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ANALYSIS OF ENERGY DISSIPATION DURING THE IMPACT OF AIR WEAPON PROJECTILES INTO GRANULAR MATERIALS – COMPARISON OF ANALYTICAL MODEL AND EXPERIMENTAL RESULTS

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Abstract: *This paper presents an analysis of energy dissipation during the impact of projectiles fired from an air rifle and an air pistol into granular materials of different grain sizes. The study aims to compare analytically calculated energy values with experimental results using an integrated approach that combines mathematical modeling and high-speed imaging. Projectile velocity immediately before impact was estimated using numerical simulations in MATLAB, accounting for aerodynamic drag. Based on this velocity, the projectile's kinetic energy and its distribution into deformation, heat, vibration, and residual energy were determined. The experimental setup included controlled firing conditions with sand targets of varying grain sizes. The impact process was recorded using digital imaging, and the recorded image sequences were analyzed to estimate particle motion, material displacement, and morphological changes in the granular targets. The results indicate a reasonable consistency between the analytical model and experimental estimates for coarse sand. The observed deviations may be associated with granular heterogeneity, projectile geometry, and uncertainties inherent in the optical measurement method.*

Keywords*: energy dissipation, projectile impact, granular materials, kinetic energy, air rifle, air pistol, numerical modeling, high-speed imaging, experimental analysis*

1. INTRODUCTION

Energy dissipation during the impact of a projectile into granular materials represents a complex physical process involving the interaction between the projectile and the discrete structure of the material [1]. This phenomenon has significant applications in ballistics, the development of protective systems, and the analysis of material behavior under dynamic loading [2].

In the case of low kinetic energy projectiles, such as pellets from air weapons, the effects of energy dissipation depend on a large number of parameters: projectile velocity, its geometry, angle of impact, as well as the granulometric composition of the target [3, 4].

The aim of this paper is to compare an analytical model with experimental results of energy dissipation, with a particular focus on the influence of weapon type and material granulation.

2. THEORETICAL AND EXPERIMENTAL METHODOLOGY

In order to achieve a comprehensive understanding of energy dissipation mechanisms, a combined theoretical and experimental approach was adopted. The

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mathematical model provides a basis for predicting projectile behavior, while the experimental methodology enables validation and detailed analysis of the impact phenomena.

2.1. Mathematical Model

The motion of the projectile is modeled as the motion of a material point under the influence of gravity and aerodynamic drag [3, 4]. The kinetic energy of the projectile is defined by the standard expression [3]:

$$E_k = \frac{mv^2}{2} \quad (1)$$

The projectile velocity immediately before impact is determined by numerically solving the differential equations of motion using the Runge–Kutta method [3, 5]. The model includes the following parameters: projectile mass, initial velocity, air resistance coefficient, and air density.

Based on the calculated velocity, the total kinetic energy is determined and further distributed into the following components [3]:

- Energy transferred to the target E_m,
- Plastic deformation energy E_d,
- Thermal energy E_T,
- Sound and shock wave energy E_v
- Residual energy E_R .

The kinetic energy is not entirely transferred to the target, but is divided into several components and is expressed as follows [3]:

$$E_k = E_m + E_d + E_T + E_v + E_R \quad (2)$$

- In the case of granular targets, the energy transferred to the target consists of three main components [3, 5]:
- compression energy — grain separation E_1,
- inertial energy of the grains within the target E_2 ,
- friction energy E_4 .

The compression energy is calculated using the following formula [3]:

$$E_1 = \frac{am}{2b}\ln\left(1+\frac{b}{a}v_0^2\right) \quad (3)$$

The inertial component is obtained as the remainder of the total work in the target after subtracting the compression energy and, if applicable, the other energy components [3]. Unlike the compression and inertial components, the friction energy is not explicitly separated in the basic Poncelet formulation, but is introduced in practice as an empirical approximation [3]:

$$E_4 = E_m f_0 (1+\alpha \sin^2\theta) \quad (4)$$

with typical values of approximately $f_0 \approx 0.05$, i.e. 5% for normal impact, and $\alpha \approx 1$ for oblique impacts. This approximation is based on measurement results and experimental calibrations. It represents an empirical approximation based on measurements [3].

In terminal ballistics, the angle θ denotes the angle at which the projectile impacts the target relative to the normal to its surface.

This distribution serves as the basis for comparison with the calculated and experimentally determined energy values presented in the Results and Analysis section.

2.2. Experimental Methodology

The experimental investigation was conducted using two types of air weapons: the STEYR LG 110 air rifle and the STEYR LP 10 air pistol. Their relevant technical characteristics are presented in Table 1 [6, 7].

Table 1. Technical characteristics of the STEYR LG 110 air rifle and the STEYR LP 10 air pistol [6, 7]

Characteristics	STEYR LG 110 (Rifle)	STEYR LP 10 (Pistol)
Overall length	1170 mm	400 mm
Overall height	200 mm	142 mm
Barrel length	550 mm	227 mm
Caliber	4.5 mm / .177 in	4.5 mm / .177 in
Mass	4750 g	968 g
Width	—	50 mm
Propulsion	Compressed air	Compressed air
Trigger	Mechanical	Mechanical
Trigger pull	50–250 g	50–250 g
Muzzle energy	24 J	17 J
Initial projectile velocity	240 m/s	160 m/s

Furthermore, the experimental conditions were defined through a combination of parameters such as the firing angle, projectile type, and target granulation [5]. The targets were composed of sand with three different granulations, whose characteristics are shown in Table 2 [5].

Table 2. Characteristics of granular materials [5]

Sand Type	Specific density [kg/m3]	Granulation [mm]
Coarse sand	1770	~4-10
Medium-grained sand	1700	~3
Fine sand	1340	~0-0.3

For recording and analyzing the impact process, a Panasonic DMC-FZ200 digital camera was used at a recording rate of 40 frames per second [8].

For the analysis of the granular target response after projectile impact, an existing C++-based image-

processing program using the OpenCV library was modified and adapted to the specific requirements of the present experimental investigation [5].

The image-processing procedure involved tracking selected reference particles in consecutive frames recorded at 40 frames per second, corresponding to a time interval of 0.025 s. Particle velocities were estimated from their displacements between successive frames. Due to particle overlap, occlusion, and motion blur, only clearly identifiable reference particles were included in the tracking procedure.

Image segmentation and contour analysis were applied to characterize morphological changes in the granular target, including particle cloud formation, crater geometry, and subsequent erosion. The granular targets were placed in wooden frames measuring 640 × 640 × 120 mm (width × height × depth), providing known geometric dimensions of the experimental setup. Geometric corrections were considered to account for the inclination of the target and the angular position of the camera.

The resulting measurements were used to estimate particle velocities and the spatial characteristics of displaced granular material. The analysis was subject to limitations associated with image resolution, particle overlap, and the estimation of three-dimensional quantities from two-dimensional images.

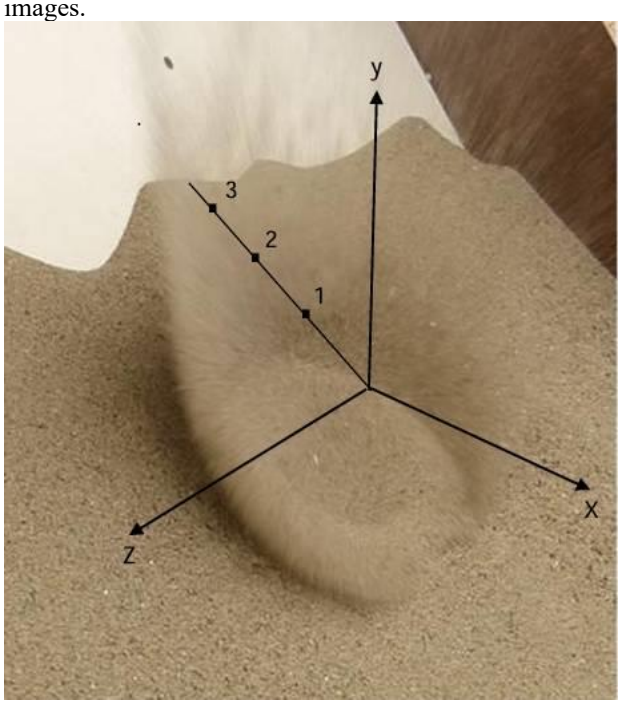


Figure 1. Analysis of photographs of the sand surface

3. RESULTS AND ANALYSIS

Analytical calculations of projectile velocity and energy, as well as their distribution, are presented in Table 3.

Table 3 – Comparison of calculated compression energy and experimentally determined energy

Air weapon type	Sand Type	Calculated compression energy E1 [J]	Experimental energy Eexp [J]
STEYR LG 110	Coarse sand	0.566	0.618
STEYR LP 10	Coarse sand	0.470	0.395

The experimental energy values are estimates based on the volume of displaced material, its density, and the average velocity of selected reference particles. The quantitative comparison was limited to coarse-grained sand due to the greater reliability of optical particle velocity measurements.

Based on the data from Table 3, it can be observed that the projectile fired from the air rifle produces higher calculated compression energy and higher experimentally determined energy compared to the projectile fired from the air pistol, which directly affects the intensity of energy dissipation in the target [5].

Each experimental configuration was repeated three times (n = 3). For coarse sand under normal impact conditions, the standard deviation of the recorded particle cloud volume was 6,844.57 mm³ for the STEYR LG 110 rifle and 1,550.20 mm³ for the STEYR LP 10 pistol. These values characterize the variability of the volumetric response between repeated experiments. The maximum recorded volume was used for the subsequent energy estimation.

In addition to the comparison between analytically calculated compression energy and experimentally estimated energy presented in Table 3, the distribution of the projectile kinetic energy into individual components was also analyzed. The calculated energy values for both air weapons impacting coarse sand at an angle of 0° are presented in Table 4.

Table 4 - Model-based energy components for projectile impact into coarse sand at 0°

Energy component	**LG 110 [J]**	**LP 10 [J]**
Compression energy	0.566	0.470
Inertial energy	9.721	4.253
Friction energy	0.541	0.248
Deformation energy	0.343	0.158
Thermal energy	0.162	0.075
Vibration energy	0.114	0.053
Residual energy	0.000	0.000

As shown in Table 4, the inertial component accounts for the largest proportion of the projectile kinetic energy, while smaller contributions are associated with compression, friction, deformation, thermal effects, and vibrations. These components were calculated using adopted coefficients of the mathematical model. Thermal and vibration-related energies were not directly measured, and no temperature measurements were performed during the experiments. Therefore, the presented values represent a model-based energy distribution rather than independently measured energy components.

The analysis of the experimental results shows significant differences in material behavior depending on granulation [5]. The cumulative volumetric particle size distribution of the three sand types, presented in Figure 2, shows clear differences in the internal structure of fine sand, medium-grained sand, and coarse sand [5]. These differences are important for understanding the mechanisms of energy dissipation in granular materials.

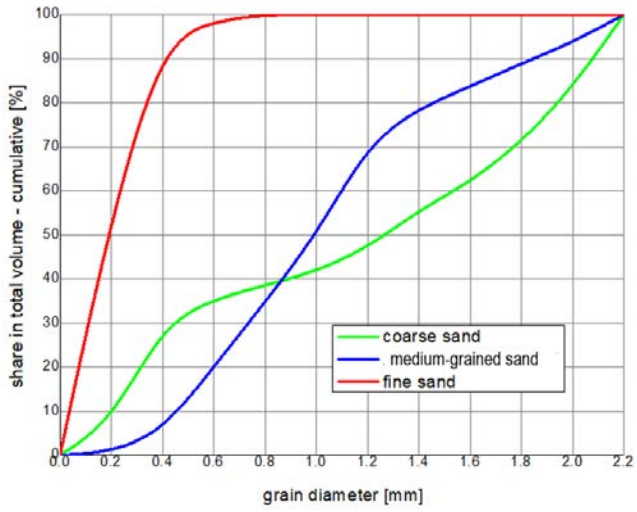


Figure 2. Cumulative volumetric particle size distribution as a function of particle diameter for three sand types

In the case of fine sand, localized energy dissipation is observed, manifested through a small "cloud" volume and limited material displacement. In contrast, coarse sand exhibits more pronounced material displacement and a more gradual dissipation of energy in deeper layers [5]. In this analysis, the combined volume of the particle "cloud" and the locally displaced material in the impact zone is treated as the total impact-related displaced volume. This behavior is illustrated in Figure 3, where the combined cloud and impact volume shows a significantly stronger response of coarse sand compared to fine sand [5].

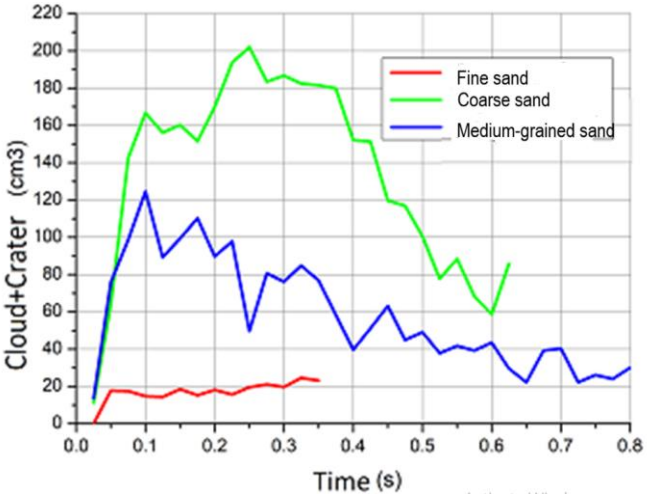


Figure 3. Change in combined cloud and impact-related displaced volume as a function of time for an air rifle shot using a flat-tip diabolo projectile at a firing angle of 0°

The differences between the analytically calculated and experimentally estimated energy values can be partly attributed to the heterogeneous structure of granular materials and the geometry of the projectile. Unlike a homogeneous continuous medium, sand consists of discrete particles with different sizes, shapes, and local packing arrangements. During impact, these characteristics affect interparticle contacts, friction, grain rearrangement, and the spatial distribution of transferred energy. Consequently, the actual granular response may differ from the simplified resistance assumptions adopted in the analytical model.

Projectile tip geometry also influences the interaction between the projectile and the granular target. Flat-tip projectiles produce a more pronounced initial displacement of grains, while conical-tip projectiles exhibit a different spatial and temporal distribution of material displacement and erosion. These differences are consistent with the experimentally observed variations in particle cloud formation and erosion dynamics.

Additional discrepancies may arise from the limitations of optical particle tracking, particularly particle overlap, irregular trajectories, and the use of average particle velocities in estimating the kinetic energy of displaced material. Therefore, the observed differences should be interpreted as the combined effects of granular heterogeneity, projectile geometry, and measurement uncertainty, rather than as the consequence of a single isolated factor.

The obtained results also indicate that the shape of the projectile tip significantly affects the mode of energy transfer [5]. This is consistent with previous analyses of pellet geometry and aerodynamic behavior [9, 10]. The experimental observations indicate that flat-tip projectiles can produce higher and more irregular material displacement and erosion, whereas conical-tip projectiles exhibit a different, more time-distributed granular response [5].

4. CONCLUSION

The results indicate reasonable consistency between the analytical model and the experimentally estimated energy values for coarse sand. The observed differences reflect the complexity of granular material behavior and the limitations of the optical measurement method. Further experimental investigations and statistical analysis are required to establish the model's predictive accuracy across different granular materials.

The obtained results may be applied in the analysis of protective materials and in the optimization of structures exposed to impact loading.

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