Effects of Environment Temperature on The Attenuation of Quasi-Spherical EFP Velocity

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Abstract. A comparison of multiple quasi-spherical EFP warhead tests conducted during different seasons of the year revealed that EFP velocities in the cold season were low. In this paper, the experimental phenomenon is analyzed theoretically base on the principles of EFP and flight dynamics. Due to the difference of air density caused by the different temperature, the aerodynamic drag of EFP with the same aerodynamic shape and initial velocity is obviously different. Because of the hypervelocity of EFP, The impact velocity of EFP on target is also significantly affected after flying over 100 meters. In the paper, the flight velocities of a quasi-spherical EFP at different temperatures is calculated by MATLAB, which is in good agreement with the experimental results. It is necessary to consider the change of environment temperature in engineering practice of quasi-spherical EFP warhead in order to improve kinetic energy margin.

1. Introduction
The formation of EFP (Explosively Formed Penetrator) is a nonlinear dynamic process with complex forming mechanism and many influencing factors. From an engineering point of view, armour-piercing power and intensity are the most important indexes to evaluate the performance of EFP warhead. Normally, the application distance of EFP warhead is 100 to 150 meters and EFP which meets the requirements of engineering application should have high stability and certain design margin in the whole process of explosive forming, long-distance flight, impacting target and armor piercing. Most of the energy of EFP armor piercing comes from its own kinetic energy. Under the same condition of forming and impacting the target, the change of the velocity of impacting the target will directly affect the armour-piercing power.

The commonly used EFP is rod and quasi-spherical EFP, among which quasi-spherical EFP has good flight stability and is almost not affected by the flight form. It can theoretically guarantee stable armor piercing power and intensity, and has high application value in engineering practice. Due to the difficulty of designing long pole EFP, the feasibility of quasi-spherical EFP is generally preferred, especially for some new tantalum alloy EFP. The quasi-spherical EFP was applied to the Russia's SPBE-D terminal sensitive projectiles and China's early rocket terminal sensitive projectiles.
2. Analysis of experimental phenomena

A EFP warhead has been designed by use of Quasi-master spherical scheme. This scheme has been tested and verified in the early stages of the program. The test is concentrated in the warm season, and the test fry height is 100m. The average line speed of the EFP at 90m was obtained through tests, concentrated between 140 ms\(^{-1}\) and 1480 ms\(^{-1}\). The test data are shown in Table 1. The static explosion test of this scheme was continued in the winter and the test warhead, test device and test methods were kept the same. The average speed at 20m and 90m was tested by the net target velocimetry method. The test data is shown in Tables 2 and 3.

By comparing the test data, it can be found that the winter (ambient temperature 5 °C and 18 °C) tests show that the EFP flight speed is generally low. The average speeds (ms\(^{-1}\)) at 20m in the three groups are 1681, 1665.2, and 1690.8, and the average speeds (ms\(^{-1}\)) at 90m in the three groups are 1479.2, 1444, 1421.2. Average speed decreases with decreasing ambient temperature.

The target board was penetrated mainly by the kinetic energy of the projectile. The kinetic energy of the projectile to drop was caused directly by the low flying speed. Insufficient kinetic energy of EFP will weaken the damage to the target, such as incomplete penetration (Figure 3 and Figure 4).

Obviously, the reason for the decrease in EFP speed is that the initial speed of EFP formation is low or large speed decay during flight. The initial speed of EFP depends on the EFP warhead itself, that is, the technical status of the experimental prototype, such as component size, material properties, charge density, charge process, etc. The speed decay during EFP flight mainly depends on factors other than the warhead, such as test projectile support, ballistic flight, etc. The technical status of the prototype of this solution has not changed. In terms of external factors, the technical status of relevant test methods and devices has not changed. Therefore, it is preliminarily determined that the speed attenuation of the EFP during the ballistic flight directly affects its target speed.
3. The velocity model of EFP
The velocity model of EFP in ballistic flight can refer to the typical fragment velocity model[1]. After the initial velocity of EFP is obtained and the detonation product is removed, EFP will fly in the air. At this time, EFP will be affected by two kinds of forces, namely, gravity and air resistance. Gravity causes the flight trajectory of EFP to bend, and air resistance causes the velocity decay of EFP. Because the distance from EFP to the target is not too long, the time is very short. Therefore, the influence of gravity can be ignored, and EFP trajectory can be approximately regarded as a straight line.

The differential equation of EFP motion is:

$$m \frac{dv}{dt} = -\frac{1}{2} C_D \rho_a V^2$$

Where, $C_D$ is the aerodynamic drag coefficient; $\rho_a$ is the air density; $S$ is the upwind display area of EFP; $m$, $v$, $t$ respectively represent the mass, velocity and time of EFP.

Transforms the above formula to obtain:
In the formula, \( v_x \) is the storage velocity, and the power index of \( e \) is called the attenuation coefficient. It can also be seen from the formula that the main factors affecting the attenuation coefficient of EFP velocity are aerodynamic drag coefficient \( C_D \), the local air density \( \rho_a \), windward area \( S \) and mass \( m \).

For a quasi spherical EFP in a specific state, the initial velocity \( V_0 \) and mass \( m \), as well as the windward area \( S \) of the EFP are relatively stable, there is no significant fluctuation. According to the aerodynamics theory, the aerodynamic drag coefficient \( C_D \) depends on the size, shape and velocity of the projectile. Therefore, when the size and shape of the EFP are fixed, the aerodynamic drag coefficient \( C_D \) is only related to its own speed. The average flight speed of the EFP in general engineering application is mostly concentrated at Mach 4-6. The change curve between the drag coefficient of the fixed object and the speed is usually as shown in Figure 1. When the Mach number changes above Mach 4, the change curve tends to be gentle. When a projectile such as EFP flies within 100m distance, its velocity will not exceed Mach 1, so \( C_D \) can be approximated as a constant.

Through aerodynamic simulation and empirical data statistics, the EFP resistance coefficient \( C_D \) in this paper is about 0.75.

The shape quasi-spherical EFP is stable. In the scheme, a large number of EFP hole shapes were obtained by using the method of gauze capture. The average diameter of the holes is 40mm, and the shapes are basically the same. Due to the stable forming of EFP, its resistance coefficient \( C_D \) can be regarded as a constant within flight distance of 100 meters. In fact, not all EFPs have stable resistance coefficient \( C_D \). Quasi-spherical EFPs tend to be spatially symmetrical, and can maintain the same shape of the windward face at any time. Because the attitude of EFP in flight is difficult to capture, the length-diameter ratio of quasi spherical EFP is 1, the windward section of any flight attitude can be regarded as circular, and the resistance coefficient is stable. For example, the resistance coefficient of EFP in this test scheme is 0.75, while the length-diameter ratio of rod EFP is usually 2~3, the windward section of quasi spherical EFP in different flight attitude can present circular or slender irregular shape, and the resistance coefficient is irregular. The drag coefficient is about 0.5 at zero angle of attack, and increases to 1.7 with the increase of angle of attack.

4. The effect of temperature on air density

According to the analysis of the EFP speed model, \( C_D \), \( S \) and \( m \) in the attenuation coefficient of a quasi-spherical EFP can be regarded as constants. The air density \( p \) is generally considered constant. However, in this paper, a statistical analysis of the EFP test data of a scheme was conducted, and it was found that the average speed of the EFP showed a decreasing trend with the decrease of the ambient temperature. It can be concluded that \( p \) in the velocity attenuation coefficient has some relationship with the flight speed of the EFP, and there is a certain relationship between the ambient
temperature and the air density. The CIPM-2007 air density calculation formula was released by the International Measurement Committee CIPM in February 2008\(^3\):

\[
\rho_a = \frac{P_M a}{ZRT} \left[1 - x_v \left(1 - \frac{M_v}{M_a}\right)\right]
\]

(3)

In the formula, \(\rho_a\)-Air density, \(P\)-Atmospheric pressure, \(M_v\)-Molar mass of water, \(M_a\)-Molar mass of dry air, \(Z\)-Air compression factor, \(R\)-Molar gas constant, \(T\)-Aerodynamic temperature of ITS-90, \(X_v\)-Mole fraction of water vapour.

The formula shows that air density is directly proportional to atmospheric pressure and inversely proportional to temperature. Table 4 is the air density table at 1atm, -20°C~30°C.

**Table 4.** Air density table at 1atm, -20°C~30°C.

| Temperature (°C) | Density (kg/m\(^3\)) |
|-----------------|-----------------------|
| -20             | 1.395                 |
| -15             | 1.367                 |
| -12             | 1.352                 |
| -10             | 1.341                 |
| -8              | 1.331                 |
| -6              | 1.321                 |
| -4              | 1.311                 |
| 0               | 1.301                 |
| 2               | 1.291                 |
| 4               | 1.271                 |
| 6               | 1.261                 |

It can be seen from Table 4 that the air density difference at -20°C and -30°C is 0.249kg/m\(^3\), which is 19.3% compared with 1.29kg/m\(^3\) used in general cases.

5. Analysis of the Numerical Simulation Results

The EFP can fly at a hypersonic range of Mach 4–6. During the EFP high-speed flight, the media resistance of the environment is huge, so the density of the media is a factor that cannot be ignored. Li Yan, Tang Geshi, Li Zheng and others analyzed the influence of atmospheric resistance on the orbit correction of low-orbit spacecraft, especially studied the effect of temperature on atmospheric density, and believed that temperature would affect the atmospheric density and increase the spacecraft's flight resistance\(^4\). EFP projectiles are small in size, and their effective time is extremely short. Few researchers pay attention to the flight process of EFP, but the speed of EFP is indeed an important factor that directly affects the projectile energy.

According to the differential equation of EFP motion according to formula (1), a simulation block diagram is established using Matlab's Simulink module. The input variables are air density and drag coefficient, and the output results are EFP speed and flight distance. Calculation parameter settings can be found in Table 5

**Table 5.** Parameter setting.

| m(kg) | d(m)   | \(V_0(\text{ms}^{-1})\) | \(C_D\) | \(\rho_a\) |
|-------|--------|--------------------------|---------|-----------|
| 0.35  | 0.04   | 1690                     | 0.75    | (Table 4) |

**Table 6.** Calculated speed at 90 meters temperature of -18°C

| Temperature (°C) | Velocity (ms\(^{-1}\)) |
|-----------------|-------------------------|
| -20             | 1425.4                  |
| -15             | 1430.1                  |
| -12             | 1432.6                  |
| -10             | 1434.5                  |
| -8              | 1436.2                  |
| -6              | 1438.1                  |
| -4              | 1439.7                  |
| 0               | 1441.3                  |
| 2               | 1443.1                  |
| 4               | 1444.7                  |
| 6               | 1446.4                  |

| Temperature (°C) | Velocity (ms\(^{-1}\)) |
|-----------------|-------------------------|
| 8               | 1449.8                  |
| 10              | 1451.3                  |
| 12              | 1453                    |
| 14              | 1454.6                  |
| 16              | 1456.1                  |
| 18              | 1457.8                  |
| 20              | 1459.4                  |
| 22              | 1461.1                  |
| 24              | 1462.7                  |
| 26              | 1464.4                  |
| 28              | 1466.1                  |
| 30              | 1467.8                  |
The speed attenuation of the quasi-spherical EFP at a given initial velocity at different temperatures was obtained through simulation calculations. The calculated initial speed was set to 1690 ms\(^{-1}\). Table 6 is the calculated speed at 90 meters. The comparison with the test data is shown in the table 7. It can be seen from Table 7 that the calculated results are in good agreement with the overall test data, but the specific values are still different. This is because \(C_D\), \(S\) and \(m\), which have a small change during the calculation, are regarded as a constant, and there are some errors in the distance and the test instrument itself, and there are also some accidental factors that are not considered in the test environment. The simulation calculations well reflect the tendency of the EFP speed to change with the ambient temperature, and also show that the influence of the ambient temperature on the density of the air medium cannot be ignored.
Table 7. The velocity at 90 meters(\text{ms}^{-1}) .

| Temperature | Experiment$^a$ | Calculate$^b$ |
|-------------|---------------|---------------|
| -18°C       | 1421.2        | 1427.3        |
| 5°C         | 1444          | 1447.2        |
| 25°C        | 1479.2        | 1463.6        |

$^a$ The average value.
$^b$ The interpolation data from Table 6.

6. Conclusions

The EFP of engineering applications is typically fly at high speed in air. The flight resistance of EFP is directly affected by the density of the air. But the density of the air is significantly affected by the ambient temperature. The air density fluctuation caused by ambient temperature is particularly evident in high latitudes, with fluctuations of more than 10% in the coldest and hottest seasons.

EFP relies on kinetic energy to damage the target. The fluctuation of EFP velocity directly affects the damage effect of EFP to the target. Because the change of ambient temperature exists objectively, the influence of external application environment should be fully considered in the design of EFP warhead to improve the design margin of kinetic energy.

7. References

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