Ballistic facility for heavy bodies acceleration

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Abstract. This paper discusses the issues of creating a ballistic facility for use in laboratory conditions and achieving throwing speeds of up to 2000 m/s for massive objects. The design of the facility was proposed and the results of the analytical calculation of the achieved speeds were presented. The verification of the analytical calculation and the results of experiments on the prototype ballistic facility was done.

1. Introduction
At present, aeroballistic facilities are widely used in scientific research, both in the field of collision of solids and in aerophysics problems. The current state of methods for accelerating bodies to hypersonic speeds and the possibility of using various propelling devices (gas, light-gas and powder guns, explosive, explosive-cumulative and rail-accelerated accelerators) in aeroballistic experiments are discussed in reviews [1–6]. The main direction of development of traditional acceleration tools is to increase the speed by reducing the mass of accelerated bodies. In most existing aeroballistics facilities, the mass of objects is several grams [7]. In this paper, we consider the possibility of increasing the mass of accelerated objects. To this end, the task was set to create a laboratory ballistic facility for high-speed throwing massive bodies weighing up to 1 kg.

2. Mathematic model of a single-stage ballistic facility
As the main scheme for the facility, the one of a single-stage ballistic gun was chosen, in which the projectile is accelerated only due to the pressure of the pushing gas. The peculiarity of the scheme under consideration is the use of a barrel of large elongation (up to L/D = 500), which makes it possible to accelerate rather heavy bodies in comparison with the known light-gas guns. The use of compressed gas simplifies the design of the facility and allows its use in laboratory conditions.

The design model of a single-stage ballistic facility is shown in figure 1. Pressure receiver 3 contains a specific mass \( m_03 \) of compressed gas with parameters \( P_{03} \) and \( T_{03} \). Barrel 2 is attached to pressure receiver 3, in which accelerated projectile 1 is placed. After being released from the holding device, projectile 1 begins to move along the barrel with increasing speed \( W_3 \) under the influence of the compressed gas coming from the receiver. Compressed gas flows from tank 3 into space 2 behind the projectile. For simplicity, it is assumed that there is no air in front of the projectile. Projectile 1 is affected by static pressure \( P_3 \), which depends on stagnation pressure \( P_{03} \) and on velocity \( W_{30} \) of the projectile. As the projectile moves, the volume-average gas-dynamic parameters \( P_{03} \) and \( T_{03} \) decrease. The velocity of the projectile depends on the rate of change of pressure in the pressure receiver, on the barrel length, and on the mass of the projectile.
In accordance with the methodology of [8], a one-dimensional quasistationary calculation model was created, which considers the flow of a perfect inviscid gas with constant thermophysical properties from tank 3 to tank 2. The change in parameters in tank 3 is described by the relations for the adiabatic process of gas outflow through a constant section hole.

\[
P_{03}(t) = P_{03}(0) \cdot (1 + B \cdot t)^{\frac{2\gamma}{\gamma-1}}
\]

\[
T_{03}(t) = T_{03}(0) \cdot (1 + B \cdot t)^{\frac{-2}{\gamma-1}},
\]

where:

\[
B = \frac{\gamma - 1}{2} \cdot R_f \cdot \mu \cdot m \cdot \frac{F}{\sqrt{T_{03}(0)}} \cdot \sqrt{\frac{\gamma}{R_f \cdot \left(\frac{2}{\gamma} + 1\right)^{\frac{\gamma+1}{\gamma-1}}}}
\]

The gas parameters in volume 3 are considered as stagnation parameters for moving gas in volume 2 acting on accelerated projectile 1.

\[
P_{02} = P_{03}
\]

\[
T_{02} = T_{03}
\]

The static pressure acting on the projectile is determined by stagnation pressure \( P_{02} \) and the velocity (Mach number) of the projectile.

\[
P_2 = P_{02} / (1 + \frac{\gamma - 1}{2} \cdot M_1^2)^{\frac{\gamma}{\gamma-1}}
\]

To determine the Mach number \( M_1 \), the relative velocity of the projectile in relation to the maximum possible speed at a given stagnation temperature \( T_{02} \) is determined.

\[
L a_1 = \frac{W_1}{\sqrt{2 \cdot C_p \cdot T_{02}}}
\]

Static temperature corresponding to this speed

\[
T_2 = T_{02} \cdot (1 - L a_1^2)
\]

Mach number corresponding to the velocity of the projectile at this static temperature:

\[
M_1 = \frac{W_1}{\sqrt{\gamma \cdot R_f \cdot T_2}}
\]

The force acting on the projectile

\[
R_1 = P_2 \cdot F
\]

The acceleration

\[
A_1 = R_1 / m_1
\]

Projectile speed gain

\[
dW_1 = A_1 \cdot dt
\]

Changing the position of the projectile
\[ dX_1 = W_1 \cdot dt + A_1 \cdot dt \cdot dt / 2 \]

Unsteady equations are solved by the Euler method with constant step \( dt \) in time. The calculation continues from the beginning of the projectile moving to its leaving from the barrel \( (X_1 = L) \). Tables 1 and 2 show the results of calculating the achieved velocities of the projectiles using air and helium as the working gas.

**Table 1.** Working gas is air, the volume of the gas receiver is 0.14 m\(^3\), \( T = 600 \) K, the barrel length is 30 m, and the diameter is 50 mm.

| Projectile weight, kg | 120 bar | 140 bar | 160 bar | 180 bar | 200 bar |
|-----------------------|---------|---------|---------|---------|---------|
| 0.1                   | 928.17  | 938.54  | 946.79  | 954.00  | 961.12  |
| 0.2                   | 872.37  | 886.31  | 897.58  | 907.05  | 914.92  |
| 0.3                   | 831.63  | 847.99  | 861.09  | 872.37  | 882.05  |
| 0.4                   | 798.23  | 816.82  | 831.63  | 844.30  | 854.72  |
| 0.5                   | 769.94  | 789.87  | 806.09  | 819.89  | 831.63  |

**Table 2.** Working gas is helium, the volume of the gas receiver is 0.14 m\(^3\), \( T = 600 \) K, the barrel length is 30 m, and the diameter is 50 mm.

| Projectile weight, kg | 120 bar | 140 bar | 160 bar | 180 bar | 200 bar |
|-----------------------|---------|---------|---------|---------|---------|
| 0.1                   | 1832.88 | 1885.29 | 1928.65 | 1964.07 | 1994.92 |
| 0.2                   | 1551.58 | 1619.19 | 1675.94 | 1723.34 | 1764.31 |
| 0.3                   | 1361.29 | 1435.02 | 1497.86 | 1551.58 | 1597.81 |
| 0.4                   | 1219.96 | 1296.40 | 1361.29 | 1417.79 | 1467.65 |
| 0.5                   | 1110.55 | 1186.20 | 1252.27 | 1309.63 | 1361.29 |

It can be seen that the maximum possible speed for a heavy projectile weighing 0.5 kg using heated air is 832 m/s; and when using heated helium, it is 1361 m/s.

3. **The results of experiments on a prototype ballistic facility**

To test the basic structural elements, a model (prototype) of a ballistic facility was developed and manufactured (see figure 2).

![Figure 2](image)

**Figure 2.** Scheme of the prototype ballistic facility.

1 - pressure receiver, 2 - projectile, 3 - barrel, 4 - muzzle attachments, 5 - target.

The prototype of ballistic facility consists of pressure receiver 1, into which compressed gas is supplied. A pallet with projectile 2 is installed in ballistic barrel 3 and secured using a special holding device. The ballistic barrel is made of a honed \((Ra = 0.3)\) pipe with inner diameter of 50 mm and length of 8 to 21.5 m. At the end of the barrel, muzzle nozzle 4 is installed, on which longitudinal grooves are made to divert the gas stream. The pressure receiver is a cylinder (figure 3) with volume of 0.04 m\(^3\), equipped with a push gas supply line and a manometer to control the initial pressure.
The pallet is made in the form of a cylinder, at the end of which a rubber cuff is installed, which carries out the sealing of the barrel. The material of the pallet PTFE was chosen due to the low slip coefficient. The projectile is placed in the pallet (figure 4). Various options for separating the projectile and the pallet were considered. The main method of separation was chosen aerodynamic. The pallet consists of two or four identical parts, not fastened together. When a projectile with a pallet leaves the barrel, the pallet is divided into its components due to aerodynamic forces. The accelerator acceleration speed is determined using target frames mounted on a section of the barrel, with a known distance between them. The time interval between the operations of the target frames was determined using the high-speed ADC LA-2USB with frequency discretization of 500 kHz. Using the prototype of a ballistic facility, test experiments were performed to accelerate heavy bodies. For the experiments, pallets made of PTFE were used, in which metal cylinders h×d = 15×15 mm were installed. The receiver was filled with gas with a required pressure and then a shot was fired. A series of experiments for cylinders h×d = 15×15 mm and barrel with length of L = 8 m was made. The total mass of the pallet and cylinder was 130 g. Mass of the cylinders was 20.8 g. Air was used as the pushing gas. The receiver was 40 dm³. The results of a series of experiments are shown in tables 3 and 4.

### Table 3. The results of experiments using air.

| №   | m, kg | $P_{rec}$, MPa | $U_{exp}$, m/s | $U_{theor}$, m/s | Δ, % |
|-----|-------|----------------|---------------|------------------|------|
| 1   | 0.13  | 0.5            | 218           | 236              | 7.6  |
| 2   | 0.13  | 1              | 290           | 323              | 10.2 |
| 3   | 0.13  | 1.5            | 340           | 380              | 10.5 |
| 4   | 0.13  | 2              | 397           | 447              | 11.2 |
| 5   | 0.13  | 3              | 430           | 493              | 12.8 |
| 6   | 0.13  | 4              | 470           | 523              | 10.1 |
| 7   | 0.13  | 4              | 430           | 523              | 17.8 |
| 8   | 0.13  | 4              | 450           | 523              | 14.0 |
| 9   | 0.13  | 4              | 500           | 523              | 4.4  |
| 10  | 0.13  | 4              | 485           | 523              | 7.3  |
| 11  | 0.13  | 5              | 490           | 550              | 10.9 |
Figure 5. Dependence of speed on pressure in the receiver (barrel length 8 m, diameter 0.05 m).

The solid line in the graph (figure 5) shows the dependence of the speed obtained in the theoretical calculation on the pressure in the receiver. The dashed lines show the experimental velocity values at various initial pressures in the receiver. It is seen that the experimentally obtained velocity values are consistent with the calculated data. The average deviation of the values is 10%. The resulting difference is caused by the absence in the theoretical model of the friction forces of the pallet when moving along the barrel of the installation. Several experiments (No. 6-10), performed at pressure in the receiver of 4 MPa, show a spread of the obtained velocities, i.e. repeatability of experiments. Table 4 shows the results of experiments using helium as a pushing gas and different barrel lengths (table 4). In experiment No. 2, steel rod h×d = 300×10 mm with a mass of 323 g was used.

| № No. | m, kg | P_{rec}, MPa | U_{exp}, m/s | U_{theor}, m/s | Δ, % | L, m |
|-------|-------|--------------|--------------|---------------|------|------|
| 1     | 0.130 | 5            | 700          | 727           | 3.7  | 8    |
| 2     | 0.323 | 4            | 420          | 490           | 14.3 | 21.5 |

It is seen that the use of helium can significantly increase the speed of throwing heavy projectiles.

Conclusion

The theoretical and practical study of the possibility of creating a single-stage ballistic facility for throwing projectiles weighing from 0.1 to 0.5 kg at a speed of 600 to 1300 m/s has been performed. A mathematical model has been developed that describes the acceleration of propelled projectile in a single-stage gas ballistic facility. Parametric calculations of various acceleration options for projectiles weighing from 0.1 to 0.5 kg were performed. When using compressed air, it is possible to obtain a throwing speed of projectile up to 832 m/s with weighing 0.5 kg. When using helium, it is possible to obtain a throwing speed of up to 1361 m/s. A prototype of a ballistic facility with the barrel diameter of 50 mm and length of up to 21.5 m was created. Trial experiments were carried out, which confirmed the correctness of the main decisions in the created installation. When using air without heating, the acceleration speed of 500 m/s was obtained. When using helium, the acceleration speed of 700 m/s was obtained.

Acknowledgments

This work was carried out within the framework of the Program of Fundamental Scientific Research for the Russian state academies of sciences in 2013-2020 (project No. AAAA-A17-117030610121-9)
and was partly supported within the framework of the Program of Basic Research of the Presidium of the Russian Academy of Sciences entitled “Basic Fundamentals of Breakthrough Technologies in the Interests of National Security”.

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