Recoil reduction method of gun with lateral nozzle controlled by electromagnetic valve

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Abstract. A new recoil reduction method of gun was proposed in this work to reduce the recoil without reducing the muzzle velocity and changing the continuous firing mode. Its recoil reduction mechanism was studied based on the two-phase flow theory. First, combining the gas-solid two-phase flow in the barrel, the electromagnetic control in the electromagnetic valve, the fluid-solid coupling in the piston cavity, and the transient gas flow in the exhaust pipe, an eight-stage mathematical model of the gun propulsion process was established. Next, the propagation law of the rarefaction wave in the barrel was discussed. Then, the propulsion difference between the gun proposed here and the traditional gun was presented. The results showed that the proposed method could reduce the recoil impulse by 38.20% without reducing the muzzle velocity under reasonable matching of the structural parameters.

1. Introduction
Recoil reduction is the key bottleneck in reconciling the conflict between the gun power and maneuverability. Excessive recoil severely restricts the loading of high-power traditional guns on the modern vehicles. Considering the energy of the propellant gas venting from the muzzle usually accounts for over 40% of the total energy of propellant during the propulsion process, numerous studies have been done on the methods using the energy of the propellant gas to reduce the recoil. The muzzle brake [1] is a typical example. However, its efficiency is limited. Kathe [2] proposed a concept of rarefaction wave gun to reduce the recoil by venting the propellant gas through the breech. Nevertheless, the back blast device of the rarefaction wave gun cannot be reused because the propellant gas ejects directly from the breech. Thus it is difficult to achieve continuous firing, which restricts its development in engineering application. Liao [3], Chen [4], and Cheng [5] studied the reversely jet low recoil gun, which vents the propellant gas through the orifice on the barrel and sprays it. Although this gun can achieve continuous firing, the pressure of the projectile base drops once the propellant gas vents through the orifice, resulting in a decrease of muzzle velocity. Besides, the higher the recoil reduction efficiency, the lower the muzzle velocity. Zhang [6], Wang [7], and Zhang [8-10] studied the propulsion process of the rarefaction wave gun on the basis of the two-phase flow theory. Zhang [10] proposed a front orifice rarefaction wave gun. However, his simulation ignores the opening process of the orifice and the movement of the control device, so the real recoil reduction efficiency could not be obtained. Xiao [11] studied the launching process of a time-delay nozzle device. Due to the use of the classical interior ballistics theory and the lumped parameter method [12],
it is difficult to simulate the transient nonuniformity of the flow field in the barrel and to capture the motion of the rarefaction wave, so the accurate opening time of the orifice could not be obtained.

In this work, a gun with lateral nozzle controlled by electromagnetic valve was proposed to reduce the gun recoil greatly without reducing the muzzle velocity and breaking the continuous firing mode of the gun. This method controls the opening and closing of the rear spray channel by an electromagnetic valve. Therefore, it could make the rarefaction wave just catch the projectile at the muzzle. In this way, this method can achieve the purpose of reducing the recoil significantly, not reducing the muzzle velocity, and achieving the continuous firing. As the gun proposed here is equipped with a lateral exhaust pipe, an electromagnetic valve, its propulsion process is quite different from that of the traditional gun. Therefore, the propulsion process of this gun is numerically simulated on the basis of the two-phase interior ballistics theory, considering the opening process of the barrel vent, the electromagnetic control in the electromagnetic valve, and the interaction between the piston-spring system and the propellant gas. Then, the propulsion difference between the gun proposed here and the traditional gun are analysed. Finally, the changes in the muzzle velocity and the recoil reduction efficiency are discussed.

![Figure 1. Structure diagram of the gun with lateral nozzle controlled by electromagnetic valve.](image)

2. Theoretical model

2.1. Stage analysis of the propulsion process

The schematic of the gun with lateral nozzle controlled by electromagnetic valve is shown in figure 1. Its propulsion process can be divided into eight stages according to the difference in the flow characteristics of the propellant gas in the barrel before and after the recoil reduction device is enabled. The first stage is from igniting to the moment when the projectile starts to move. This stage of the gun with lateral nozzle is the same as that of the traditional gun. The second stage, which is immediately after the first stage, ends when the projectile reaches the front hole. At this stage, the projectile speeds up with the pressure of the projectile base increasing. The piston cannot move under the action of the spool, though the propellant gas will flow into the piston cavity and push the piston. The third stage is not finished until the piston starts to move. At this stage, a small amount of propellant gas flows into the front hole and pushes the movable conductive block to move. Then the electromagnetic valve is energized, and the spool moves. Without the restriction of the spool, the piston starts to move upwards under the action of the propellant gas. The fourth stage ends when the rear spray channel is fully opened. At this stage, the high-pressure propellant gas in the piston cavity flows into the exhaust pipe. Meanwhile, the propellant gas in the barrel flows into the piston cavity at high speed while the gas flow in the barrel is bidirectional. Therefore, the pressure at the barrel vent reduces sharply, resulting in a rarefaction wave which travels towards the breech and the projectile base simultaneously. The fifth stage is not finished until the propellant gas reaches the nozzle exit. At this stage, the propellant gas propels the projectile to speed up. In the meantime, the propellant gas in the exhaust pipe flows and expands. The sixth stage ends when the projectile arrives at the muzzle. At this stage, the propellant gas in the barrel continuously flows into the exhaust pipe, leading to a further decrease of pressure in the barrel. In the meantime, the propellant gas ejects from the nozzle, producing a forward
thrust to abate some of the rearward momentum. The seventh stage finishes when the rear spray channel is closed completely. At this stage, the piston begins to move back under the action of the spring force. The eighth stage is the residual stage. All the remaining propellant gas in the barrel ejects from the muzzle, and the spool returns to its initial position due to the decrease of pressure in the barrel.

It is observed that the flow fields of the barrel, the piston cavity, and the exhaust pipe become coupled when the rear spray channel is opened. Besides, the flow field zones, boundary conditions, and fluid-solid coupling state of the propellant gas flow in the barrel, the piston cavity, and the exhaust pipe are different at each stage of the propulsion process. Therefore, some proper simplifications are needed [3].

2.2. Numerical model

The governing equations of the two-phase flow model in the barrel include the mass conservation equations of the gas and solid phase, the momentum conservation equations of the gas and solid phase, and the energy conservation equation of the gas phase. According to the different flow characteristics of the propellant gas before and after the recoil reduction device is enabled, the equations are as follows in a conservative vector form.

\[
\begin{align*}
\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} &= \begin{bmatrix} H \end{bmatrix} \quad \text{Before projectile reaches barrel vent} \\
&= \begin{bmatrix} H - J \end{bmatrix} \quad \text{After projectile reaches barrel vent}
\end{align*}
\]

\[
U = \begin{bmatrix} A\varphi \rho_g u_g \\ A(1-\varphi)\rho_p u_p \\ A\varphi \rho_g (e_g + \frac{u_g^2}{2}) \\ A(1-\varphi)\rho_p u_p \\ A\varphi \rho_g (e_g + \frac{u_g^2}{2}) \\ A(1-\varphi)(\rho_p u_p^2 + p + \tau_p) \\ A\varphi \rho_g (e_g + \frac{u_g^2}{2} + \frac{p}{\rho_g}) \end{bmatrix}, \quad F = \begin{bmatrix} A\varphi \rho_g u_g \\ A(1-\varphi)\rho_p u_p \\ A\varphi \rho_g (e_g + \frac{u_g^2}{2}) \\ A(1-\varphi)(\rho_p u_p^2 + p + \tau_p) \\ A\varphi \rho_g (e_g + \frac{u_g^2}{2} + \frac{p}{\rho_g}) \end{bmatrix}
\]

\[
H = \begin{bmatrix} A(m_e + m_{ign}) \\ -Am_t \\ A(m_e u_p + m_{ign} u_{ign} - f_s) + p \frac{\partial A\varphi}{\partial x} \\ A(f_s - m_e u_p) + p \frac{\partial A(1-\varphi)}{\partial x} + \tau_p (1-\varphi) \frac{\partial A}{\partial x} \\ A(m_e (e_p + \frac{p}{\rho_p} + \frac{u_p^2}{2}) + m_{ign} H_{ign} - f_s u_p - Q_s) - p \frac{\partial A\varphi}{\partial x} \end{bmatrix}, \quad J = \begin{bmatrix} Am_t \\ 0 \\ Am_t u_t \\ 0 \\ Am_t (e_t + \frac{p_t}{\rho_t} + \frac{u_t^2}{2}) \end{bmatrix}
\]

Where \( A \) is the cross-section area of the barrel, \( \rho_g \) and \( \rho_p \) are the gas and solid density, \( u_g \) and \( u_p \) are the gas and solid velocity, \( e_g \) and \( e_p \) are the gas and solid internal energy, \( \varphi \) is the porosity, \( p \) is the pressure, \( \tau_p \), \( Q_s \), and \( f_s \) are the intergranular stress, interphase heat transfer, and interphase drag, \( m_e \) is the gas generation rate of the solid propellant per unit volume, \( m_{ign} \) is the gas generate rate of the ignition powder per unit volume, \( u_{ign} \) is the velocity of the ignition powder, \( H_{ign} \) is the enthalpy of the ignition powder, \( m_t \) is the mass flow rate per unit volume of the propellant gas out of the barrel from the barrel vent, \( \rho_t \), \( p_t \), \( e_t \), and \( u_t \) are the density, pressure, internal energy, and velocity of the propellant gas flowing through the barrel vent.
The dynamic model of gas-solid coupling in the piston cavity and the governing equations of gas flow in the exhaust pipe can be referred to literature [3]. The electromagnetic control model can be referred to literature [13]. The constitutive equations needed to close the above governing equations, such as the interphase drag, the interphase heat transfer and the intergranular stress, can be referred to literature [12, 14]

2.3. Defining conditions for the governing equations
The boundary conditions were different at different stages of the propulsion process. The breech was taken as the solid wall. The projectile base was taken as the solid wall before the projectile moved. After the projectile moved, the projectile base was taken as the moving wall. The nozzle exit and muzzle exit were taken as the free outlet boundary [12].

3. Results and discussions

3.1. Decision of the opening time of the rear spray channel
The gun with lateral nozzle is transformed from a traditional gun according to the principal shown in figure 1. The propulsion process of these two guns was numerically simulated and compared. As for the gun with lateral nozzle, the opening time of the rear spray channel is controlled by the piston motion and the electromagnetic valve. The valve motion is mainly determined by the parameters, such as the size of barrel vent and the spring stiffness. The flow field in the barrel and the exhaust pipe becomes coupled after the fourth stage of the propulsion process, so the relationship between these parameters is complicated and nonlinear. It is difficult to derive an analytical expression to solve this relationship. The reasonable match of these parameters can only be obtained by numerous calculations, and a set of better parameter matches was obtained, as shown in Table 1.

| Parameter                  | Value | Length of barrel (m) | Propellant mass (kg) | Location of barrel vent (m) | Location of front hole (m) | Sectional area of the barrel (mm²) | Sectional area of the rear spray channel (mm²) |
|----------------------------|-------|----------------------|----------------------|-----------------------------|------------------------------|------------------------------------|-----------------------------------------------|
| Barrel diameter (m)        | 0.030 | 2.457                | 0.119                | 0.26                        | 1.03                         | 491                                | 615                                           |

Figure 2. Velocity of projectile and rarefaction wave front.
3.2. Rarefaction wave front propagation

A large amount of propellant gas in the barrel ejected out after the rear spray channel was opened, resulting in a sudden decrease of pressure at the barrel vent. Then the effect of the pressure drop travelled towards the breech and the projectile base in the form of continuous rarefaction waves [2]. The motion characteristics of the projectile and the rarefaction wave front are shown in figure 2 and 3. At 1.79 ms, the projectile began to move. The rarefaction wave was produced at the barrel vent at 4.29 ms, and then travelled towards the projectile base and the breech. Meanwhile, the projectile was 0.96 m away from the barrel vent. The velocity of the projectile and the rarefaction wave both increased monotonically, but the velocity of the rarefaction wave was higher than that of the projectile. Therefore, 1.44 ms after the rarefaction wave was produced, the rarefaction wave caught the projectile. In the meantime, the projectile just reached the muzzle. During this process, the rarefaction wave moved 2.24 m with an average speed of 1555.56 m/s, while the projectile moved 1.28 m with a speed of 888.89 m/s.

Figure 3. Position of projectile and rarefaction wave front.

Figure 4. Breech pressure comparison of the two guns.
3.3. Performance comparison

3.3.1. Projectile velocity and pressure in the barrel. The comparisons of the pressure in the barrel of the two guns are shown in figure 4 and 5. It should be pointed that figure 5 displays the projectile base pressure during the interior ballistics period, and displays the muzzle pressure during the after-effect period. It can be seen that the pressure peak of the breech and the projectile base occurred before the rarefaction wave reached the breech and the projectile base at 4.33 and 5.73 ms, respectively. Then the breech pressure and the projectile base pressure of the gun with lateral nozzle reduced greatly compared with those of the traditional gun. However, those flow field parameters of the two guns were the same before the rarefaction wave arrived. Therefore, when the propellant gas in the barrel ejected from the barrel vent, the gas pressure at other locations would not reduce immediately, and the effect of the pressure drop at the barrel vent travelled in the form of rarefaction waves. Where the rarefaction wave reached, the flow field parameters would be changed. Before the rarefaction wave arrived, there was no obvious change.

As shown in figure 5 and 6, the propelling impulse imparted to the projectile of the two guns was almost the same, so the velocity-time curve of the projectile of the two guns was not much different.
3.3.2. Recoil reduction efficiency. The analysis here is for the parts that are fixed with the gun barrel, excluding the parts with relative motion to the gun barrel. Besides, the recoil reduction effect of the buffer devices, such as the muzzle brake, was not considered. Here we define the force towards the muzzle as the positive. The recoil comparison of the two guns is shown in figure 7. Compared with the recoil of the traditional gun, that of the gun with lateral nozzle declined slightly from 4.33 ms because the breech pressure reduced, as shown in figure 4 and 7. At 4.79 ms, the propellant gas ejected from the nozzle, producing a strong forward thrust, so the recoil of the gun with lateral nozzle declined rapidly and became positive. However, the peak of breech pressure occurred before the propellant gas ejected from the barrel, so the peak of the recoil did not change.

It can be seen from figure 8 that the recoil impulse of the gun with lateral nozzle also dropped from 4.33 ms. During the propulsion process, the recoil impulse of the traditional gun was 549.74 Nꞏs, while that of the gun with lateral nozzle was 339.74 Nꞏs, so the recoil reduction efficiency was 38.20% according to the related calculation [5].

It should be pointed out that there are many parameters which affect the recoil reduction efficiency, such as the size of the barrel vent, length of the exhaust pipe, and nozzle expanding angle. Thus the structure of the gun with side to rear jet needs to be optimized.

4. Conclusion
A gun with lateral nozzle controlled by electromagnetic valve was proposed in this study, and the interior ballistics two-phase flow model of its propulsion process was established. The performance comparison of the traditional gun and the gun with lateral nozzle was discussed. Besides, the recoil reduction mechanism of the gun with lateral nozzle was revealed. The recoil reduction method
proposed in this work does not break the ammunition structure of the existing weapons. Besides, the reset device is stable, and the continuous firing mode of the gun is not affected. Thus, this method has a good application prospect.

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