

Three-Dimensional Flow Field Simulation and Recoil Reduction Effect Analysis of Muzzle Brake with Convergent-Divergent Curved Side Holes

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Abstract. Aiming at the problem of low recoil efficiency in the current muzzle brakes, based on the design scheme of the muzzle brake with U-shaped curved side holes, a muzzle brake with convergent-divergent curved side holes is designed. Taking a 30mm aircraft gun muzzle brake as an application case, and using the state of the internal bore gas flow when the projectile reaches the muzzle position as the initial condition, a computational method is adopted, where polyhedral meshes are used for the stationary region and hexahedral structured meshes are used for the moving region. Three-dimensional numerical simulation calculations are carried out for the convergent-divergent side hole muzzle brake with both the inlet convergent angle and the outlet divergent angle being 40°. And the flow field results are compared with those of the muzzle brake with U-shaped curved side holes. The calculation results show that the muzzle brake with convergent-divergent side holes also has the characteristics of smooth flow guiding and side wall pressure increasing. The convergent-divergent side hole muzzle brake is subjected to a higher recoil force, and by utilizing the change of the cross-sectional area of the throat on the basis of the muzzle brake with U-shaped curved side holes, the ejection speed of the propellant gas is increased. The average ejection speed of the propellant gas from the side holes is increased by 2.26%. The peak force on each convergent-divergent side hole is greater than that on each curved side hole, with an average increase of 7.1%. The maximum recoil force of the convergent-divergent side hole muzzle brake is increased by 11.3% compared with that of the muzzle brake with curved side holes, and the counter-recoil impulse is increased by 11.2%, showing a better counter-recoil effect.

Keywords: Convergent-divergent; muzzle brake; dynamic mesh; three-dimensional flow field; braking force

1. Introduction

Currently, inclined side hole designs in aircraft gun muzzle brakes have become relatively common [1]. These inclined side holes utilize propellant gas venting laterally and rearward from the barrel to reduce recoil impulse. Considering that straight inclined holes are not conducive to smoothly channeling larger volumes of propellant gas, improved constant-cross-section curved side hole muzzle brakes demonstrate superior flow guidance and sidewall pressurization characteristics, consequently achieving higher total braking forces [2]. Building upon the constant-cross-section curved side hole design, this study develops a convergent-divergent curved side hole configuration that enhances propellant gas ejection velocity through throat area variation, thereby further improving braking performance.

In muzzle flow field simulations, computational fluid dynamics (CFD) techniques have been extensively applied [1-2]. Li Guihu [3] employed MATLAB software to conduct comprehensive optimization of interference-fit steel-titanium ring structure muzzle brakes. Zhiqun S [4] investigated flow fields and recoil reduction efficiency for three representative muzzle brake configurations using RANS-based cavitation models coupled with $k-\omega$ transport turbulence models. Guo Lifeng [5] integrated dynamic and static mesh technologies to analyze projectile motion,

numerically solving Euler and turbulence equations to reveal pressure distribution characteristics across vehicle components under muzzle flow field effects. Wang Meiyi [6] conducted comparative analyses between two-dimensional flow field modeling and experimental imaging to study flow distribution in large-caliber balanced guns.

For the proposed convergent-divergent curved side hole muzzle brake, this research employs three-dimensional Navier-Stokes equations to numerically simulate the flow states of propellant gas through each row of side holes during projectile movement. The study elucidates the interaction mechanisms between projectile motion and gas flow through both the central bore and multiple rows of convergent-divergent side holes. Through comparative analysis of flow field distributions and braking force variations between constant-cross-section and convergent-divergent curved side hole designs, this work demonstrates the advantages of the convergent-divergent configuration, providing valuable references for structural optimization of novel side hole muzzle brakes.

2. Design Scheme and Meshing for Muzzle Brake with Convergent-Divergent Curved Side Holes

2.1 Three-Dimensional Modeling

This paper presents a muzzle brake design featuring converging-diverging curved side holes for a 30 mm aircraft cannon, based on the original scheme of a curved side hole muzzle brake with constant cross-section. By altering the throat cross-sectional area, the design aims to increase the exhaust velocity of propellant gas, thereby reducing the recoil force of the cannon.

The models of both the curved side hole muzzle brake and the converging-diverging curved side hole muzzle brake are shown in Figure 1. The overall transverse dimension of the muzzle brake is 280 mm, with a symmetrical design of 5 rows and 2 columns per row. The throat cross-sectional area of the curved side hole is 120 mm², with a fan-shaped ring profile symmetric about the horizontal axis, 10 mm in width and 80° in angle. The straight side hole section connected to the central cylindrical bore is inclined forward along the projectile's motion direction at a 50° angle to the horizontal axis, while the straight side hole section connected to the propellant gas outlet is inclined toward the rear of the barrel at a 130° angle. In the converging-diverging curved side hole muzzle brake, the throat section retains the fan-shaped ring profile with an 80° angle. However, the straight side hole sections in the constant cross-section design are replaced with converging and diverging passages, both featuring entrance and exit angles of 40°.

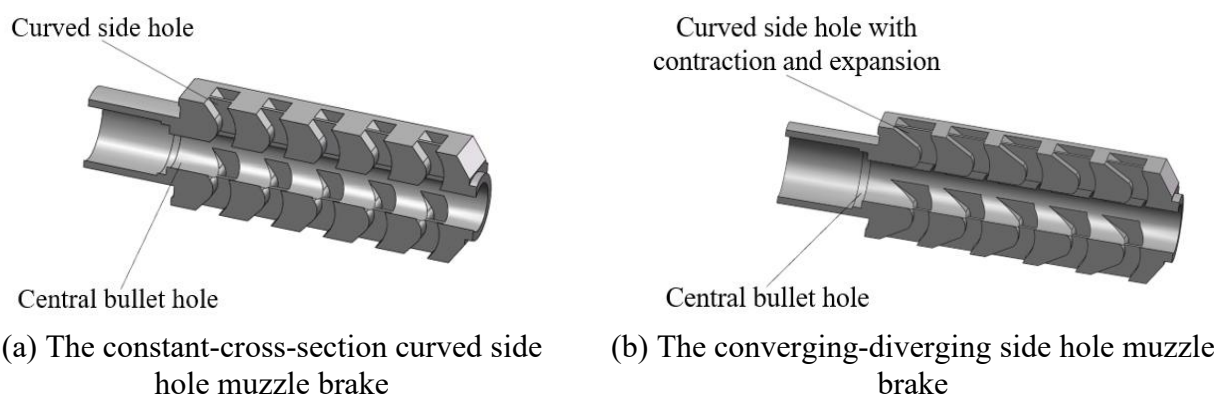


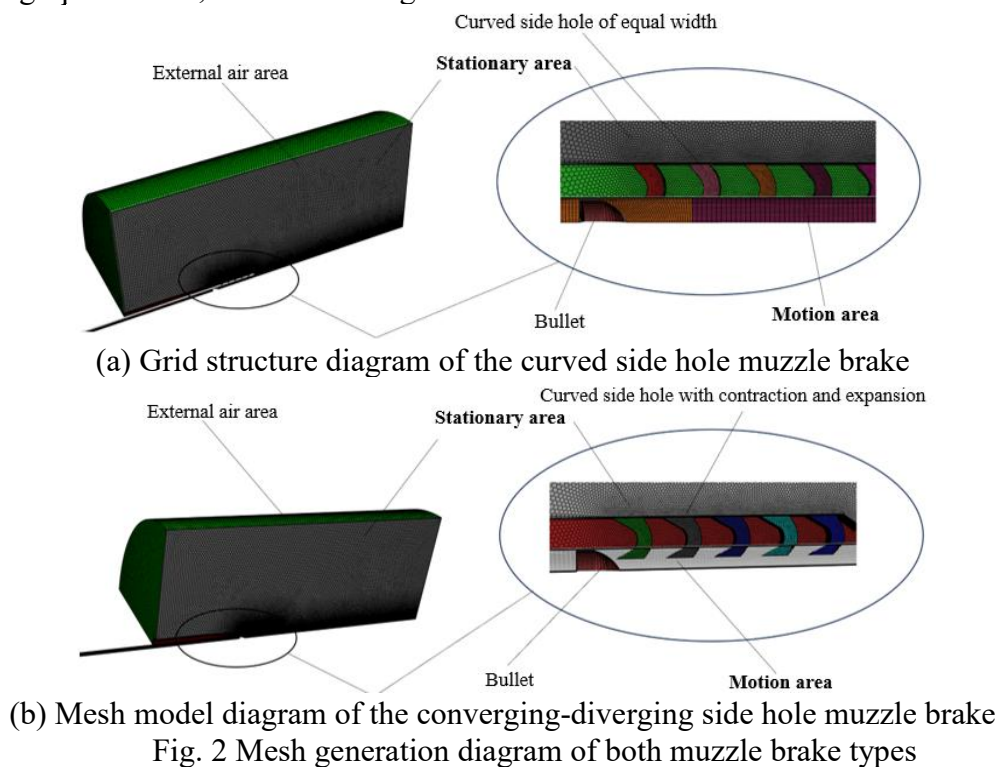
Fig. 1 3D models of the converging-diverging curved side hole muzzle brake and the curved side hole muzzle brake

The high-temperature, high-pressure propellant gas first passes through the converging section and reaches the narrow throat. The curved narrow throat section smoothly directs the propellant gas toward the rear sides of the muzzle brake, ensuring uniform gas distribution along the curved throat surface. Subsequently, the gas continues to expand and accelerate in the diverging section, resulting

in high-speed propellant gas being ejected toward the rear sides, thereby further enhancing the recoil reduction effect.

2.2 Mesh Generation

Due to symmetry, a quarter-section of the device was selected as the computational domain for analysis. Given the 30 mm aircraft cannon barrel length of 2457 mm, the external ballistic flow field was defined as a cylindrical region with a diameter of 1000 mm, extending 1000 mm forward and 500 mm rearward from the muzzle. The fluid domain was extracted from the 3D model of the device. The coordinate system was established with the origin at the breech center point and the positive X-axis aligned with the muzzle direction. The 3D flow field model was constructed and meshed using SpaceClaim, as shown in Figure 2.



To simulate projectile motion, a partitioned mesh generation approach was adopted for different zones of the computational domain. The stationary fluid regions were discretized using polyhedral meshes to enhance computational efficiency and accuracy. Compared to hexahedral meshes, polyhedral elements offer advantages in handling complex 3D geometries with fewer cells while maintaining high mesh quality. Due to the projectile's movement, the fluid regions ahead of and behind it are dynamic and thus treated as moving zones. Given the complexity of 3D dynamic meshing, the dynamic layering method was employed to prevent negative volume errors during computation. The moving zones were meshed with structured hexahedral grids. As the projectile advances, the cells ahead of it are gradually removed, while new cells are generated behind it. Non-overlapping regions are defined as walls. Data exchange between the moving and stationary zones is achieved through numerical interpolation at the Interface boundary, where the flux values at the moving-stationary boundary are computed based on the control volumes.

3. Boundary Condition Parameter Settings

The primary boundary conditions include the no-slip wall conditions at the breech, barrel, and all surfaces of the device's ports, the Interface boundary conditions for data transfer between the pressure outlet of the external flow domain and the flow fields of the stationary and dynamic regions, as well as the symmetry plane boundary conditions.

The projectile motion in the flow field is simulated using dynamic meshing combined with a six-degree-of-freedom model, with the initial projectile velocity obtained from the interior ballistic calculation. To improve computational convergence, the Courant number and relaxation factors can be appropriately reduced [8]. Here, the Courant number is set to 2, with relaxation factors of 0.5 for turbulent kinetic energy, 0.5 for turbulent dissipation rate, and 1 for turbulent viscosity. The projectile motion from 0 to 0.22 ms corresponds to the interior ballistic phase, while the period from 0.22 ms to 0.5 ms represents the after-effect phase. During the computation, the axial resultant forces acting on the breech and the device are monitored. To ensure accurate simulation of the flow field within the device, the time step is set to 10^{-6} s at the start of the computation. The simulation terminates after the after-effect phase concludes. The initial conditions of the projectile and the internal ballistic parameters of the aircraft cannon are detailed in Reference [1].

4. Three-Dimensional Flow Field Simulation Results and Comparative Analysis

4.1 Velocity and Pressure Vector Distributions

Figure 3 presents the three-dimensional velocity contour distributions of both the converging-diverging side-hole muzzle brake and the curved side-hole muzzle brake at different time instants.

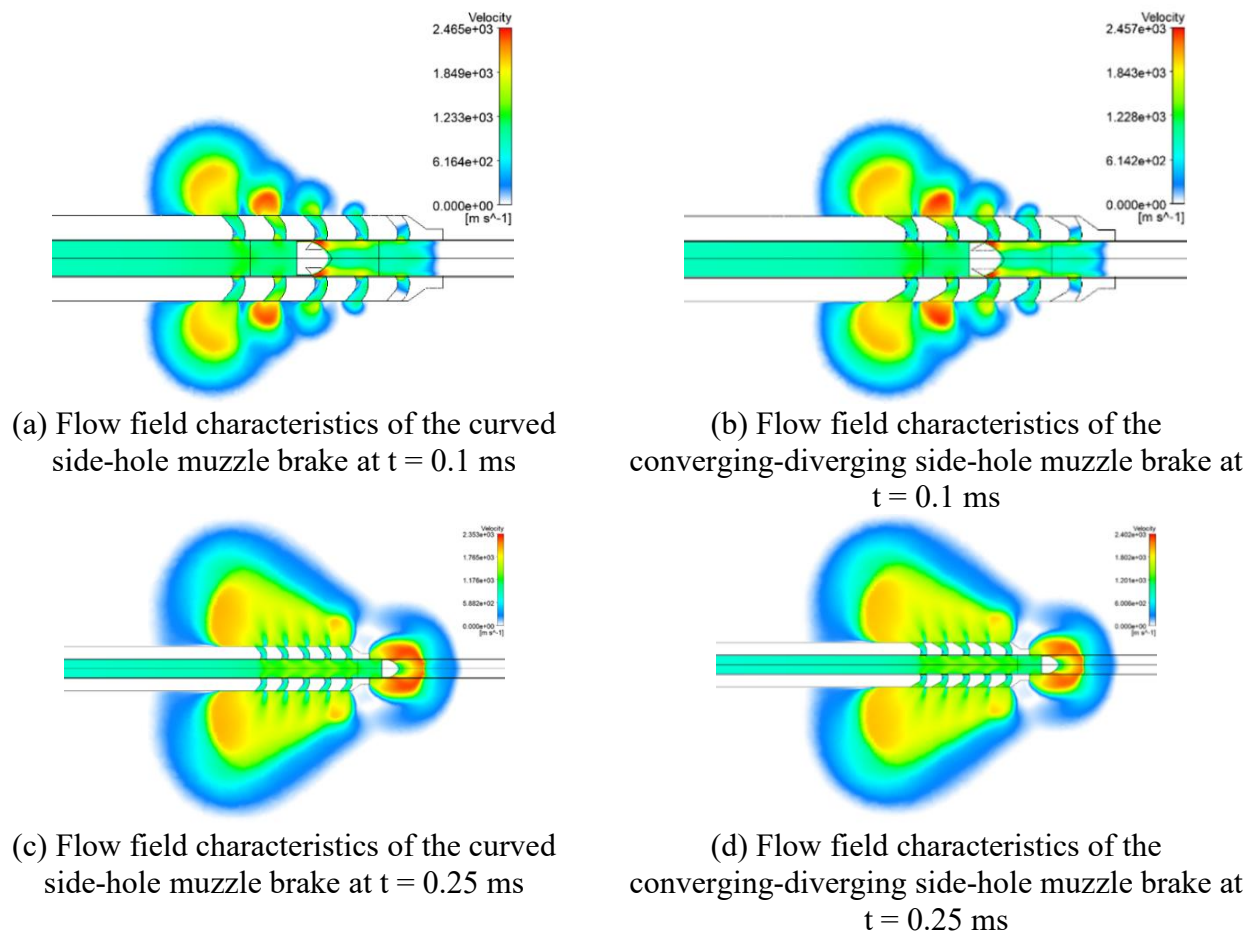


Fig. 3 Three-dimensional velocity contour distributions of both muzzle brake designs

Figure 3 demonstrates that upon the projectile entering both muzzle brake configurations, the gas velocity fields exhibit the following characteristics: The high-temperature, high-pressure propellant gas undergoes compression and accelerates upon entering the side ports, forming supersonic exhaust jets upon exiting. A portion of the gas is deflected by the projectile base obstruction into the side channels, where it is further redirected through curved throat sections and expelled obliquely

rearward at increased velocity. As the projectile passes successive side ports, the propellant gas forms progressively diminishing conical oblique shock waves at each port.

Comparative analysis reveals significant performance enhancement in the converging-diverging design. Where the conventional curved side-port muzzle brake achieves exhaust velocities of 2359 m/s, 2376 m/s, 2430 m/s, 2350 m/s, and 2345 m/s across its five ports, the optimized configuration increases these velocities to 2422 m/s, 2457 m/s, 2455 m/s, 2409 m/s, and 2386 m/s respectively. This corresponds to measurable improvements of 2.7%, 3.4%, 1.0%, 2.5%, and 1.7% per port.

Figure 4 presents the three-dimensional pressure contour distributions of both the converging-diverging side-hole muzzle brake and the curved side-hole muzzle brake at different time instants.

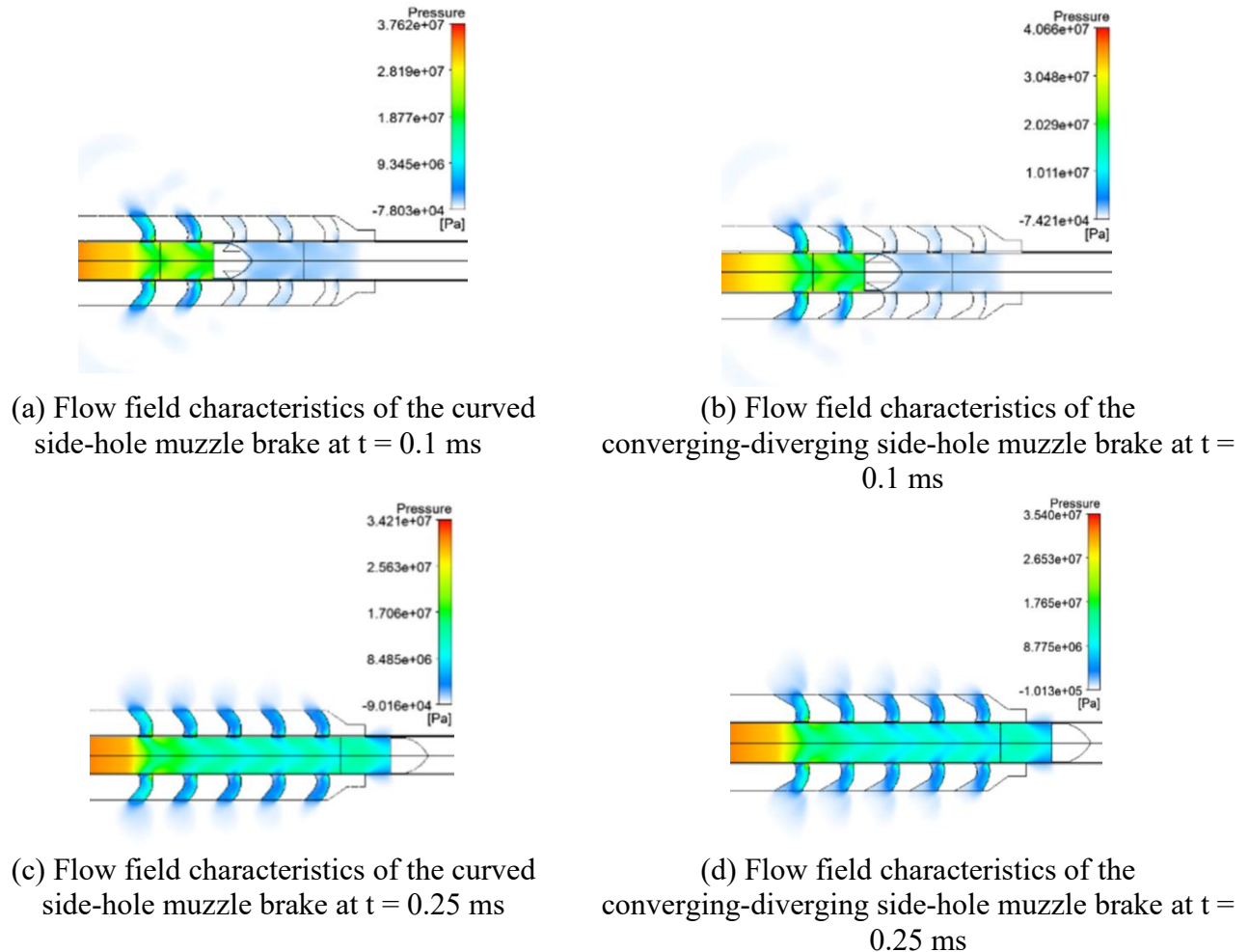


Fig. 4 Pressure distribution in the bore and side ports of both muzzle brake designs

Figure 4 demonstrates that when the projectile base passes through each row of side ports in the converging-diverging muzzle brake, the propellant gas undergoes deflection and is smoothly guided into the side channels. This results in a uniformly distributed pressure along the outer walls of each port row, with sequentially decreasing pressure magnitudes. The muzzle flow field distribution shows fundamental consistency between the converging-diverging and curved side-port designs, confirming that the converging-diverging configuration maintains the essential flow-smoothing and sidewall pressure-enhancing characteristics of conventional muzzle brakes.

4.2 Force Analysis and Comparison of Both Muzzle Brake Designs

Analysis of the pressure contours and wall pressure monitoring data for both the converging-diverging and curved side-hole muzzle brakes reveals the axial force distribution across their respective side ports, as shown in Figure 5. Both muzzle brake configurations exhibit similar

axial force characteristics during projectile transit. As the projectile base sequentially passes each side port, the blocked propellant gas rapidly diverts into the ports, causing an immediate increase in axial force. Due to forward gas leakage through the projectile-barrel clearance, the force profile for ports beyond the first row demonstrates an initial minor peak followed by a rapid rise to the maximum force value. In both designs, the axial forces gradually decline after reaching their respective peak values.

The converging-diverging muzzle brake's side ports sequentially reached their peak axial forces at 62 μs , 99 μs , 135 μs , 172 μs , and 208 μs , with maximum force values measuring 5257 N, 4230 N, 3575 N, 3052 N, and 2630 N respectively. In comparison, the conventional curved side-hole design exhibited peak forces at nearly identical temporal intervals of 61 μs , 99 μs , 134 μs , 171 μs , and 209 μs , but with lower magnitudes of 4874 N, 3931 N, 3339 N, 2864 N, and 2479 N. Quantitative analysis reveals that the converging-diverging configuration generates consistently higher peak forces across all ports, demonstrating a 7.1% average improvement in axial force transmission. Throughout the temporal evolution, the pressure distribution within the optimized ports maintained superior values while exhibiting a more gradual decay profile compared to the conventional design. This enhanced performance confirms that the converging-diverging geometry provides additional recoil reduction capability beyond what the curved side-hole configuration achieves.

Figure 6 presents the total recoil force (i.e., the combined axial force from all side ports) for both muzzle brake configurations. Analysis of the force characteristics in the converging-diverging curved side-hole muzzle brake reveals that as the projectile sequentially passes each port, a portion of propellant gas flows through the gap between the projectile and central bore into subsequent ports, maintaining the total recoil force without decline and confirming the design's effective flow redirection capability. The total recoil force reaches peak values of 6290 N at 63 μs , 9789 N at 100 μs , 12079 N at 137 μs , 13678 N at 172 μs , and 14863 N at 207 μs , consistently exceeding the corresponding peak forces of 5737 N, 8808 N, 10901 N, 12346 N, and 13357 N observed in the conventional curved side-hole muzzle brake. Throughout the entire process, the total recoil force of the converging-diverging design remains higher than that of the curved side-hole configuration.

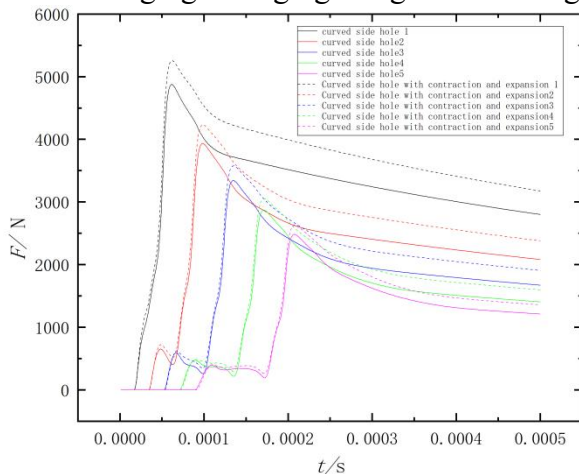


Fig. 5 Axial force distribution across side port rows for both muzzle brake designs

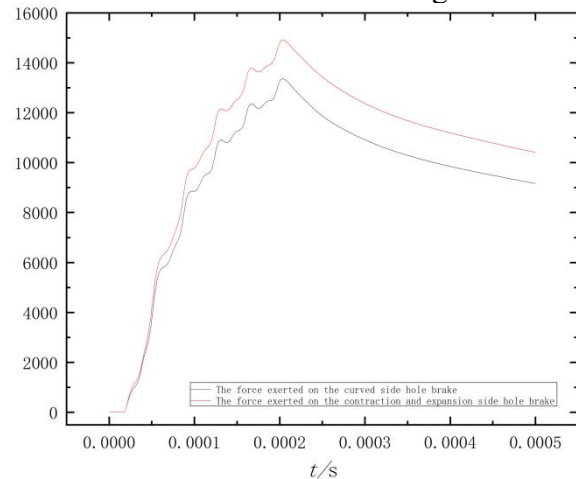


Fig. 6 Recoil force profiles of both muzzle brake designs

Quantitative comparisons indicate that the maximum recoil force in the converging-diverging design is 11.3% higher than that of the curved side-hole configuration. Furthermore, the total axial force before projectile exit is 10.6% greater, while the recoil impulse at muzzle exit shows an 11.2% improvement, confirming superior recoil reduction performance.

Efficiency calculations demonstrate that the conventional curved side-hole muzzle brake achieves a recoil reduction efficiency of 49.1%, whereas the converging-diverging design with 40° contraction/expansion angles attains 53.7% efficiency, representing a measurable enhancement in braking effectiveness.

5. Summary

(1) Building upon the conventional constant-cross-section curved side-hole muzzle brake, this study proposes an optimized converging-diverging curved side-hole muzzle brake design. Three-dimensional numerical simulations demonstrate significant performance enhancements: The exhaust gas velocities through individual ports increase from baseline values of 2359 m/s, 2376 m/s, 2430 m/s, 2350 m/s, and 2345 m/s to improved levels of 2422 m/s, 2457 m/s, 2455 m/s, 2409 m/s, and 2386 m/s respectively, representing velocity increments of 2.7%, 3.4%, 1%, 2.5%, and 1.7%, with an average improvement of 2.26% in propellant gas exhaust velocity.

(2) Force analysis reveals superior mechanical performance in the converging-diverging design, with peak axial forces measuring 5257 N, 4230 N, 3575 N, 3052 N, and 2630 N across successive port rows, compared to 4874 N, 3931 N, 3339 N, 2864 N, and 2479 N in the conventional design - demonstrating a 7.1% average enhancement in force transmission.

(3) Throughout the projectile's passage across each converging-diverging curved side port, the total recoil force of the optimized muzzle brake consistently exceeds that of the conventional curved side-hole design. The maximum recoil force demonstrates an 11.3% enhancement compared to the baseline configuration, accompanied by an 11.2% improvement in recoil impulse magnitude, confirming superior recoil mitigation performance.

6. Acknowledgements

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7. References

- [1] Qiu Ming, Xie Hao, Song Jie, et al. Numerical simulation of flow field of muzzle brake with multi-row oblique-side-holes. *Journal of Ballistics*, 2025, 37(1): 121-128.
- [2] Deng Zilong, Qiu Ming, Song Jie, et al. Smooth diversion and side wall pressurization characteristics of curved side holes in muzzle brake. *Journal of Nanjing University of Science and Technology*, 2024, 48(06): 709-718.
- [3] Li Guihu, Li Zhenxin, Zhao Junkui, et al. Research on muzzle brake with steel-titanium composite structure. *Mechanical Engineering & Automation*, 2022, (04): 35-37.
- [4] Zhiqun S, Qiang L, Yujing H, et al. Numerical study on the flow field characteristics and efficiency of different underwater gun muzzle brakes. 2023 3rd International Conference on Fluid and Chemical Engineering. Wuhan, China: ICFCE, 2023: 2610.
- [5] Guo Lifeng, Zhang Qi, Sun Jintao, et al. Analysis of the influence of different structures of muzzle brakes on the chassis of an amphibious artillery. *Journal of Ordnance Equipment Engineering*, 2024, 45(6): 96-103.
- [6] Wang Meiyi, Wang Hao. Numerical simulation and flow characteristics of muzzle flow field in ultra large caliber propelling gun. *Journal of Gun Launch & Control*, 2017, 38(2): 15-19.
- [7] Qiu Ming, Song Jie. New principles and technologies for utilizing energy from weapons and gunpowder. BeiJing: National Defense Industry Press, 2022.
- [8] Yu Haiwei, Yuan Juntang, Wang Zhenhua. Novel design of lightweight muzzle brake with enhanced performance for additive manufacturing. *Journal of Machine Design*, 2021(S02): 40-45.