Ground effects on the hypervelocity jet flow and the stability of projectile

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ABSTRACT
The significant influence of the ground on the hypervelocity jet flow as well as the stability of the projectile cannot be discarded due to the intensity and the wide influence range. The present study examines two three-dimensional simulation models, one with the ground effects included and the other without, based on FLUENT software, using the finite volume method (FVM). The simulation models couple the FVM model with a standard k-ε turbulence model and unstructured dynamic grid based on the Local Remeshing method. An intermediate ballistic model and the six-degrees-of-freedom model are also utilized. For the 300-caliber 1730 m/s countermass propelling gun, two different flow phenomena, with and without the ground effects, were examined. The simulation results indicate that the effect of the ground surface on the jet flow and the projectile emerged gradually at 1.5 ms. The hypervelocity muzzle shock wave was reflected off the ground, creating a new shock-wave phenomenon in the opposite direction. The wave system interacted with the muzzle shock wave so that the pressure in the lower half of the domain was significantly higher than that in the upper half. This phenomenon produced a complete shock-wave surface. Shock waves at the ground produced a vortex, which gradually expanded and developed. The wavefront, which was formed by the ground reflection, led to a new wavefront, producing vortices at the wavefront and propagated towards the front and rear of the main shock wave. The hypervelocity jet flow twisted and generated a more complex wave system. The distorted gas jet caused the projectile to be disturbed, and the lift and torque were influenced so that the parameters such as the angular velocity of the rotation were changed.

1. Introduction
Research regarding flow shock waves induced by fire-powered projectiles is well established due to the practical applications. The flow-induced shock wave can significantly influence muzzle flow performances (Jiang, Fan, & Hong-zhi, 2008; Zhuo, Feng, & Wu, 2015). As the projectile propagates at a high speed in the chamber and moves the air in front of the projectile, a series of compressional waves form, moving toward the muzzle and generating a precursor flow field. With the projectile exiting the muzzle, the high-temperature and pressure propellant gas behind the projectile quickly moves out and forms a complex and strong propellant flow-field pattern (Sun & Cai, 2001; Xiao-Peng, Qian, & Dai, 2009). It is difficult to obtain data regarding this flow via experimental methods owing to the extremely short duration and the existence of the muzzle smoke and flame. Most significantly, the jet flow of a large-diameter hypersonic projectile is abnormally violent, resulting in any sensors near the muzzle being displaced or damaged. (Isfahani, Tasdighi, Karimpour, Shirani, & Afrand, 1968; Wang, Zheng, Jia, & Cui, 2011).

The development mechanism in the flow field, distribution regularities of the shock wave, and the after-effect period of the projectile are already well understood (Fouatih, Medale, Imine, & Imine, 2016; Tan, 2006; Viré, Spinneken, Piggott, Pain, & Kramer, 2016; Xin, 2008). Hence, a further emphasis must be placed on revealing flow physics and fluid dynamic behaviors. An accurate computation of the flow field is significant regarding aerodynamics. (Feng, Shi, Fei, & Hui, 2001; Kogelschatz, 2003).

Recent advances in computational fluid dynamics techniques have made numerical simulations of these complex flow fields a highly effective alternative to experimental studies. The experimental study undertaken by Merlen and Dyment (1991) showed a similar rule in muzzle flow fields, and a theoretical analysis has been described in detail. Considering the motion of projectiles, the disturbance in the flow field caused by projectiles motion has been studied by Ma (Le, 2004). A numerical simulation of 122 mm vehicular artillery flow field undertaken by Jiang and Wang (2010) obtained qualitatively accurate results, and the flow phenomenon of 713 m/s
projectile firing was analyzed in detail. The interaction between projectile and flow field was described by Dai, Xu, and Sun (2007), as well as the structure and capacity of muzzle flow-field development process, and 3D unsteady chemical reaction control equations were used to study 7.62 mm 735 m/s projectiles with muzzle brake. Florio (2010) numerically studied the muzzle flow field with a side-opening bore device at the muzzle using the 2D axisymmetric Navier–Stokes (N-S) equations and a k-ε turbulence model.

Previous studies on the muzzle flow fields did not take the ground into consideration, and all of them were full-space symmetric numerical simulation models. The author of this paper, taking the ground into account, established a half-space muzzle flow-field simulation model. This study examines two 3D simulation models, with and without the ground, to analyze the ground effects on a hypervelocity jet flow of a 300-mm-caliber 1730 m/s countermass propelling gun, with a particular focus on flight stability. The research will result in a theoretical foundation for experiments on large-caliber hypervelocity countermass propelling guns.

\section{Mathematic models}

Without considering the effect of external heating and body force, three-dimensional, time-dependent, unsteady, compressible N-S equations are used as the governing equations (Rehman, Chung, Joung, Suwono, & Jeong, 2011; Wang, Wang, Jiang, & Tao, 2017; Zhang, Chen, Jiang, & Li, 2013):

$$\frac{\partial Q}{\partial t} + \frac{\partial f}{\partial x} + \frac{\partial g}{\partial y} + \frac{\partial h}{\partial z} = 0$$  \hspace{1cm} (1)

In Eq. (1), $Q$ is the vector of the conservative variables, and $f, g,$ and $h$ are the vectors of the convective flux. They are expressed as:

$$Q = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho e \end{bmatrix}$$  \hspace{1cm} (2)

$$f = \begin{bmatrix} \rho u \\ \rho u^2 + p - \tau_{xx} \\ \rho uv - \tau_{xy} \\ \rho uw - \tau_{xz} \\ (\rho e + p)u - u\tau_{xx} - v\tau_{xy} - w\tau_{xz} + q_x \end{bmatrix}$$  \hspace{1cm} (3)

$$g = \begin{bmatrix} \rho v \\ \rho uv - \tau_{xy} \\ \rho v^2 + p - \tau_{yy} \\ \rho vw - \tau_{yz} \\ (\rho e + p)v - u\tau_{xy} - v\tau_{yy} - w\tau_{yz} + q_y \end{bmatrix}$$  \hspace{1cm} (4)

$$h = \begin{bmatrix} \rho w \\ \rho uw - \tau_{xz} \\ \rho vw - \tau_{yz} \\ \rho w^2 + p - \tau_{zz} \\ (\rho e + p)w - u\tau_{xz} - v\tau_{yz} - w\tau_{zz} + q_z \end{bmatrix}$$  \hspace{1cm} (5)

where:

$$\tau_{xx} = \frac{2}{3} \mu \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right)$$

$$\tau_{yy} = \frac{2}{3} \mu \left( \frac{\partial v}{\partial y} + \frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} \right)$$

$$\tau_{zz} = \frac{2}{3} \mu \left( \frac{\partial w}{\partial z} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)$$

$$\tau_{xy} = \mu \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) = \tau_{yx}$$

$$\tau_{xz} = \mu \left( \frac{\partial u}{\partial z} + \frac{\partial v}{\partial x} \right) = \tau_{zx}$$

$$\tau_{yz} = \mu \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial z} \right) = \tau_{zy}$$

The total energy per unit flow is expressed as

$$e = \frac{p}{\rho(\gamma - 1)} + \frac{1}{2}(u^2 + v^2 + w^2)$$

where $p$ is the pressure, $\rho$ is the gas density, $u, v,$ and $w$ are the velocity components of the fluid, and $\gamma$ is the gas-specific heat ratio. The ideal gas state equation is $p = \rho RT$, where $R$ is the universal gas constant, and $\mu$ is the laminar viscous coefficient. $\tau_{xx}, \tau_{xy}, \tau_{xz}, \tau_{yx}, \tau_{yy}, \tau_{yz}, \tau_{zz}, \tau_{zx},$ and $\tau_{zy}$ are the viscous forces of different direction; $k$ is the heat conductivity; and $q_x, q_y,$ and $q_z$ are the volumetric heating rates in unit mass.

\section{Simulation model and boundary conditions}

\subsection{Unstructured dynamic mesh}

In the example to be discussed here, a dynamic grid technique was adopted to handle the changing grid caused by the projectile movement based on FLUENT software. The dynamic meshing algorithm is used to calculate and adjust the internal grid nodes. The dynamic meshing includes three distinct algorithms: Layering, Smoothing, and remeshing. Layering includes the generation and removal of the boundary grids. The algorithm can generate and remove the grids according to the expansion...
and contraction of the grids in the calculation domain. Using Spring Smoothing, the connection between the node properties is unchanged when nodes are generated or eliminated. The connection and number of the nodes remain the same, and thus the nodes are either compressed or stretched. When remeshing methods are utilized, the local nodes and grids will increase or decrease when the grid rate and the maximum size are beyond a user-specified standard.

Considering the disturbance of the hypervelocity jet flow relative to the projectile movement, it is evident that the projectile is unable to move in one direction only, and therefore the Layering method with a structured grid cannot achieve the simulation aim; hence, the Smoothing algorithm combined with the remeshing algorithm was used. Additionally, a size function allowed for smooth transition between grids.

For the Spring Smoothing method, the Spring Constant Factor controls the boundary node displacements for the motion of the interior nodes at a given boundary node. In this paper, the value of the Spring Constant Factor \( k \) was 1. When the model contains deforming boundary zones, boundary node relaxation (BNR) is used to control how the node positions are updated on the deforming boundaries. The interior node displacements \( \Delta \vec{x}_\text{adj} \) compared with the boundary node displacements \( \Delta \vec{x}_b \) are controlled using the BNR. The value of the BNR constant in this paper was set to \( \beta = 0.5 \).

For the remeshing algorithm, when the boundary displacement is beyond the local cell size, the cell quality can deteriorate, or the cells can degenerate. This will invalidate the mesh (e.g., resulting in negative cell volumes) and, consequently, lead to convergence problems when the solution updates to the next time step. To circumvent this problem, remeshing agglomerates cells that violate the skewness or size criteria and locally remeshes the agglomerated cells or faces. If the new cells or faces satisfy the skewness criterion, the mesh is locally updated by the new cells. Otherwise, the new cells are discarded. The maximum cell skewness in this paper was set to 0.85.

Therefore, this paper mainly applies the Local-remeshing algorithm. For the dynamic grid process using nonstructural mesh reconstruction technology, it mainly includes two steps: grid deformation and grid reconstruction. In the whole domain, it is found that the grids are of poor quality, and therefore the area is reconstructed according to certain rules. The grids are removed over the entire domain to create a “hole.” Then, new grids are regenerated in the “hole” region and are integrated into the original grids. Aiming at the common boundary problem of multibody separation, the local mesh reconstruction method can deal with different resulting problems after grid deformation with high efficiency.

Figure 1 shows the grid reconstruction along with projectile movement.

### 3.2. Grid division and boundary conditions

The system arrangements are identified as case A and B. For case A, a 3D simulation model was established for an accurate depiction of the hypervelocity jet flow with the ground effects. The half 3D physical model can adequately describe the problem and therefore decrease the amount of grids, increasing computational efficiency. For this model, the tube caliber was 300 mm, the length of the exterior flow field was 11 m, and the width between the left boundary of the computational domain and the muzzle axis was set to 4 m. It is noteworthy that the height between the top boundary and the muzzle axis was set to 4 m, to avoid the boundary pollution phenomenon. The cannon tube was placed 1.8 m from the ground for a total of 4 million grid cells.

For case B, a 3D simulation model was established without considering the ground effects. A symmetric upper half and bottom half of 4 m was used as the domain, and the other parameters remained the same, resulting in 4.2 million grid cells in total. Figure 2 displays the simulation models with and without the ground effects.

For grid convergence tests, two models with a total of 4.2 million and 5 million grid cells were used. The pressure at the point (2000 mm, 1000 mm) is chosen for grid convergence tests. Figure 3(a) shows the location of the monitoring point, which is on the plane of symmetry. In the entire calculation domain, the muzzle center is taken as the origin, the center axis of the gun body is the X direction, the vertical ground is the Y direction, and XY is located on the plane of symmetry plane. As shown in Figure 3(b), the simulation results of these two meshes differed by no more than 1%, and so the results
Figure 2. Simulation model with and without ground effects. (a) Physical model with ground effects. (b) Mesh model with ground effects. (c) Physical model without ground effects. (d) Mesh model without ground effects.

Figure 3. (a) Location of the monitoring point (2000 mm, 1000 mm) for grid convergence tests. (b) Comparison of the pressure at Point (2000 mm, 1000 mm) for grid convergence tests.

were considered to be convergent and independent of the spatial discretization.

In the computational domain, the cannon tube was specified as a solid wall boundary condition, and the pressure-outlet boundary condition was applied at the domain boundary around the muzzle flow field. As mentioned previously, in order to perform the necessary calculations, a number of C-language based user-defined subroutines were created. The muzzle was applied to the pressure-inlet boundary condition, which was obtained through the aftereffect period User-defined Function (UDF) program. The six-degrees-of-freedom (6DOF) UDF program is used to control the projectile while moving in the tube and exiting the chamber. The symmetry boundary condition was specified along the axis of symmetry. Along the domain boundaries, impermeable wall and temperature near wall conditions were applied. The precursor pressure and temperature around the muzzle flow field were set at 101,325 Pa and 300 K, respectively.

In the example to be discussed here, the muzzle pressure and the muzzle velocity were 46.3 MPa and 1730.4 m/s, calculated by the interior ballistics program. The artillery aftereffect period phenomenon is a complex and unsteady aerodynamic phenomenon. According to the Luhowski empirical formula of the aftereffect period, the relationship between the muzzle pressure and the time is as follows:

\[ p = p_g e^{-At}, \]

\[ A = \frac{s p_g}{(\beta - 0.5)\omega v_0}, \]
\[ \beta = 0.5 + \frac{4 - k}{2k} \frac{a_g}{v_0 \sqrt{1 + \frac{3-k}{6} k}}, \]
\[ a_g = \sqrt{\frac{k p_g}{\rho_g}} \]  

Here, \( s \) is the muzzle cross-section, \( \omega \) is the charge, \( v_0 \) is the muzzle velocity, \( k \) is the specific heat ratio of the gunpowder gas, \( \rho_g \) is the average density of powder gas in the chamber, and \( p_g \) is the muzzle pressure.

In this paper, the aftereffect period muzzle pressure was
\[ p = 46.3 \times 10^6 e^{-24.886t} \]

and the muzzle pressure curve is shown in Figure 4 (Bao & Qiu, 1995; Jin & Weng, 2003; Weng & Wang, 2006):

### 4. Results and analysis

#### 4.1. Numerical verification

To verify the reliability of the algorithm, the author used the Local-remeshing algorithm to simulate the separation process of three-dimensional objects outside of the aircraft and compared them with the experimental results (Snyder, Koutsavdis, & Anttonen, 2003). The center-of-gravity location is chosen as the comparison parameter to verify the algorithm. This parameter can be found in the reference. As shown in Figure 5, the simulation results of the center of gravity location are consistent with the experimental results, indicating the reliability of this algorithm.

#### 4.2. Analysis of the hypervelocity jet flow with ground effects

Along with the projectile moving out of the muzzle, the wave system structure and the forming process of the hypervelocity jet flow can be determined with the coupling of the aftereffect period program and the 6DOF kinematic equations. In Figure 6(a)–(f), the pressure contours of the hypervelocity jet flow over time with the ground effects are shown.

The high-temperature and pressure propellant gas escaped from the projectile bottom through rapid dissemination, developing in the anterolateral direction. As displayed in Figure 6(a)–(b), the shock wave at the bottom of the projectile formed clearly as the propellant gas velocity ejected out of the muzzle was higher than the projectile velocity, and further strengthened. The shock wave further hinders the formation of the Mach disk. The Mach disk increased gradually, which can be explained as the effect of the shock wave at the bottom of the projectile becoming weaker.

Before 1.5 ms, the development of jet flow was not sufficient, and little effect of the ground on the hypervelocity jet flow was noted. The shock wave surface showed longitudinal symmetry. As shown in Figure 6(c), the ground effects were significant with the development of the muzzle shock wave around 2.0 ms. The muzzle shock wave was reflected by the ground, generating a new opposing shock-wave surface. The reflection also formed a new complete surface and vertex on the ground that expanded gradually, as shown in Figure 8(b). The opposite-direction shock wave reflected by the ground interacted with the muzzle shock wave and generated a secondary shock-wave surface, as shown in Figure 6(d) and (e). The new shock wave continued spreading upward and interacted with the bottlenecked wave at the muzzle center domain shown in Figure 6(f).
Figure 6. Pressure contours of the hypervelocity jet flow with ground effects.

The shock wave was then pushed to the front and rear. A vortex formed on this new shock wave surface and expanded gradually. It can be seen that the shock wave of the bottom of the projectile was influenced by the local high pressure at the front of the bottled-shaped wave near the ground. The bottle-shaped wave is formed by the influence of the ground. The whole hypervelocity jet flow twisted, resulting in a more complex wave structure.

Figure 7 illustrates the hypervelocity jet flow without the ground effects. The wave surface is longitudinally symmetric, and the bottle-shaped wave develops fully, resulting in a fully defined pressure-based wave. Figure 8(a)–(b) shows the 3D pressure contours on the ground of the hypervelocity jet flow. A complete circular surface was generated on the ground, and the pressure distribution matched that of the hypervelocity propelling jet flow.

The pressure caused by the muzzle shock wave reflected on the ground was always higher than that of the incident shock wave if the angle between the incident shock wave and the ground was not zero. The gas parameters at the front of the incident shock wave are the pressure ($p_0$), density ($\rho_0$), and gas particle velocity ($\mu_0 = 0$). The pressure ($p_1$), density ($\rho_1$), wave velocity ($D_1$), and particle velocity ($\mu_1$) represent the gas parameters behind the shock-wave surface. The pressure ($p_2$), density ($\rho_2$), wave velocity ($D_2$), and particle velocity ($\mu_2$) represent the gas parameters behind the reflected shock-wave surface. The following relation was found to be true at the moment of collision in that the muzzle shock wave where an unsteady strong shock-wave system formed. The normal reflection overpressure of the strong shock wave can be expressed as follows:

\[
\frac{p_2 - p_0}{p_1 - p_0} = 1 + \frac{2kp_1}{(k-1)p_1 + (k+1)p_0},
\]

thus

\[
p_2 = p_1 + \frac{2kp_1(p_1 - p_0)}{(k-1)p_1 + (k+1)p_0},
\]

where $k = 1.4$.

The normal reflection pressure was observed to be higher, since the airflow behind the reflection shock wave was abruptly slowed down by the ground surface. Figure 9(a) shows the shock wave normal reflection sketch, where the subscripts (0–2) represent the corresponding gas states. As the ground acted as a rigid
body, a stagnation zone formed between the wall and the reflected shock wave.

The shock-wave regular oblique reflection sketch is shown in Figure 9(b). There are two reflections: regular reflection and Mach reflection, depending on the incident angle. The pressure relationship of the regular oblique reflection is as follows:

$$\frac{p_2}{p_1} = \frac{7}{6} M_1^2 \sin^2 \varphi_1 - \frac{1}{6},$$

where $\varphi_1$ is the densification jumping angle.

When the Mach reflection occurred, one wave propagated through the gas near the surface, but two waves (the incident wave and the reflected wave) propagated through the gas further away. This phenomenon occurred due to the existence of a contact discontinuity between the Mach wave and the reflected wave. The shock wave Mach reflection is shown in Figure 9(c).

The reflection of muzzle shock wave was extremely complex. The normal reflection, regular oblique reflection, and Mach reflection appeared alternatively and influenced one another.

Figure 10 shows the velocity vector at $t = 3.0$ ms. An opposite-direction shock wave is displayed in the figure, in which ground effects occurred. The new blast spread toward the front and rear, and interacted with the muzzle shock wave, leading to the pressure in the bottom half of the domain that was much greater than that in the upper half.

Table 1 and Figure 11 show the coordinates of six monitoring points in the hypervelocity jet-flow domain with

Table 1. Coordinates of the monitoring points.

| Monitoring point | Up (mm, mm) | Down (mm, mm) |
|------------------|-------------|---------------|
| (a)              | (500, 1000) | (500, −1000)  |
| (b)              | (−500, 1500)| (−500, −1500)|
| (c)              | (−500, 1800)| (−500, −1800)|
| (d)              | (1000, 1500)| (1000, −1500)|
| (e)              | (2000, 1500)| (2000, −1500)|
| (f)              | (2000, 1800)| (2000, −1800)|
the ground effects. A comparison of the pressure in the upper and lower domains based on the axis of the center is shown in Figure 12(a)–(f). The monitoring points (a)–(f) contrast significantly, but show a different state at the same time. The ground effect was weaker for the monitoring points located near the muzzle, which has an intense shock wave. For the monitoring points closer to the ground, the muzzle shock wave was weaker, but the effect of the ground became significant, as well as the time of the ground effects.

4.3. Ground effects on projectile stability

This paper analyzed two models: one took the ground effects into consideration and the other did not. Figure 13(a)–(c) shows the contrast curves of the drag force, the lift force, and the pitching moment force for these two models. As we can see in Figure 13(a), the drag force of the projectile of the two models mentioned above is basically the same. However, Figure 13(b)–(c) shows that the ground effects significantly influence the lift force and the pitching moment of the projectile. Within 1–3 ms, the lift force of the projectile with the ground effects was 0.01 MPa higher than that without the ground effects, and the pitching moment was approximately 0.02 MPa higher.

Figure 13(a) indicates that the ground effects slightly influence the propagation direction of the projectile. When the projectile moves in the air, it is mainly affected by air resistance, in addition to gravity. According to the different causes, the air resistance can be divided into three sections: friction resistance, eddy current resistance, and shock resistance. Friction resistance is caused by the interaction between the air molecules and the surface of the projectile. The pressure difference between the front and the rear of the projectile causes the eddy current resistance. When the projectile moves at a supersonic velocity, the front and the rear of the projectile will create a shock wave, which will generate the shock resistance. It can be seen that the drag force is mainly determined by the direction of the projectile, so the ground just has a slight influence on the drag force of the projectile.

However, there is a significant difference on the lift force and the pitching moment of the projectile. The lift of the projectile is mainly caused by the pressure difference between the pressure above the projectile and the pressure below it. When the muzzle shock wave was reflected by the ground, it generated a new opposing shock wave. The new blast spread toward the front and the rear and interacted with the muzzle shock wave, leading to the much higher pressure in the bottom half of the domain than in the upper half. This phenomenon generates a pressure difference between the bottom and
the top of the projectile, leading to a significant difference on the lift force and the pitching moment. Figure 14 shows the rate of the angular velocity curves of the projectile. The figure shows that the angular velocity has also changed due to the ground effects. In addition, the results presented in Figures 13 and 14 show a small difference before 1.5 ms; this is probably because at the beginning, the moving grid is not very stable, and it will produce some slight concussion and error. As shown in Figure 13(a), it is the comparison of the drag force. The ground effects have little effect on the propagation direction of the projectile, since when the projectile moves in the air, it is mainly affected by air resistance, in addition to the gravity, but the results show a slight difference between these two cases. Therefore, it is considered that the slight difference is caused by the moving grid itself.

Figure 15 shows the velocity curves of the projectile. After the projectile exited the muzzle, the projectile accelerated as a function of the gas jet. As the projectile moved away from the muzzle, the influence of the gas jet became weaker. At this time, the projectile was in decelerating motion. At the same time, it shows that the role of the aftereffect period cannot be ignored.

5. Conclusions

In this paper, two simulation models, one with the ground effects and the other without, were established to analyze the ground effects on a hypervelocity jet flow and the projectile stability. The results indicate that:

(a) A new wave system was generated as the muzzle shock wave was reflected by the ground; the new wave interacted with the jet wave and generated a new wave surface and vertex. The new surface expanded toward the front and rear.
(b) The two opposite-direction shock waves lead to a significantly higher pressure in the lower half of the domain than in the upper half. The hypervelocity jet flow twists and becomes more complex.
(c) The twisted jet flow disturbs the flight stability of the projectile. Some parameters such as the lift force and the pitching moment of the projectile are changed, and so the ground has some influence on the flight stability of the projectile.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Bao, T. Y., & Qiu, W. J. (1995). *Internal ballistics* (pp. 214–218). Beijing: Beijing Institute of Technology Press.
Dai, S. L., Xu, H. Q., & Sun, L. (2007). Numerical simulation of gun muzzle flow field including movable boundary. *Journal of Ballistics, 19*(3), 93–96.

Feng, H. E., Shi, X. J., Fei, H. P., & Hui, Y. Z. (2001). Computation of axisymmetric jet flow with spalart-allmaras turbulence model. *Journal of Propulsion Technology, 22*(1), 43–46.

Florio, L. A. (2010). Effect of vent opening area and arrangement on gas flow field as gas propelled cylinder exits a flow tube. *Meccanica, 45*(4), 475–501.

Fouadhi, O. M., Medale, M., Imine, O., & Imine, B. (2016). Design optimization of the aerodynamic passive flow control on naca 4415 airfoil using vortex generators. *European Journal of Mechanics – B/Fluids, 56*(2), 82–96.

Isfahani, A. H. M., Tasdighi, I., Karimipour, A., Shirani, E., & Afrand, M. (1968). *A joint lattice Boltzmann and molecular dynamics investigation for theromohydraulic simulation of nano flows through porous media*. Gualteri Mapes Denugis curialium distinctiones quinque /. AMS.

Jiang, X. H., Fan, B. C., & Hong-Zhi, L. I. (2008). Numerical investigations on dynamic process of muzzle flow. *Applied Mathematics and Mechanics (English Edition), 29*(3), 351–360.

Jiang, K., & Wang, H. (2010). Numerical simulation of muzzle flow field based on dynamic meshing technique. *Journal of Gun Launch & Control, 3*, 1–4.

Jin, Z. M., & Weng, C. S. (2003). *Advanced interior ballistics*. Beijing: Higher Education Press.

Kogelschatz, U. (2003). Dielectric-barrier discharges: Their history, discharge physics, and industrial applications. *Plasma Chemistry & Plasma Processing, 23*(1), 1–46.

Le, G. (2004). Numerical simulation of muzzle blast flow fields of large caliber guns. *Acta Armamentarii, 25*(1), 19–22.

Merlen, A., & Dyment, A. (1991). Similarity and asymptotic analysis for gun-firing aerodynamics. *Journal of Fluid Mechanics, 225*(225), 497–528.

Rehman, H., Chung, H., Joung, T., Suwono, A., & Jeong, H. (2011). Cfd analysis of sound pressure in tank gun muzzle silencer. *Journal of Central South University of Technology, 18*(6), 2015–2020.

Snyder, D., Koutsavdis, E., & Anttonen, J. (2003). Transonic store separation using unstructured cfd with dynamic meshing – 33rd aiaa fluid dynamics conference and exhibit (aiaa).

Sun, D. C., & Cai, T. M. (2001). Effecting parameters of supersonic flowfield with secondary injection. *Journal of Propulsion Technology, 22*(2), 147–150.

Tan, L. B. (2006). Gun recoil force reduction technology. *Journal of Gun Launch & Control, (4)*, 69–72.

Viré, A., Spinneken, J., Piggott, M. D., Pain, C. C., & Kramer, S. C. (2016). Application of the immersed-body method to simulate wave-structure interactions. *European Journal of Mechanics – B/Fluids, 55*(S3), 330–339.

Wang, J. L., Wang, H., Jiang, K., & Tao, R. Y. (2017). Analysis on the gas interference characteristics during the transonic gasbag separation of cluster munition. *Beijing Ligong Daxue Xuebao/Transaction of Beijing Institute of Technology, 37*(4), 348–353 and 359.

Wang, S. S., Zheng, J., Jia, C. Z., & Cui, K. B. (2011). Numerical simulation of muzzle blast flow field with muzzle brake. *Fire Control & Command Control, 36*(2), 148–151.

Weng, C. S., & Wang, H. (2006). *Computing interior ballistics*. Beijing: National Defense Industry Press.

Xiao-Peng, S. U., Qian, L. F., & Dai, J. S. (2009). Muzzle flow field simulation of gun with a muzzle attachment. *Computer Simulation, 26*(9), 15–18.

Xin, L., & Beijing. (2008). Numerical investigation into the mechanism of under-expanded supersonic jet instability. *Chinese Journal of Theoretical & Applied Mechanics, 40*(5), 577–584.

Zhang, H., Chen, Z., Jiang, X., & Li, H. (2013). Investigations on the exterior flow field and the efficiency of the muzzle brake. *Journal of Mechanical Science & Technology, 27*(1), 95–101.

Zhao, C., Feng, F., & Wu, X. (2015). Development process of muzzle flows including a gun-launched missile. *Journal of Aeronautics, 28*(2), 385–393.