Sound Effect of RPG-7 Anti-Tank Grenade Launcher for Shooting Training

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Abstract:
The purpose of this research is to use the released energy of the liquid carbon dioxide for the PET bottle to burst, which can simulate safely and cheaply the combat sound effects. This article deals with the mathematical modelling of the problem, which is the base for the design of this device that would simulate the sound effects of the RPG-7 launching and that can be used for the RPG-7 hand-held anti-tank grenade launcher in combat shooting training. The prototype of this device has been extensively tested and has shown to be suitable for military use.

Keywords:
Sound effect, shooting training, practice grenade, RPG-7

1. Introduction
The simulation of firearms sound effects during the combat shooting training is crucial for soldiers. To guarantee safety while training, as well as low operating costs, numerous sound generators have been used, such as digital sound amplifiers or specific devices capable of generating sound effect that uses explosives, detonation of an oxygen-propane mixture, or the released energy of compressed/liquid gas.

The operating principle of simulation of the sound effect is shown in Fig. 1. A certain amount of carbon dioxide (CO₂) passes through the open control valve into the PET bottle. The pressure within the PET bottle increases rapidly and causes its explosion. Liquid CO₂ is safely used in many civilian applications and hence it is both easily available and cheap. Empty PET bottles are also obtainable in mass quantities. Thus, we can conclude that this is an advantageous way to simulate a real firing experience of the RPG-7 in military training.

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Fig. 1 Scheme of the sound generating: 1 – CO\textsubscript{2} tank, 2 – PET bottle, 3 – control valve

The burst pressure of a PET bottle depends on its sheet thickness, internal volume, and material what it is made of. PET bottles sheet thickness is from 0.30 mm. Usually, 1.5 litre PET bottles burst in the range of pressures 1.17 to 1.38 MPa. For example, a 1.5 litre soda bottle explodes at 1.2 MPa, a 2 litre soda bottle bursts at 1.31 MPa, and a Trader Joe’s bottle with thick sheet can withstand over 1.38 MPa [1, 2].

Experiments held in the Weapon Technology Centre of the Le Quy Don Technical University in Hanoi have shown that the burst pressure of common 1.5 litre PET soda bottles is about 1.2 MPa and the bottle explosion produces a sound with an intensity of the sound pressure level 135 dB. Bottles break in the longitudinal direction and hence no plastic fragments are produced. Therefore, it is possible to introduce this system to the design of training version of the PG-7 anti-tank grenade (see Fig. 2).

Fig. 2 Design drawing of the training RPG-7 grenade launcher: 1 – CO\textsubscript{2} tank, 2 – PET bottle, 3 – control valve, 4 – nozzle, 5 – profile groove, 6 – launcher tube, 7 – practice grenade, 8 – spring, 9 – firing pin, 10 – lever, 11 – connecting pipe

Before shooting the gun, the CO\textsubscript{2} tank 1 is inserted into the front position of the training warhead body 7 and here it is kept by the lever 10. The tank 1 compresses the spring 8 in this position. When the trigger is pressed, the firing pin 9 starts moving and it causes the lever 10 to be released. The force exerted by the compressed spring 8 starts acting on the tank 1 with attached control valve 3 and makes them move towards the bottom of the practice grenade. The control valve 3 is connected with the profile groove 5 of the training warhead body. When the control valve is open, the CO\textsubscript{2} starts to discharge through the valve 3 and the connecting pipe 11 into the PET bottle 2, which is located behind the gun nozzle 4. This causes the rapid increase in pressure inside the PET bottle.
When the pressure reaches the maximum value (the burst pressure), the PET bottle explodes.

The article deals with a mathematical model for calculating the pressure rise within the PET bottle. This mathematical model has been developed for determining the required amount of CO\textsubscript{2} and the design parameters of the sound generating device. The aim of presented research is to integrate this device into the body of the PG-7 practice grenade and to ensure the reliable PET bottle explosion at a desired time after initiation.

2. Computational Model of Explosion Chamber Pressurising

The simplified scheme of the given device is shown in Fig. 3. The system is composed of the CO\textsubscript{2} tank 1, the explosion chamber with a PET bottle 2, and the control valve 3 connecting both chambers.

\begin{figure}[H]
  \centering
  \includegraphics[width=0.7\textwidth]{fig3}
  \caption{Scheme of the thermodynamic system: 1 – CO\textsubscript{2} tank, 2 – explosion chamber, 3 – control valve}
\end{figure}

The carbon dioxide in tank 1 can coexist in two phases: liquid and gaseous. The control valve 3 is located above the liquid CO\textsubscript{2} surface (see Fig. 3). Therefore, it is possible to assume that the carbon dioxide will flow from tank 1 into chamber 2 only in its gaseous state, causing the pressure rise within explosion chamber 2. Discharging gaseous CO\textsubscript{2} causes the immediate phase non-equilibrium. Consequently, in order to achieve the phase equilibrium, a certain amount of liquid CO\textsubscript{2} (corresponding to the amount of discharged gaseous CO\textsubscript{2}) is evaporating to maintain the constant pressure in the tank 1. Due to the high density of liquid CO\textsubscript{2}, the volume of the liquid CO\textsubscript{2} tank may not be great enough to ensure the required amount of gaseous CO\textsubscript{2} for the PET bottles explosion. It allows us to integrate this compact device into the PG-7 practice grenade.

A computational model of the explosion chamber pressurising is based on the mass and energy conservation of the adiabatic system, because the heat transfer is neglected during rapid thermodynamic processes connected with the PET bottle explosion. These fundamental laws are completed by the real gas equation of state [3] for the gaseous CO\textsubscript{2}. Thermodynamic properties of CO\textsubscript{2} are available in [4-6].

Tank 1 is filled with a sufficient amount of CO\textsubscript{2}, which is presented in two phases: liquid of mass \( m_{l1} \) and gaseous of mass \( m_{g1} \). The total CO\textsubscript{2} mass is the sum of the masses of the constituents

\[ m_1 = m_{g1} + m_{l1} . \]  

At the phase equilibrium, the density of the liquid phase \( \rho_l(T) \) depends only on the temperature and may be determined according to the tables of CO\textsubscript{2} properties [4]. Thus, the volume of liquid CO\textsubscript{2} is

\[ V_{l1} = \frac{m_{l1}}{\rho_l(T_1)} . \]
Then, the volume of gaseous CO$_2$ $V_{g1}$ is given by the difference of the CO$_2$ tank volume $V_1$ and the volume of liquid phase $V_{l1}$ as

$$V_{g1} = V_1 - V_{l1}.$$  \hfill (3)

The pressure $p_1$ can be determined by the van der Waals equation of state [1] for the gaseous CO$_2$ of the mass $m_{g1}$ and the temperature $T_1$ in form

$$p_1 = \frac{r T_1}{V_{g1}} - \frac{a m_{g1}^2}{V_{g1}^2} b,$$  \hfill (4)

where $r$ is the CO$_2$ specific gas constant, constant $a$ provides a correction for the intermolecular forces and constant $b$ represents a correction for finite molecular size. The values of constants $a$, $b$ may be obtained by the theorem of corresponding states [3] using the CO$_2$ critical point conditions [4].

If tank 1 contains only a little amount of CO$_2$ in the gaseous phase, then the pressure $p_1$ is determined by Eq. (4) introducing $m_{g1} = m_1$ and $V_{g1} = V_1$. If we add a certain amount of CO$_2$ to tank 1, then the $p_1$ pressure increases until reaching the maximum value, i.e. the pressure of saturated vapour $p_s$, at the phase equilibrium. After reaching the pressure $p_s$, the liquid phase appears. During CO$_2$ tank 1 filling, the pressure $p_1 = p_s$ remains constant until the CO$_2$ liquid phase occupies the whole tank volume $V_{l1} = V_1$. If filling the CO$_2$ tank continues, then the pressure is rapidly increasing due to the liquid CO$_2$ compression. The dependence of the CO$_2$ saturation pressure $p_s$ on the temperature $T_1$ is shown in Fig. 4.

![Fig. 4 CO$_2$ saturated vapour pressure dependence on temperature](image)

Equations (1) to (4) form the basis for the computational algorithm (see Fig. 5), which enables us to determine the state variables of CO$_2$ for the given mass $m_1$ and temperature $T_1$. Thus

$$m_{l1} = m_{l1}(m_1, T_1), \quad m_{g1} = m_{g1}(m_1, T_1), \quad p_1 = p_i(m_1, T_1).$$  \hfill (5)
By using this computational algorithm for the given CO₂ tank of volume $V_1 = 185$ ml, we can obtain the pressure $p_1$ dependence on the two-phase fluid mass $m_1$ for various temperatures $T_1$ as shown in Fig. 6a. Furthermore, the pressure $p_1$ and the mass fractions of gaseous $x_{mg1}$ and liquid $x_{ml1}$ phases related to the two-phase fluid mass $m_1$ at the temperature $t_1 = 15$ °C are shown in Fig. 6b.
Assuming that valve 3 of the flow area $A$ is immediately opened (see Fig. 3), the mass flow rate of the gaseous phase through valve 3 is calculated as the adiabatic discharge of an ideal gas from tank 1 into chamber 2 neglecting flow losses by applying the Saint-Venant and Wantzel’s formula [7-8] for CO$_2$ as

$$\frac{dm_{g1}}{dt} = |\dot{m}| = A \sqrt{\frac{2\kappa}{\kappa-1} \frac{p_1^2}{r T_1} \left[ \left(\frac{p_2}{p_1}\right)^{\frac{2}{\kappa}} - \left(\frac{p_2}{p_1}\right)^{\frac{\kappa+1}{\kappa}} \right]} \quad \text{for} \quad \frac{p_2}{p_1} \geq \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa}{\kappa-1}}$$

$$\frac{2\kappa}{\kappa-1} \frac{p_1^2}{r T_1} \left[ \left(\frac{2}{\kappa+1}\right)^{\frac{2}{\kappa-1} - \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{\kappa-1}}} \right] \quad \text{for} \quad \frac{p_2}{p_1} < \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa}{\kappa-1}}$$

(6)

Where, $|\dot{m}|$ is the mass flow rate between CO$_2$ tank 1 and the explosion chamber 2 for the pressure drop $p_2/p_1$ and $\kappa = c_p/c_V \approx 1.3$ is the adiabatic exponent, that is the ratio of the constant-pressure and the constant-volume specific heat capacities of gaseous CO$_2$.

The mass flow rate $|\dot{m}|$ dependence on the pressure drop $p_2/p_1$ for the case of the valve flow area $A = 0.4$ cm$^2$ at the temperature $t_1 = 15$ °C and the pressure $p_1 = 5.1$ MPa is shown in Fig. 7. Here, the mass flow rate is constant $|\dot{m}| = 0.58$ kg/s for $p_2 \leq 0.55p_1$ and then decreases rapidly for smaller pressure differences between both chambers.

![Fig. 7 Mass flow rate related to the pressure drop for the flow area $A = 0.4$ cm$^2$ at the temperature $t_1 = 15$ °C and the pressure $p_1 = 5.1$ MPa](image)

For a short time step $\Delta \tau$, the mass of CO$_2$ within the tank is decreased by the discharged gaseous CO$_2$ $\Delta m_{g1}$ from tank 1 into chamber 2, thus

$$\Delta m_{g1} = |\dot{m}| \Delta \tau .$$

(7)

This causes the phase non-equilibrium in tank 1. In order to achieve the phase equilibrium, a certain amount of liquid CO$_2$ is evaporating. The mass $\Delta m_{l1}$ of evaporated CO$_2$ during a time step is given by

$$\Delta m_{l1} = m_{i1}(m_{i1}, T_{i1}) - m_{i1}(m_{i1} - \Delta m_{g1}, T_i - \Delta T_i) .$$

(8)

Here, we apply the computational algorithm (5), which is given in Fig. 5.
Due to the CO₂ vaporization, the temperature $T_1$ of the thermodynamic system including: the CO₂ gaseous and liquid phases and walls of the CO₂ tank 1, decreases. Assuming the high convective heat transfer coefficient for a boiling liquid and the high thermal conductivity of a walls material and assuming the same temperature within the whole system, the temperature drop $\Delta T_1$ can be determined from the energy balance of the thermodynamic system in form

$$\Delta T_1 = \frac{L(T_1)\Delta m_{l1}}{m_{l1}c_{pl} + m_{g1}c_{pg} + m_wc_w},$$  \hspace{1cm} (9)

where $L(T_1)$ is the CO₂ specific latent heat of vaporization at temperature $T_1$, $m_{l1}$ and $m_{g1}$ are masses of liquid and gaseous phases, $m_w$ is the mass of CO₂ tank and $c_{pl}$, $c_{pg}$, $c_w$ are corresponding specific heat capacities.

Equations (8) and (9) enable us to determine the change in the liquid CO₂ mass $m_{l1}$ and the change in the temperature $\Delta T_1$ for the time step $\Delta \tau$ using a numerical method.

The mass of gaseous CO₂ in the explosion chamber 2 during its pressurization is

$$m_{g2} = m_{g2}^{(0)} + \int_0^\tau |\dot{m}|d\tau,$$ \hspace{1cm} (10)

where $m_{g2}^{(0)}$ is the initial mass of gaseous CO₂ in the explosion chamber 2 before the control valve 3 opening.

The gaseous CO₂ flowing into the explosion chamber 2 causes an increase in the pressure $p_2$, which can be determined by the van der Waals equation of state in analogy with Eq. (4) as

$$p_2 = \frac{rT_2}{V_2} - \frac{am_{g2}^2}{m_{g2} - bV_2^2},$$ \hspace{1cm} (11)

where $V_2$ is the volume of the explosion chamber 2 and $T_2$ is the gas temperature in this chamber.

The temperature $T_2$ can be determined by applying the principle of conservation of energy to the thermodynamic system [9] for the explosion chamber 2, if the filling is in the gaseous phase and the temperature change is not too great, thus

$$T_2 = \frac{m_{g2}^{(0)}c_VT_2^{(0)} + \int_0^\tau |\dot{m}|c_pT_1d\tau}{m_{g2}c_V},$$ \hspace{1cm} (12)

where the upper subscript $(0)$ denotes the initial values of variables before the control valve opening.

3. Results of Solution of the Explosion Chamber Pressurising

It is seen from Eqs (9) and (10), that the main factor causing the pressure increase in the explosion chamber is the added mass of gaseous CO₂ which flowing through the control valve. The added mass flow rate $|\dot{m}|$ is proportional to the valve flow area $A$, the pressure $p_1$ and temperature $T_1$ in the CO₂ tank, and the pressure drop between both chambers by Eq. (6). If the CO₂ tank still contains the liquid state of CO₂ then the
vaporization of CO₂ occurs to compensate the gas discharge and to keep the phase equilibrium. The mass of evaporated CO₂ is given by Eq. (8) and the temperature drop $\Delta T_1$ is determined by Eq. (9). When the all liquid CO₂ is evaporated, then the discharging process continues as the adiabatic gas flow between both chambers. The described problem can be solved using the computational algorithm which is given in Fig. 8.

![Fig. 8 Computational algorithm for solution of thermodynamic processes](image)

The input data of the solution for the observed case of the device for simulation of the RPG-7 sound effect are as follows:

$m_1^{(0)} = 50 \text{ g}, V_1 = 185 \text{ ml}, V_2 = 1500 \text{ ml}, A = 0.4 \text{ cm}^2, t_1^{(0)} = 15^\circ \text{C}, p_2^{(0)} = 0.1 \text{ MPa}$.

The computation ends when the same pressure in the CO₂ tank and the explosion chamber is reached. The obtained results of the solution of the ongoing thermodynamic processes for the given example are clearly shown in Fig. 9.
It can be observed in Fig. 9a that the mass of CO₂ liquid phase $m_{l1}$ decreases to zero at the first 70 ms due to its vaporization. The mass of gaseous phase $m_{g2}$ in the explosion chamber is increasing, but the rate of this increase is smaller when the liquid phase in the CO₂ tank is entirely vaporized. This is the reason for the increase in pressure $p_2$ in the explosion chamber, as seen in Fig. 9b. The pressure $p_1$ decreases, although the tank still contains the liquid CO₂, due to the temperature $t_1$ decrease (Fig. 9c). The pressure $p_1$ drops significantly after the moment when the liquid phase in the CO₂ tank is entirely vaporized. It is seen in Fig. 9b that the time of explosion $Ex$ occurs 58 ms after the moment of the valve opening, when the pressure $p_2$ within the explosion chamber reaches the value of 1.2 MPa.

Results obtained using the described computational algorithm enable us to observe influence of changes in various design parameters or initial conditions. The results of such calculations are presented in Fig. 10.

Fig. 9 Time courses of state variables in CO₂ tank and explosion chamber

Fig. 10 Influence of some parameters on the pressure in explosion chamber:

a) influence of valve flow area $A$, b) influence of initial mass $m_1^{(0)}$, 

c) influence of initial temperature $t_1^{(0)}$ and CO₂ mass $m_1^{(0)}$
The impact of the size of the valve flow area $A$ is shown in Fig. 10a. It is seen that the larger the flow area $A$ is, the greater is the increase rate of pressure $p_2$ in the explosion chamber and then the time for reaching the PET bottle burst pressure 1.2 MPa is shorter.

The influence of the initial mass $m_1^{(0)}$ of the CO$_2$ tank filling is shown in Fig. 10b. The maximum pressure $p_{2\text{max}}$ in the explosion chamber increases with the initial mass $m_1^{(0)}$ of CO$_2$, but the rate of pressure rise is almost independent of the initial mass of the CO$_2$ for greater values of initial mass. It is seen that the initial mass of the CO$_2$ must be greater than 30 g to reach the PET bottle burst pressure 1.2 MPa. If we want to reduce the time delay in reaching the burst pressure, enlarging the valve flow area $A$ is a better solution compared with increasing the initial mass of CO$_2$.

The dependence of the maximum pressure $p_{2\text{max}}$ reached in the explosion chamber related to the initial mass $m_1^{(0)}$ of CO$_2$ for various initial temperatures $t_1^{(0)}$ is given in Fig. 10 c). Here, it is illustrated that the maximum reached pressure increases with the initial mass $m_1^{(0)}$ and the initial temperature $t_1^{(0)}$. The rate of the pressure $p_{2\text{max}}$ increase in relation to the initial mass drops significantly at low initial temperatures, because the pressure of CO$_2$ saturated vapour $p_s$ decreases rapidly with the drop in temperature (see Fig. 4). Therefore, the entire vaporization of CO$_2$ in the liquid phase does not occur if the pressure equilibrium of both chambers is achieved at low working temperatures.

Due to the limited space for integration of the developed device for simulating the sound effects into the body of the PG-7 practice grenade, the maximum possible volume of CO$_2$ tank is $V_{1\text{max}} = 185$ ml. Regarding to the safety standard [10], the CO$_2$ tanks have never been filled more than 67 % of the available volume. Therefore, the maximum allowed mass of CO$_2$ filling within this tank is $m_{1\text{max}}^{(0)} = 124$ g.

Another important design parameter is the explosion chamber volume $V_2$ which includes the volume of a PET bottle. The dependence of the maximum pressure $p_{2\text{max}}$ reached in the explosion chamber related to the size of its volume $V_2$ for various initial temperatures $t_1^{(0)}$ is given in Fig. 11.

![Fig. 11 Maximum pressure $p_{2\text{max}}$ in explosion chamber related to its volume $V_2$ for various initial temperatures $t_1^{(0)}$ and mass of CO$_2$ filling $m_{1\text{max}}^{(0)} = 124$ g](image-url)
This diagram allows us to choose the appropriate volume of the explosion chamber. The volume and the burst pressure of used PET bottle determine the intensity level of desired sound effect to meet the requirements for a military training.

The accuracy of the presented mathematical model was verified experimentally by measuring the value of maximum pressure $p_{2\text{max}}$ reached in the explosion chamber using a manometer. The results for various masses of CO$_2$ filling are shown in Tab. 1. It is seen that the results of theoretical solution correspond quite well with experimental measurements.

| Tab. 1 Comparison of calculated and measured values of maximum pressure in explosion chamber for various masses of CO$_2$ filling |
| Mass of CO$_2$ filling $m_{\text{max}}^{(0)}$ [g] | 10  | 30  | 60  | 90  | 120 |
| Calculated values $p_{2\text{max}}$ [MPa] | 0.45 | 1.14 | 2.03 | 2.38 | 2.49 |
| Measured values $p_{2\text{max}}$ [MPa] | 0.43 | 1.1  | 1.95 | 2.25 | 2.35 |
| Difference [%] | 4.7  | 3.6  | 4.1  | 5.8  | 6.0  |

4. Conclusion
In this study, the mathematical model for calculating the pressure rise within the explosion chamber has been developed. Results obtained using this algorithm allow us to analyse various influences of changes in some design parameters or initial operating conditions. This model is the base for the design of the device that simulates the sound effects of the RPG-7 anti-tank grenade launching during the combat shooting training.

The accuracy of the presented mathematical model was verified experimentally by measuring on the prototype of this device. It can be stated that the results of theoretical solution correspond quite well with experimental measurements.

With regard to the experience with testing of the prototype and the given model analysis, the future improvement and development of this mathematical model is expected by involving the phenomena of the heat transfer and the two-phase fluid flows. The heat transfer between the two-phase fluid [11] and the CO$_2$ tank walls influences the fluid temperature which is a significant parameter in the CO$_2$ phase equilibrium. Furthermore, the assumption of the CO$_2$ discharge as an ideal gas flow is not very relevant to the observed problem. Therefore, the isentropic flow of the two-phase fluid, involving the sound velocity of the two-phase CO$_2$ mixture [12], should also be included in future studies.

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