Influence of Magnetically Confined Plasma on the Muzzle Velocity of Gun Projectile

YU WANG, TIEHUA MA, DONGXING PEI, CHANGXIN CHEN, KAIQIANG FENG, DEBIAO ZHANG, AND ZHIBO WU
Science and Technology on Electronic Test and Measurement Laboratory, North University of China, Taiyuan 030051, China
Corresponding author: Yu Wang (18235193412@163.com)

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ABSTRACT

Under the influence of gun barrel design, materials, and propellant, improving projectile muzzle velocity is the bottleneck in gun development. An innovative method based on magnetically confined plasma theory was therefore proposed to improve the projectile muzzle velocity. Compared with the traditional methods for increasing the projectile muzzle velocity, the method proposed in this study has a simpler design structure, a broad applicability to different caliber guns with lower cost, and an obvious effect on improving muzzle velocity. The core idea was to use the magnetic field to constrain the plasma generated by gunpowder combustion ionization in the gun bore to increase the projectile bottom pressure, thereby increasing the projectile muzzle velocity. First, the mechanism of increasing the projectile muzzle velocity by magnetically confined plasma in the gun barrel was analyzed. Second, a new gunpowder gas thermal ionization model was established based on interior ballistic and plasma theories. The fourth-order Runge-Kutta algorithm was used to numerically simulate the changes in plasma density and conductivity during the combustion ionization of gunpowder. The effects of different ionized seed contents and propellant forces on the density and conductivity of plasma were numerically simulated to improve the ionization efficiency of gunpowder. Adding ionized seeds or propellant force improves the ionization efficiency of gunpowder, increases the binding force of the magnetic field on plasma, and enhances the projectile muzzle velocity. Finally, shooting tests were performed with a test barrel. Experimental results verified the correctness of the theoretical analysis and numerical simulation.

INDEX TERMS

Magnetically confined plasma, projectile muzzle velocity, projectile bottom pressure, thermal ionization model.

I. INTRODUCTION

Projectile muzzle velocity is a crucial index used to evaluate gun ballistic performance [1]–[3]. The greater the projectile muzzle velocity is, the greater the gun power and the stronger the penetrating power will be. For the interior ballistics of guns, the projectile muzzle velocity depends on the projectile bottom pressure, but the bottom pressure is limited by the barrel design, materials, and propellant [4]. The basic methods for increasing projectile velocity, such as increasing the amount of gunpowder and extending the length of the body tube cannot solve this problem efficiently. As a result, improving projectile muzzle velocity is the bottleneck in gun development. Innovative methods must be studied to improve projectile muzzle velocity.

Researchers in the country and abroad have proposed innovative methods to increase projectile velocity. Ankara and Turkey [5] studied the effects of the grain size and temperature of double-base solid propellants on projectile muzzle velocity. They found that increasing fuel temperature and decreasing particle size can improve projectile muzzle velocity. Martin et al. [6] evaluated the effect of initial temperature on the interior ballistics of a 120 mm mortar system and concluded that the projectile muzzle velocity increases with increasing initial temperature. Although the reduction of particle size and increase in the initial temperature of gunpowder can serve as references for the research on increasing projectile muzzle velocity, the scope of use is limited, and they are difficult to apply and popularize in actual combat. Cheng and Zhang [7] studied different multi-dimensional flow and energy conversion behavior of combustion gas and propellant grains in two typical structures of dual chambers.
with a propelled body. The dual combustion chamber can increase projectile velocity. Krcmar et al. [8] designed a complex dual combustion chamber for a gun to increase bore pressure and muzzle velocity. The dual combustion chamber has many advantages over traditional combustion chambers. However, it has a limited range of use, complicated structure, and high cost. Larionov et al. [9] and Ermolaev et al. [10] studied a traveling charge technique to increase projectile velocity. In this method, the propellant is combusting behind the projectile constantly, which pushes the projectile efficiently. However, the traveling charge system requires liquid propellants or solid propellants with a high burning rate and efficiency. But Su et al. [11] designed a large muzzle kinetic energy railgun by electromagnetic launch technology to increase the projectile muzzle velocity. Citak et al. [12] examined the effects of variables, such as the voltage applied to coils, the number of turns of the coils, and the number of capacitors on the maximum muzzle velocity. Electromagnetic guns have a higher muzzle velocity than that of conventional guns. Nevertheless, electromagnetic launchers have a high requirement for the electrical power systems, and they are inconvenient to use in battlefields. Sanghavi et al. [13] improved a new propellant not only to prevent catastrophic disasters due to unplanned initiation of currently used gun propellants but also to realize enhanced energy levels to increase projectile muzzle velocity. This new propellant, however, is still in the experimental stage. Francesconi et al. [14] studied a two-stage light gas gun through theoretical and numerical simulation methods. They proposed a method to increase projectile speed without any rise in the maximum breech pressure. Zhang and Wang [15] studied a rarefaction wave gun to improve projectile muzzle velocity. This gun differs from a conventional gun in terms of launch process and structure. Although rarefaction wave guns have been developed for many years, few achievements have been made.

In view of the deficiencies of the abovementioned methods for increasing projectile velocity, an innovative method based on magnetically confined plasma theory was proposed to improve projectile muzzle velocity. When a gun is fired, the gunpowder will ionize into high-temperature plasma [16]. The magnetic field can constrain the motion of the plasma in the gun barrel [17]–[20], and then affect the internal ballistic characteristics of the gun by affecting the airflow in the gun chamber. Magnetic confined plasma technology is relatively mature and has many applications in various fields, such as magnetohydrodynamic (MHD) power generation [21]–[23], nuclear fusion [18], [24], [25], laser plasma source [26]–[28], and astrophysics [19], [20], [29]. Nonetheless, few people in and out of the country have applied magnetically confined plasma to improve the muzzle velocity of guns. Compared with the traditional methods for increasing the projectile muzzle velocity, the method proposed in this study has a simpler design structure, a broad applicability to different caliber guns with lower cost, and an obvious effect on improving muzzle velocity. The core idea was to use the magnetic field to constrain the plasma generated by gunpowder combustion ionization in the gun bore to increase the projectile bottom pressure, thereby increasing the projectile muzzle velocity. The higher the plasma density is, the higher the electrical conductivity and the better the magnetic field confinement will be.

First, the mechanism of increasing projectile muzzle velocity by magnetically confined plasma in the gun barrel was analyzed. Second, a new gunpowder gas thermal ionization model was established based on the interior ballistic and plasma theories. The fourth-order Runge-Kutta algorithm was used to numerically simulate the changes in plasma density and conductivity during the combustion ionization of gunpowder. The effects of different ionized seed contents and propellant forces on the density and conductivity of plasma were numerically simulated to improve the ionization efficiency of gunpowder. Finally, shooting tests were performed with a test barrel. The effects of different magnetic field intensities on projectile bottom pressure and muzzle velocity were studied by applying a magnetic field outside the test barrel. The influence of ionized seeds on projectile muzzle velocity was also studied.

The remainder of this manuscript is organized as follows: In Section 2, the mechanism of magnetically confined plasma increasing projectile muzzle velocity is analyzed, and a thermal ionization model of gunpowder gas is established. In Section 3, the changes in plasma density and conductivity in powder combustion products are numerically simulated. The effects of ionized seed content and propellant force on the plasma density and conductivity of combustion products are also numerically simulated. Finally, the theoretical and simulation results are verified through experiments. In Section 4, the conclusion is presented.

II. MECHANISM ANALYSIS AND MODEL BUILDING

A. MECHANISM ANALYSIS

The combustion process of gunpowder is complicated. And the fluid flow time in the chamber is very short, the viscosity does not play a large role. Moreover, there is no significant heat exchange with the outside world during the whole transient process. Therefore, several hypotheses are made [30]: (1) Some MHD symbols like magnetic field $B$, velocity field $V$, and fluid density $\rho$ are functions of a spatial variable $x$ and a time variable $t$. (2) The plasma is nonviscous and adiabatic. (3) Chemical reactions during plasma flow are disregarded. (4) The fluid is a complete conductor. (5) The plasma has a steady flow. A one-dimensional flow control model of magnetic fluid is established. The components of velocity field $V$, electric field $E$, and magnetic field $B$ in frame $0$-xyz are as follows:

\[
\begin{align*}
V &= (u, 0, 0) \\
E &= (0, 0, E) \\
B &= (0, B, 0)
\end{align*}
\]
The one-dimensional flow control model of magnetic fluid is as follows: [31]

\[
\begin{cases}
\frac{d\rho}{dt} + \frac{d\rho u}{dx} = 0 \\
\rho \left( \frac{du}{dt} + u \frac{du}{dx} \right) = \frac{d}{dx} \left[ -P + \left( \lambda_f + 2\mu_f \right) \frac{du}{dx} \right]
\end{cases}
\]

(2)

where \( \rho \) is the plasma density in the gun chamber, \( u \) is the plasma flow velocity in the bore, \( P \) is the average pressure in the chamber, and \( \lambda_f \) and \( \mu_f \) are fluid viscosity coefficients.

The plasma flow is assumed to be steady. From the first formula in (2), we can obtain \( (d\rho u) / (dx) = 0 \), hence,

\[ \rho u = c \]

(3)

where \( c \) is an integral constant. The second formula in (2) is accordingly simplified as follows:

\[ \left( \lambda_f + 2\mu_f \right) \frac{du}{dx} = cu + P + \frac{1}{2\mu} B^2 - l \]

(4)

where \( l \) is an integral constant. The magnetic fluid is nonviscous, adiabatic and high-temperature gas, as a result,

\[
\begin{cases}
\left( \lambda_f + 2\mu_f \right) = 0 \\
\frac{P}{\rho} = a^2
\end{cases}
\]

(5)

where \( a \) is an constant. Equation (4) can be simplified as follows:

\[ \frac{c^2}{\rho} + a^2 \rho + \frac{1}{2\mu} B^2 = l \]

(6)

After the integration constant \( l \) is determined, if \( c^2/\rho + a^2 \rho \) takes the minimum value, then the magnetic field \( B \) will take the maximum value. \( c^2 \) and \( a^2 \) are both constants greater than zero. When \( u = a \), \( c^2/\rho + a^2 \rho \) takes the minimum value. The magnetic field \( B \) will take the maximum value. Equation (5) is used as the fitting curve, and the relationship between \( B \) and \( \rho \) is shown in FIGURE 1. Formula (3) implies that the larger \( \rho \) is, the smaller the velocity \( u \) will be. The red curve above the two points of \( u = a \) is the subsonic region, and the black curve below is the supersonic region. The black curve below is the corresponding curve of magnetic field intensity and plasma density because gunpowder gas belongs to supersonic flow during thermal expansion.

The black curve in FIGURE 1, presents that with an increase in magnetic field intensity, the plasma density in the barrel also increases gradually. From the pressure and density formula \( P = a^2 \rho \), the average pressure in the gun bore also increases gradually. The relationship between the average pressure and the projectile bottom pressure is as follows [32]:

\[ \frac{P_d}{P} = \frac{\varphi_1}{\varphi_1 + \frac{\omega}{3m}} \]

(7)

where, \( P_d \) is the projectile bottom pressure; \( \varphi_1 \) is the resistance coefficient, with a value of 1.06; \( \omega \) is the charge quality, and \( m \) is the projectile mass.

\[ \varphi_1, \omega \text{ and } m \text{ are constant values. Therefore, the projectile bottom pressure is positively correlated with the average pressure, and the relationship between the projectile bottom pressure and muzzle velocity is as follows:} \]

\[ v = \frac{\pi D^2}{4\varphi_1 m} \int_{t_1}^{t_2} P_d(t) dt \]

(8)

where \( D \) is the diameter of the projectile. The projectile movement in the chamber is generally restricted by the projectile extrusion resistance. When the projectile bottom pressure is greater than the extrusion resistance of the projectile, the projectile starts to move. The projectile bottom pressure at this time is called the starting pressure, and the corresponding time is \( t_1 \). When the projectile bottom pressure drops to 0, the corresponding time is \( t_2 \). It can be seen from (8) that the projectile muzzle velocity \( v \) is positively correlated with the bottom pressure \( P_d \). Moreover, projectile bottom pressure \( P_d \) is positively correlated with the average pressure \( P \), the average pressure \( P \) is positively correlated with magnetic field intensity \( B \). Accordingly, the projectile muzzle velocity increases with increasing magnetic field intensity \( B \).

B. GUNPOWDER GAS THERMAL IONIZATION MODEL

Cesium nitrate has a relatively low melting point, a boiling point, and a relatively low decomposition temperature, making it ideal for ionization seeds. At above 1600K, the decomposition products are all gaseous, and the content of cesium vapor in the decomposition products increases rapidly with increasing temperature. Free electrons are generated by cesium ionization, and the plasma density increases rapidly with increasing temperature. The combustion temperature of gunpowder in the gun chamber can reach above 2000K. The main decomposition products of cesium nitrate are \( Cs, N_2, \) and \( O_2 \), and the decomposition reaction equation is...
as follows:

\[
\begin{align*}
2C_sNO_3 &= 2C_s + N_2 + 3O_2 \\
C_s &= C_s^+ + e^- 
\end{align*}
\] (9)

Internal ballistic and plasma theories are combined to establish a thermal ionization model for gunpowder gas. The model includes internal ballistic [32], gas temperature [32], plasma density [33], and conductivity [34] equations. For alkali metals, the value of \(2g_i = g_0\) is approximately 1, and \(m_e\) is the electron mass.

\[
\begin{align*}
\psi &= \left( XZ \left( 1 + \lambda Z + \mu Z^2 \right) \right) (Z < 1) \\
\psi &= \left( XZ \frac{Z}{Z_K} \left( 1 + \lambda Z \frac{Z}{Z_K} \right) \right) (1 \leq Z < Z_K) \\
\psi &= \left( 1 + \lambda Z \frac{Z}{Z_K} \right) (Z \geq Z_K)
\end{align*}
\]

\[
\begin{align*}
\frac{dZ}{dt} &= \frac{u_1}{e_1} \rho \mu
\end{align*}
\]

\[
\begin{align*}
\varphi &= \frac{SP}{\varphi f \psi dV}{dt} \\
SP(l + \varphi) &= f \omega \psi - \frac{\theta}{2} \varphi m v^2
\end{align*}
\]

\[
\begin{align*}
SP(l + \varphi) &= \omega \psi RT \\
n_e n_i &= \frac{(2\pi m_e kT)^{1.5}}{\hbar^2} \frac{2g_i}{g_0} \exp \left( -\frac{qE_i}{kT} \right)
\end{align*}
\]

\[
\sigma = \ln \left( \frac{1.23 \times 10^{-7} \pi^{1.5}}{n_e} \right)
\]

Among them,

\[
\begin{align*}
X_s &= \frac{\psi_s - \xi_s}{\xi_s - \xi_s^2} \\
\lambda_s &= \frac{1 - X_s}{X_s} \\
\psi_s &= X \left( 1 + \lambda + \mu \right) \\
Z_s &= \frac{e_1 + \rho_1}{e_1}
\end{align*}
\]

\[
\begin{align*}
\xi_s &= \frac{e_1}{e_1 + \rho_1}
\end{align*}
\]

where \(\Psi\) is the percentage of gunpowder burned. \(X, \lambda, \) and \(\mu\) are the shape feature quantities before the gunpowder split. \(Z\) is the relative burned thickness of gunpowder, \(\rho_1\) is the density of gunpowder, \(u_1\) is the burning rate coefficient, \(e_1\) is the thickness of the combustion layer, \(n\) is the burning rate index, \(l\) is the projectile travel, \(v\) is the projectile speed, and \(S\) is the maximum cross-sectional area of the projectile. \(\varphi\) is the secondary work coefficient, \(\lambda\) is the free volume shrinkage length of the chamber, \(\theta\) is the thermal parameter of the powder, and \(f\) is the propellant force. \(R\) is the gas constant, \(T\) is the gas temperature, \(n_e, n_i,\) and \(n_0\) are the densities of electrons, ions, and ionization seeds, respectively. Given \(n_e = n_i,\) \(h\) is Planck Constant, \(k\) is Boltzmann Constant, \(q\) is the electronic charge value, \(E_i\) is the ionization potential of the seed, \(g_0\) is the statistical weight of the atomic ground state, and \(g_i\) is the statistical weight of the ground state of the ion. For alkali metals, the value of \(2g_i = g_0\) is approximately 1, and \(m_e\) is the electron mass.

### III. RESULTS AND CONCLUSION

#### A. NUMERICAL SIMULATION OF GUNPOWDER COMBUSTION IONIZATION

In combination with the fourth-order Runge-Kutta algorithm to numerically simulate the thermal ionization model of gunpowder gas, the relationship between plasma density and the conductivity in gunpowder combustion products is shown in FIGURE 2. In the figure, the blue curve was the relationship between plasma density and temperature, and the red curve was the relationship between conductivity and temperature. With increasing temperature, the probability of collision among particles increased due to the accelerated thermal movement of particles. This condition made the degree of thermal ionization intense, and the plasma density and conductivity increased gradually. When the temperature was less than 1650 K, the ionization degree was almost zero. When the temperature was greater than 1650 K, the slope of the plasma

![FIGURE 2. Plasma density and conductivity as a function of temperature.](image-url)
density curve became larger. The plasma density showed an increasing trend. When the temperature approached 2400 K, the plasma density reached $8.60 \times 10^{21}$ m$^{-3}$ and the conductivity reached 592.59 S/m. The conductivity was approximately proportional to temperature. According to the numerical simulation results, it can be concluded that the gunpowder gas can be ionized effectively at high temperature. Moreover, the higher the temperature is, the more favorable it is for ionization, and the higher the plasma density is, the greater the fluid conductivity is, which provides a better constraint condition for magnetically confined plasma.

**B. SIMULATION ANALYSIS OF THE EFFECT OF IONIZED SEED CONTENT ON PLASMA DENSITY AND CONDUCTIVITY**

The thermal ionization model with different ionized seed contents was numerically simulated, and the plasma contents were 1%, 2%, 3%, 4%, 5%, 6%, and 7%. The curves of plasma density as a function of time are shown in FIGURE 3. Different color dashed lines indicated the variation in plasma density with time under different ionized seed contents. When the ionized seed content were 1%, 2%, 3%, 4%, 5%, 6%, and 7%, the corresponding maximum plasma densities were $1.11 \times 10^{22}$, $1.66 \times 10^{22}$, $2.04 \times 10^{22}$, $2.34 \times 10^{22}$, $2.62 \times 10^{22}$, $2.88 \times 10^{22}$, and $3.10 \times 10^{22}$ m$^{-3}$. With increasing ionized seed content, the plasma density also increased gradually. The maximum values of the seven curves were fitted to obtain the solid black line in the figure. The slope of the curve growth gradually decreased, that is, the increased amplitude of plasma density decreased gradually. According to the numerical simulation results, it can be seen that the increase of ionized seed content is very effective to improve the plasma density.

**C. SIMULATION ANALYSIS OF THE EFFECT OF PROPELLANT FORCE ON PLASMA DENSITY AND CONDUCTIVITY**

The thermal ionization model with different ionized seed contents was numerically simulated, and the propellant force values were 900000, 910000, 920000, 930000, 940000, 950000, and 960000 J/kg. The curve of plasma density as a function of time is shown in FIGURE 5. Different color dashed lines indicated the variation in plasma density with time under different ionized seed contents. When the ionized seed contents were 1%, 2%, 3%, 4%, 5%, 6%, and 7%, the corresponding maximum conductivities were 623.59, 662.70, 687.93, 707.05, 722.62, 735.85, and 747.43 S/m. The conductivity of combustion products increased with increasing ionized seed content. As the plasma density gradually decreased, the conductivity also decreased. The maximum values of the seven curves were fitted to obtain the solid black line in the figure. Within 5% of ionized seeds, the increase in conductivity was relatively obvious. When the ionized seeds exceeded 5%, the conductivity increased slowly. The experimental results are consistent with the research results in the literature [35] about the effect of ionizing seeds on the detonation characteristics in pulse detonation engine. The greater the conductivity is, the stronger the fluid’s ability to transport electrons will be.

The addition of ionized seeds improved plasma density on the one hand and electron transport capacity on the other hand. Under the premise of the same magnetic field and velocity, the larger the amount of charge is, the larger the Lorentz force will be, thereby improving the binding force of the magnetic field on the plasma. The abovementioned mechanism analysis of magnetically confined plasma presented that the higher the plasma density is, the higher the average pressure in the chamber, projectile bottom pressure and projectile muzzle velocity will be.
propellant forces. The corresponding maximum plasma densities were $1.11 \times 10^{22}$, $1.66 \times 10^{22}$, $2.04 \times 10^{22}$, $2.34 \times 10^{22}$, $2.62 \times 10^{22}$, $2.88 \times 10^{22}$, and $3.10 \times 10^{22}$ m$^{-3}$. With increasing propellant force, the plasma density also gradually increased. The maximum values of the seven curves were fitted to obtain the solid black line in the figure. The slope of the curve growth gradually increased, that is, the increased amplitude of plasma density gradually increased.

The curve of conductivity over time is shown in Figure 6. In the figure, dashed lines of different colors were used to show the curve of conductivity changes with time under different propellant forces. When the propellant force values were 900,000, 910,000, 920,000, 930,000, 940,000, 950,000, and 960,000 J/kg, the corresponding maximum conductivities were 645.68, 667.06, 688.92, 711.26, 734.10, 757.43, and 781.27 S/m. The maximum values of the seven curves were fitted to obtain the solid black line in the figure. The conductivity of combustion products increased with increasing ionized seed content. Gunpowder force can increase the plasma density and conductivity of gunpowder gas and provides a better constraint condition for magnetically confined plasma. Therefore, the use of gunpowder with high gunpowder power is very beneficial to increase the projectile bottom pressure and velocity.

D. EXPERIMENTAL VERIFICATION

Figure 7 shows the schematic of the experimental setup. The experimental setup consisted of a gun barrel, a power chamber, a firer, a solenoid, a projectile, and a projectile bottom pressure test system. The length of the gun barrel was 1500 mm, the inner diameter was 30 mm, and the projectile charge was 45 g. An electric trigger was used to ignite the gunpowder in the chamber. Further combustion of gunpowder produced a large amount of high-temperature and high-pressure gas, which pushed the projectile. Gunpowder gas will ionize into high-temperature plasma under high-temperature and high-pressure environment. A solenoid with a length of 300 mm and an outer diameter of 100 mm was installed 925 mm from the muzzle. The solenoid was wound with two layers of copper wire. The physical diagram of the projectile bottom pressure test system is shown in Figure 8. The test system consisted of an outer cylinder, a circuit module, a substrate, and a sensor. The diameter of the test system was close to the diameter of a dollar coin. The projectile bottom pressure test system adopted a detachable design, and the projectile bottom was designed with a special space for the projectile bottom pressure test system. A sealed copper ring was used at the disassembly area to ensure that gunpowder gas will not destroy the test circuit and sensor during the launch. The pressure sensor used a piezoelectric sensor. The test system was taken out before used, powered up, and programed. After the circuit status became normal, a rubber pad and an insulated paper were placed on the circuit top. The circuit was placed inside the projectile and tightened with a pipe wrench. During the experiment, the projectile pressure test system was launched with the projectile.

The schematic of the projectile bottom pressure test system is shown in Figure 9. The analog signal was collected by the pressure sensor, and the conditioning circuit adjusted this analog signal to a suitable voltage range. When the
CPU issued commands, the analog signal was converted into a digital signal using A/D conversion chips. The digital signal was stored in a flash memory through FIFO. After the test, the test instruments were recovered, and the data were transmitted to the computer through the USB interface.

Three grams of cesium nitrate was added to the projectile to obtain the test curves of the projectile bottom pressure, as shown in FIGURE 10. The solid black line represented the test curve of projectile bottom pressure when the external magnetic field was 0 T, and the maximum projectile bottom pressure was 59.43 MPa. The solid red line represented the test curve of projectile bottom pressure when the external magnetic field was 0.1 T, and the maximum projectile bottom pressure was 61.55 MPa. The solid blue line represented the test curve of projectile bottom pressure when the external magnetic field was 0.2 T, and the maximum projectile bottom pressure was 63.33 MPa. When a magnetic field of 0.1 T was applied, the projectile bottom pressure was 3.57% higher than that without the magnetic field. When a magnetic field of 0.2 T was applied, the projectile bottom pressure was 6.56% higher than that without the magnetic field. Applying magnetic field can increase the projectile bottom pressure. The greater the magnetic field strength is, the greater the projectile bottom pressure will be. The experimental results verified the correctness of the theoretical analysis. Combined with the internal ballistic theory, the fourth-order Runge-Kutta method was used to numerically simulate the projectile bottom pressure without the magnetic field. The simulated bottom pressure curve is shown by the black dotted line in FIGURE 10. Comparison and analysis demonstrated that the numerical simulation result was basically consistent with the experimental result of gun interior ballistics, which verified the correctness of the numerical simulation.

The projectile velocity curves obtained by calculating the projectile bottom pressure test data are shown in FIGURE 11. In the figure, the black curve showed the
projectile velocity curves when the applied magnetic field was 0 T, and the maximum projectile velocity was 377.07 m/s. The red curve showed the projectile velocity curve when the applied magnetic field was 0.1 T, and the maximum projectile velocity was 435.18 m/s. After applying 0.1 T magnetic field intensity, the maximum velocity of the projectile increased by 18.85% compared with that without magnetic field. After applying 0.2 T magnetic field intensity, the maximum velocity of the projectile was increased by 15.41% compared with that without magnetic field. The solid black line was the projectile bottom pressure curve when the applied magnetic field was 0.2 T, and the maximum projectile velocity was 448.15 m/s. After applying 0.1 T magnetic field intensity, the maximum velocity of the projectile increased by 18.85% compared with that without magnetic field. Applying magnetic field can increase the projectile muzzle velocity. The greater the magnetic field strength is, the greater the projectile muzzle velocity will be. Compared with the references [5]–[15], the projectile muzzle velocity was increased by reducing the particle size, increasing the initial temperature of gunpowder, using a dual combustion chamber, and using a traveling charge technique, etc. The method proposed in this study has a simpler design structure, a broad applicability to different caliber guns with lower cost, and an obvious effect on improving muzzle velocity. Moreover, the experimental results verified the correctness of the theoretical analysis.

At a magnetic field strength of 0.1 T, 3 g of cesium nitrate was added to the projectile. This condition was compared with that without cesium nitrate. The projectile bottom pressure and velocity test curves are shown in FIGURE 12. In the figure, the solid red line was the projectile bottom pressure curve with 3 g of cesium nitrate, and the maximum pressure value was 61.55 MPa. The red dashed line was the corresponding projectile speed curve, and the maximum speed was 435.18 m/s. The solid black line was the projectile bottom pressure curve without cesium nitrate, and the maximum pressure value was 58.63 MPa. The black dashed line was the corresponding projectile speed curve, and the maximum speed was 372.51 m/s. After adding ionized seeds, the projectile bottom pressure and muzzle velocity were increased by 4.98% and 16.82%, respectively. The correctness of the numerical simulation was verified.

IV. CONCLUSION

An innovative method based on magnetically confined plasma theory was proposed to improve projectile muzzle velocity. Compared with the traditional method for increasing the projectile muzzle velocity, the proposed method had a simpler design structure, a broad applicability to different caliber guns with lower cost, and an obvious effect on improving muzzle velocity. First, the mechanism of increasing the projectile muzzle velocity by magnetically confined plasma in the gun barrel was analyzed. The magnetic confinement of plasma could increase the projectile bottom pressure and velocity. Second, a new gunpowder gas thermal ionization model was established based on interior ballistic and plasma theories. The fourth-order Runge-Kutta algorithm was used to numerically simulate the changes in plasma density and conductivity during the combustion ionization of gunpowder. After the analysis, this study concluded that with increasing temperature, the probability of collision among particles increased due to the accelerated thermal movement of particles, which made the degree of thermal ionization intense, and the plasma density and conductivity gradually increased. The effects of different ionized seed contents and propellant forces on the density and conductivity of gunpowder were numerically simulated to improve the binding force of the magnetic field on plasma. Adding ionized seeds or propellant force could increase the binding force of the magnetic field on plasma and improve the projectile muzzle velocity. Finally, the effects of different magnetic field intensities on projectile bottom pressure and muzzle velocity were studied by applying a magnetic field outside the test barrel. The influence of ionized seeds on the projectile bottom pressure and muzzle velocity was also studied. With increasing magnetic field strength, the projectile bottom pressure and muzzle velocity gradually increased. Adding ionized seeds to the powder could increase the projectile bottom pressure and muzzle velocity. The experimental results were consistent with the theoretical analysis and numerical simulation results. This research provided a new research method for improving projectile muzzle velocity. We plan to study the effect of transient magnetic field on projectile muzzle velocity in the future.

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YU WANG was born in Shanxi, China, in 1991. He received the B.S. degree from the Inner Mongolia University of Science and Technology, Inner Mongolia, in 2015. He is currently pursuing the Ph.D. degree with the North University of China. His current research interests include magnetically confined plasma and dynamic test.

TIEHUA MA received the Ph.D. degree from the Harbin Institute of Technology, Harbin, China, in 1996. He is currently a Professor with the School of Electrical and Control Engineering, North University of China, Taiyuan, China. His current research interests include new concept dynamic test and inertial navigation.

DONGXING PEI received the Ph.D. degree from the Beijing Institute of Technology, Beijing, China, in 2005. He is currently a Professor with the School of Electrical and Control Engineering, North University of China, Taiyuan, China. His current research interests include plasma and new concept dynamic test.

CHANGXIN CHEN received the Ph.D. degree from the North University of China, Taiyuan, China, in 2015. He is currently a Professor with the School of Electrical and Control Engineering, North University of China. His current research interest is new concept dynamic test.
KAIQIANG FENG received the B.S. and Ph.D. degrees from the Department of Instrument and Electronics, North University of China, Taiyuan, China, in 2015 and 2019, respectively, where he is currently pursuing the Ph.D. degree in armament science and technology. His current research interests include inertial navigation, inertial-based integrated navigation systems, and state estimation theory.

DEBIAO ZHANG was born in Shandong, China, in 1989. He is currently pursuing the Ph.D. degree in instrument science and technology with the School of Instrument and Electronics, North University of China. He is currently engaged in research on inertial navigation.

ZHIBO WU was born in Linfen, China, in 1990. He is currently pursuing the Ph.D. degree in instrument science and technology with the School of Electrical and Control Engineering, North University of China. His research interests are mainly in the areas of dynamic testing and mechanical engineering.