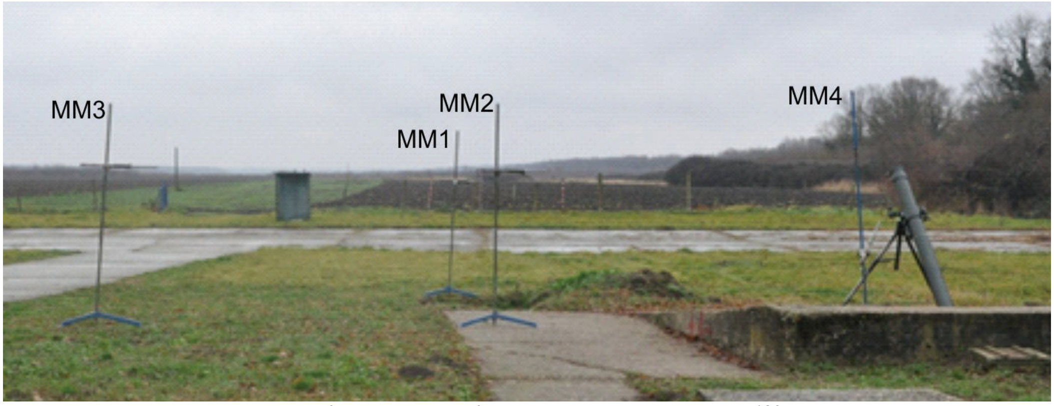


**Figure 5** Display of measuring points for overpressure measuring around 120 mm mortar

Characteristic measuring points MM1, MM2, MM3 and MM4, for which the calculation was done and overpressure meassured, are shown in Fig. 5 (during the experiment) and Fig. 6 (scheme blast pressure sensors).

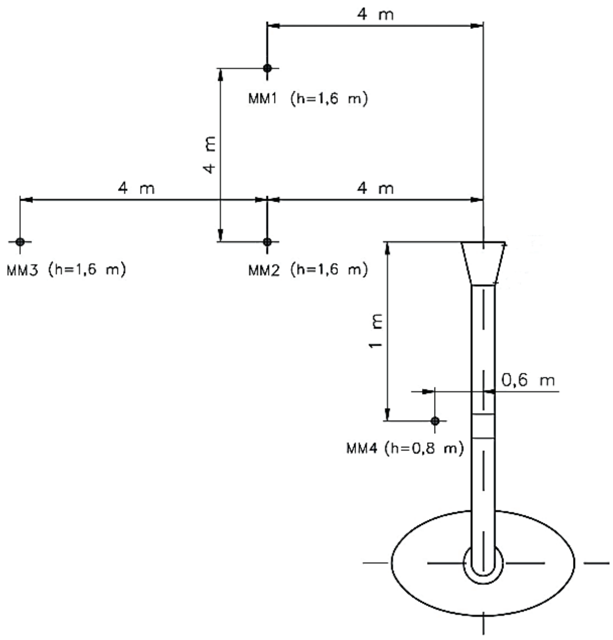


**Figure 6** Measuring points scheme

## 5 INTERIOR BALLISTIC CALCULATIONS

Interior ballistics calculations are done in the case of firing new extended range 120 mm mortar shell with a new concept of gun powder charge. Calculations were made for the powder charge (O+6), (O+7) and (O+10), which means, ignition charge and 6, 7 or 10 increment charges.

Interior ballistics calculations use the software which gives the solution of the main problems of internal ballistics for mortars with a smooth barrel, using the simplified Serebrjakov method [15]. Input data for interior ballistics calculations are given in Tab. 1.

**Tabe 1** Input data for interior ballistics calculations

| | |
|---|---|
| Mortar120 mm | |
| Shell 120 mm | |
| Gun powder | double based |
| Shell weight | 15,6 kg |
| Weight of ignition charge | 0,040 kg |
| Weight of one increment charge | 0,081 kg |
| Path of the projectile in barrel | 1,40 m |
| Gun powder chamber volume | $4{,}07\times10^{-3}$ m$^3$ |

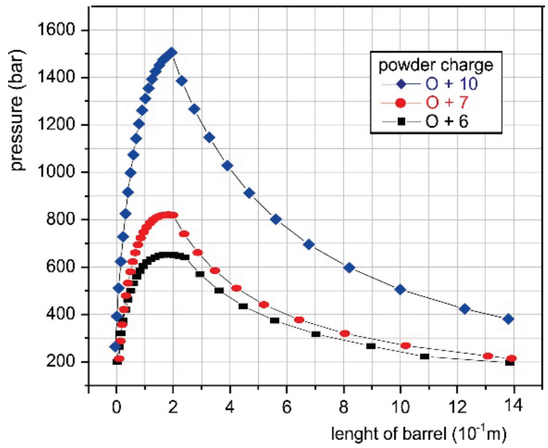


**Figure 7** Comparative overview of pressure versus barrel length for firing 120 mm

For new extended range mortar shell 120 mm new powder charge with two types double based gun powders was used.

Pressure versus barrel length, i.e. pressure calculations for three presented examples are given in Fig. 7.

It was noted that an increase in powder charge affects the increase in the working pressure in the mortar barrel. We also see that increase in powder charge affects the increase of pressure in the exit cross section of the barrel.

## 6 EXPERIMENTAL TESTING

Experimental testing was realized by firing from the mortar with and without the divergent nozzle at the barrel muzzle [16]. The overpressure values at the characteristic measuring points around the mortar barrel were measured with the PCB sensors.

The overpressure values at the characteristic measuring points around the weapon barrel were measured with the PCB sensors (Blast Presure "Pencil" sensor, Model 137A24, Pezotronics), as shown in Fig. 8. The position of all the measuring points for measuring the overpressure around the 120 mm mortar during firing is given in Fig. 5 and Fig. 6.

**Figure 8** Display of PCB sensors in gunner's place, next to a mortar

## 7 RESULTS ANALYSES

The calculation method is based on the described mathematical model and two-dimensional (2D) numerical simulation. Comparison of the overpressure computation and experiment results is given in Tab. 2. These results refer to the firing from the 120 mm mortar (barrel with divergent nozzle) with powder charge (ignition charge + 7 increment charges).

**Table 2** Overpressure computation and experimental results

| Mortar | 120 mm barrel with nozzle | |
|---|---|---|
| Mortar shell | $\Delta p$, overpressure - $10^5$ Pa | |
| Charge (0+7) | Model (2D) | Experiment |
| MM1 | 0.206 | 0.183 |
| MM2 | 0.162 | 0.124 |
| MM3 | 0.066 | 0.055 |
| MM4 | 0.129 | 0.107 |

Generally, the results obtained with a gas dynamic computation (2D) are fully satisfactory, as confirmed by the experimental results (Tab. 1, Fig. 8). In the available literature [17], there is a fact stating that the model of gas dynamic computation (2D) with the cylindrical shock wave is of a greater overpressure value in comparison to the experimental results which have been confirmed in this case.

Overpressure computation and experimental results, for the case of firing from the 120 mm mortar (barrel with divergent nozzle), with powder charge (ignition charge + 7 increments), are shown in Fig. 9.

New mortar shell has a significantly larger powder charge, which results in increasing overpressure at the gunner position. To reduce the overpressure a divergent nozzle is placed on the muzzle. The usefulness of this device is verified by firing mortars experiments.

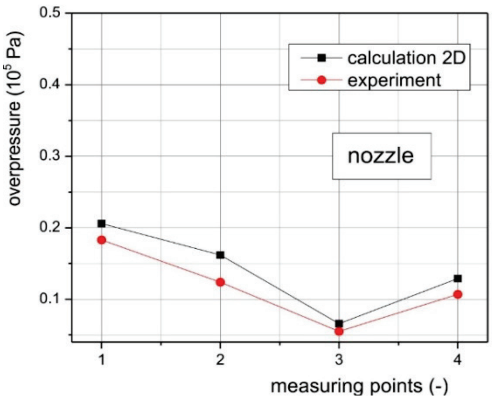


**Figure 9** Overpressure computation and experimental results, 120 mm mortar, (barrel with divergent nozzle)

We can see a significant reduction in overpressure in gunner's position (MM4) and a slight increase in overpressure of the measuring points away from the crew (MM1, MM2 and MM3).

This is a consequence of the fact that in addition to the further expansion of gases that occur in the nozzle and affect the reduction of overpressure, there comes to diverting air flow away from the crew.

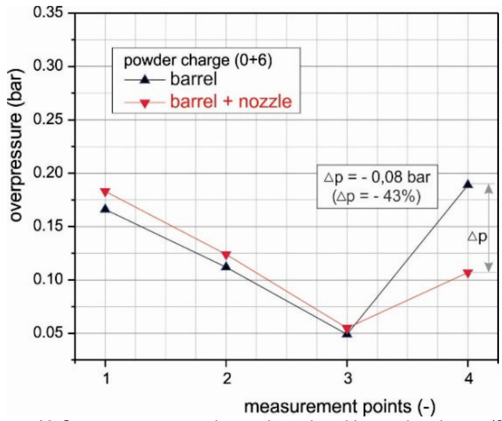


**Figure 10** Overpressure experimental results with powder charge (0+6)

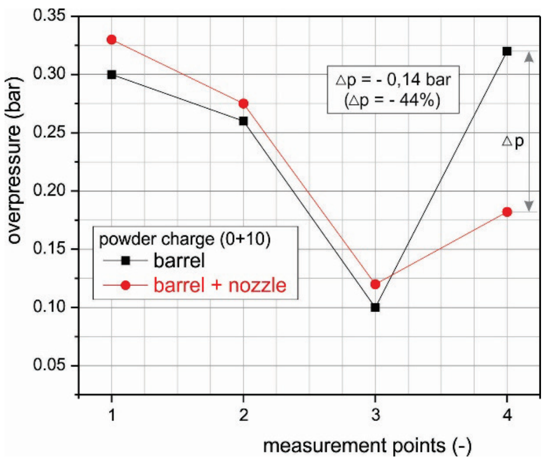


**Figure 11** Overpressure experimental results with powder charge (0+10)

A significant reduction of the overpressure, at the gunner's position, is about 40 %. In the case of firing from the 120 mm mortar with smaller powder charge (0+6) is

($\Delta p = 0{,}08\times10^5$ Pa) and the largest powder charge (0+10) is ($\Delta p = 0{,}14\times10^5$ Pa). Reducing the overpressure is evident on the gunner's site when we use a divergent nozzle during firing (Fig. 10 and Fig. 11).

During the firing with the largest powder charge blast effect which accompanies increasing the overpressure, an injury may be caused to the crew because it is very close to the weapon.

Acceptable and recommended level of overpressure for gunner is $\Delta p < 0{,}30\times10^5$ Pa. Position of the mortar crew is shown in Fig. 12, measuring point MM4 is the actual gunner's position.

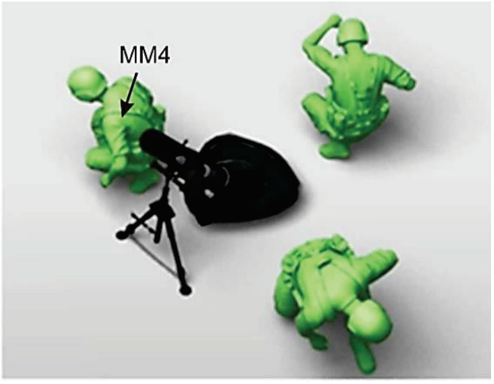


**Figure 12** Display of mortar crew during the firing

## 8 CONCLUSIONS

On the basis of the conducted analysis, based on the computation results, experimental testing with the 120 mm mortar system and applied construction solutions the following can be concluded:

- Gas dynamics computations, with 2D numerical simulation, showed that the proposed mathematical model with the applied software using the adaptively generated mesh determines the position and shock wave strength accurately and precisely enough,
- With the largest powder charge (O+10), the gunner position, using divergent nozzle achieves a reduction of overpressure of more than 40 %.
- In this case the overpressure is reduced with $\Delta p = 0{,}32\times10^5$ Pa at $\Delta p = 0{,}182\times10^5$ Pa.
- Proposed technical solution for reducing the overpressure intensity at the mortar gunner's position, gave satisfying results and is experimentally confirmed.
- In this way, better conditions for the crew during firing are achieved.

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**Contact information:**

**Miodrag LISOV,** MSc, M Eng.
**Mirko KOZIĆ,** Research Fellow PhD, M Eng.
Military Technical Institute, Ministry of Defence,
Ratka Resanovića br. 1, 11030 Belgrade, Serbia
E-mail: lisov@beotel.rs
E-mail: mkozic@open.telekom.rs

**Slobodan JARAMAZ,** Full Professor PhD, M Eng,
**Ivana IVANOVIĆ,** PhD, M Eng.
University of Belgrade, Faculty of Mechanical Engineering,
Kraljice Marije 16, 11000 Belgrade, Serbia
E-mail: sjaramaz@mas.bg.ac.rs
E-mail: iivanovic@mas.bg.ac.rs