Theoretical and experimental study of the “hydrodynamic” effect in laboratory ballistic launchers

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Abstract. This paper performs a theoretical and experimental study of the effect of increasing the velocity of projectiles during the high-speed extrusion of the polyethylene piston through a tapered section (also called a “hydrodynamic” effect). Mathematical modeling is performed using two methods. The first method is a quasi-one-dimensional description of the polyethylene piston deformation on a moving computational grid. The second method is axisymmetric modeling using the ANSYS AUTODYN package. In the experimental studies, the polyethylene piston was preaccelerated using a propellant charge, after which the escape velocity of the projectile was measured. The escape velocity of the projectile after the tapered section increased up to 50% compared to the input velocity. The experimental results are consistent with the theoretical calculations.

1. Introduction
The process of high-speed extrusion of a deformable piston (referred to as a “hydrodynamic” effect in laboratory ballistic launchers [1-3]) enables one to increase the projectile velocity due to the redistribution of velocities in the piston material. The “hydrodynamic” effect occurs in laboratory launchers with deformable pistons such as light gas guns (LGG) [1, 2, 4] or guns with a tapered adapter (GTA) [3]. The difference between LGG and GTA is that in the latter, as a rule, the deformable piston continues moving instead of stopping when it passes the tapered section. The laboratory launchers on these principles are widely used in aerodynamic and ballistic studies, the modeling of the interaction of space debris and spacecraft, study of high-speed impact, elements of testing devices for overload, etc. [4]. The hydrodynamic effect enables one to study the behavior of polyethylene at high strains and high strain rates [5, 6]. Such conditions are difficult to implement in other manners.

The general scheme of high-speed extrusion is shown in Figure 1. Energy source 1 (compressed gas or propellant) accelerates the assembly, which consists of inertial pallet 2, deformable piston 3 with length \( x_d \), and projectile 4. In the case of an LGG, elements 2 and 4 are missing. The assembly accelerates in the initial cylindrical section (barrel) 5 with diameter \( D \), passes through the tapered (conical) section 6 with length \( x_c \), and continues to move in the output cylindrical section 7 of smaller diameter \( d \). The principle of acceleration is the redistribution of velocities in the material of the piston during its extrusion through the conical tapering element. This redistribution enables the projectile to achieve an additional accelerating due to the acceleration of the front part of the deformable piston. The velocities of the inertial pallet and rear part of the deformable piston decrease in this case.

This paper presents the results of experimental and theoretical studies (and their comparison) of the process of high-speed extrusion of polyethylene in ballistic laboratory launchers.
Figure 1. Scheme of the high-speed extrusion: 1 – energy source, 2 – inertial pallet, 3 – deformable piston, 4 – projectile, 5 – initial cylindrical section, 6 – tapered section, 7 – output cylindrical section.

2. Methods

2.1. Theoretical methods

2.1.1. One dimensional model. A deformable piston motion can be described by a system of quasi-one-dimensional equations:

\[ \frac{\partial (\rho S)}{\partial t} + \frac{\partial (\rho u S)}{\partial x} = 0, \]

\[ \frac{\partial (\rho u S)}{\partial t} + \frac{\partial ((\rho u^2 - \sigma^{xx}) S)}{\partial x} = 2\pi R \sigma^{ww} - \sigma_w \frac{\partial S}{\partial x}, \]

\[ \frac{\partial (\rho ES)}{\partial t} + \frac{\partial [(\rho E - \sigma^{xx}) u S]}{\partial x} = 2\pi R \sigma^{ww} u. \]

Here, \( \rho, u \) and \( E \) are the density, velocity, and total specific energy of the material of the piston, respectively; \( S \) is the variable cross sectional area of the barrel; \( \sigma^{xx} \) is the axial component of the stress tensor; \( R \) is the bore radius; subscript “\( w \)” corresponds to the values of the parameters on the external surface of the piston: \( \sigma^w \) is the shear stress, and \( \sigma^{ww} \) is the normal stress.

These equations are supplemented by the following empirical constitution laws from [2]. The shear stress on the wall is defined as:

\[ \tau = k_0 (1 + b_1 u) \exp(-b_2 u) \sigma, \quad \text{if} \quad \sigma < \sigma_s, \]

\[ \tau = k_0 (1 + b_1 u) \exp(-b_2 u) \sigma, \quad \text{if} \quad \sigma \geq \sigma_s. \]

Here, \( \sigma \) is the axial compression pressure. For high-pressure polyethylene, the empirical constants are \( \sigma_s = 25.2 \text{ MPa}, k_0 = 0.054, b_1 = 0.027 \text{ s/m}, \) and \( b_2 = 0.00675 \text{ s/m}. \)

A deformable piston is considered in approximation of the elastoviscoplastic model. Therefore, \( \sigma^{ww} = -p + \tau^{xx}, \)

\[ \tau^{xx} = \frac{2}{3} k(h) \left( 2 \frac{\partial u}{\partial x} - u \frac{\partial S}{\partial x} \right), \quad k(h) = \mu + \tau_s / 2h, \quad h = \frac{1}{2\sqrt{3}} \left| \frac{\partial u}{\partial x} - u \frac{\partial S}{\partial x} \right|. \]

Here, \( \mu \) is the dynamic viscosity; \( \tau_s \) is the yield point at pure shear.

The two-term caloric equation of state of the piston material is used:

\[ e = E - \frac{u^2}{2} = \frac{p - c_0^2 (p - \rho_0)}{(k - 1) \rho}. \]

Here, \( e \) is the specific energy of the piston material. The values of the constants determined based on experimental data for high-pressure polyethylene are \( \rho_0 = 919.03 \text{ kg/m}^3, \ c_0 = 2380 \text{ m/s}, \) and \( k = 1.63098. \)
It can be assumed that at $p < p_0$, the material stretches until its pressure drops to zero or a conditional limit, after which it collapses.

The velocity of the piston boundaries is defined as follows. If the contact left surface has mass $m$, the piston material with pressure $\sigma_{xx} = -p + \tau_{xx}$ acts on it to the right, and the gas with pressure $p_g$ acts on it to the left, then the equation of motion of the boundary is written as

$$m \frac{du_b}{dt} = s \left( p_g - p + \tau_{xx} \right).$$

Here, $u_b$ is the boundary speed. A similar boundary condition is used for the projectile.

For the numerical solution of the system of equations due to the presence of contact boundaries that move in time, a two-step scheme of the predictor-corrector type on a moving grid was used. The flows at the interfaces were determined from the solution of Riemann problem using the advection upstream splitting method (AUSM+) [7-9].

2.1.2. Axisymmetric model. The deformation of the assembly in a tapered section was axisymmetrically modeled using ANSYS AUTODYN. The problem was solved in a two-dimensional formulation with cylindrical symmetry. In the areas of the projectile, inertial pallet and barrel wall, a Lagrange mesh was used; in the region of a deformable piston, a Eulerian mesh was used. The barrel and tapered section are considered absolutely rigid. The size of the mesh cells is 0.5 mm. The characteristics of the materials were taken from the ANSYS AUTODYN standard material library.

The axisymmetric simulation scheme and grid are shown in Figure 2.

![Figure 2. Simulation scheme and the grid.](image)

2.2. Experimental methods

Experimental studies were performed using the propellant burn acceleration of the assembly in the bore with a tapered adapter. The diameter of the initial cylindrical section is $D = 23$ mm. The diameter of the output cylindrical section varied ($d$ is 18 mm or 16 mm). The assembly consisted of a copper inertial pallet with a mass of 39.5 g, a polyethylene piston with a mass of 25 g and a copper projectile with a mass of 22 g. To measure the output velocity of the projectile, we used the barrier system, high-speed video and Doppler frequency measurement technique.

The principal view of the experimental setup is shown in Figure 3.

![Figure 3. Experimental setup for the study of the hydrodynamic effect.](image)
3. Results and discussion

Table 1 shows the results of the experimental measurements of the projectile velocity at two input assembly velocities and a comparison of the experimentally measured output velocities of the projectile with theoretical calculations for one-dimensional and axisymmetric models. Table 1 shows the experimentally measured assembly entry speed ($V_{in}$), diameter of the output cylindrical section ($d$), experimentally measured projectile exit velocity ($V_{out}$), ratio of exit to entry velocities ($V_{out} / V_{in}$), and projectile exit velocities calculated from the one-dimensional model (1D) and axisymmetric model (2D).

| $V_{in}$ | $d$ | $V_{out}$ | $V_{out} / V_{in}$ | $V_{out}$ (1D) | $V_{out}$ (2D) |
|---------|-----|-----------|--------------------|----------------|----------------|
| m/s     | mm  | m/s       | m/s               | m/s            | m/s            |
| 572     | 18  | 788       | 1.38              | 798            | 740            |
|         | 16  | 860       | 1.50              | 876            | 826            |
| 900     | 18  | 1193      | 1.32              | 1204           | 1196           |
|         | 16  | 1241      | 1.38              | 1289           | 1332           |

In the experimental studies, one of the additional factors is the presence of pressure of the propellant gases behind the assembly, which has not yet fallen to insignificant values when the assembly enters the tapered section. In addition, the limited length of the acceleration bore makes a wave reflect from the bottom of the channel of the bore after the assembly enters the cone. In one-dimensional modeling, the entire acceleration cycle of the assembly, including the burning of the propellant, is considered [8]. In the axisymmetric model, only the effect of passing the assembly through a tapered section is considered. These factors may be due to small differences in the simulation results.

Figure 4 shows the distributions of velocities and pressure in the material of a polyethylene piston, which were obtained in the calculation by the axisymmetric model. The distributions of pressures and velocities are shown at different points in time. The corresponding moments are selected so that the material has the greatest pressure or velocity gradient.

![Figure 4](image-url). Distribution of the pressure (top) and velocity (bottom) in the material of the deformable piston.

The parameter distributions in the piston material in the figure show that with the exception of the areas adjacent to the piston boundaries, the parameters are on average uniform over the cross section.
4. Conclusion

As a result this study, the effect of increasing the velocity of a projectile during the high-speed extrusion of polyethylene through a conical section was theoretically and experimentally confirmed. The experimental studies show that the increase in velocity can reach 50%. When the diameter of the output cylindrical section decreases, an increase of the velocity of the projectile is observed. The theoretical modeling results are consistent with the experimental data.

It should be noted that the acceleration of an assembly that contains a projectile and a deformable piston requires a higher energy expenditure than the acceleration of one projectile. Therefore, the energy benefit from the “hydrodynamic” effect in each case should be separately estimated. In addition, each method of acceleration (e.g., compressed gas or powder acceleration) clearly has fundamental velocity limits, which can be surpassed, including using the “hydrodynamic” effect.

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