Numerical analysis of railgun muzzle flow field with multi-component plasma

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Abstract. The railgun is a new concept launching weapon with high supersonic launching capability. Under the acceleration of Lorentz force produced by the discharge of strong pulse power source, the projectile leaves the muzzle in hypersonic speed. Due to the severe friction of armature in bore and the phenomenon of transition ablation, metal vapor is produced in the interior ballistic process and rush out of muzzle along with armature’s movement. Because of the open structure at both ends of the railgun, the pressure in the bore is much lower than the standard atmosphere, so there exists the phenomenon of muzzle gas backflow. In this paper, the coupled interface method and the multi-component plasma model are used to simulate the movement of metal vapor in the process of projectile moving out of the bore. The pressure boundary conditions and gas composition in the muzzle region of the simulation results are fitted and introduced into the MHD calculation model. The gas backflow phenomenon under the influence of multi-component gas and arc is further simulated. The results show that the muzzle arc improves the energy level of the muzzle flow field and promotes the gas backflow to a certain extent.

1. Introduction

During the launching process of the railgun, a large amount of metal vapor is produced due to the high current ablation and the severe friction between the armature and rails in the bore. With the rapid acceleration of armature movement in the bore, the metal vapor in the bore also moves at high speed and launches out of the muzzle. Therefore, the flow field in the muzzle area of the railgun is characterized by high temperature, complex components and strong convection. Meanwhile, with the high-speed movement of the armature and the separation of the armature and the rail in the bore, there is a phenomenon of arc breakdown between the two rails in the muzzle, which makes the muzzle flow field of the railgun more complex. Considering the influence of metal deposition on the insulating layer and the disturbance analysis on the process of armature exit, it is necessary to study the muzzle flow field of railgun.

In recent years, the research of railgun has attracted the attention of many scholars. However, the work of railgun muzzle mainly involves the research of its voltage and current characteristics [1-3].
With regard to the muzzle metal flame, J.J.Weimier analyzed the metal steam motion process of muzzle and breech during the launching process of railgun by high-speed camera [4]. The composition and temperature of the metal flame are studied by means of spectral analysis. Meanwhile, the phenomenon of the gas flowing back into the barrel during the development of the muzzle flame is put forward. He Yong proposed an active arc suppression circuit to suppress the muzzle arc, measured and analyzed the muzzle voltage, and compared the flow field with and without the muzzle arc through the experimental results of high-speed camera [5]. However, there are few researches on the development of metal vapor in the muzzle flow field, the influence analysis of arc combustion and the numerical mechanism.

In this paper, the dynamic grid method is used to simulate the movement of the projectile, and the dynamic grid and the static grid are combined by the boundary coupling method, in this way, the dynamic flow field model of the launching process of the railgun is established. The transport equation of components is included in the model to simulate the movement and development of metal vapor in the muzzle area. Based on the results of the dynamic grid model, the MHD model of coupled magnetic field is established to analyze the flow field under the influence of the muzzle arc. The arc shape and energy flow in the barrel are analyzed, and the influence of Lorentz force produced by the arc on the backflow is discussed.

2. Model

2.1. Geometric model

2.1.1 Model a: Dynamic launch process

![Figure 1. Geometric model of flow field of railgun.](image)
2.1.2. Model b: Arcing process

In this paper, the calculation is divided into two parts, one is the process of the projectile moving in and out of the barrel, as shown in figure 1. The purpose is to analyze the flow field characteristics of metal vapor inside and outside the barrel with the armature motion. The other part is the process of the muzzle arcing after the armature is discharged, as shown in figure 2. It mainly studies the flow field characteristics of the muzzle area under the double effects of the backflow and the arcing.

In the process of armature moving in the bore, the flow field grid is updated by the layering method. The updating method depends on the acceleration of armature movement in the bore. The minimum grid size is less than 0.001m. It is assumed that there is a large amount of copper and aluminum vapor in the front and rear end of the armature before the armature exits the muzzle. In the process of armature discharging and in a certain period of time after that, there is the phenomenon of arc breakdown between two rails in the muzzle area [6]. Figure 2 shows the flow field geometric model of the muzzle area, including two rail walls, insulation walls and some external air areas. The size of the whole calculation area is 0.2m * 0.022m * 0.03m. Among them, the position of the arc exists in the angle part of the rail wall. In order to simplify the calculation model, the two pole thermal emission principle [7] is adopted in the MHD model in this paper, so as to have the symmetry plane as shown in figure 2. In the whole model, the plasma is in a local thermodynamic equilibrium state, and the following assumptions are met:

1) The physical properties of the air in the arc ignition area are affected by the fluid temperature and other factors.
2) In this paper we ignore the interaction of arc and electrode, thus in the arc column area the plasma is electrically neutral.
3) In order to simplify the calculation and improve the computational efficiency, the magnetic conductivity of the arc is considered as constant. And within very short time after the start of backflow, the position of arc is set as a certain one.
4) The effect of metal particle friction and combustion can be ignored.
5) In the initial flow field of the arc model, an initial arc exists in the railgun.

2.2. Computational model
In the two research contents involved in this paper, they are all subject to the governing equations (1) - (4), where \( S_0 \), \( S_i \), and \( S_m \) are the corresponding source item, \( v_i \) is the velocity components in Cartesian
coordinate system, $\mu$ is the viscosity coefficient, and $\lambda$ is the thermal conductivity. In dynamic mesh model (a), the momentum source term $S_i$ is not considered temporarily, and the energy source term $S_T$ is represented by Arrhenius law defined as equation (5) of composition and temperature [8]. The quality source term $S_m$ of some regions is temporarily defined as a constant, and chemical reactions are not considered in the transport equation of components.

$$\frac{\partial (\rho u)}{\partial t} + \text{div}(\rho \vec{v} \vec{v}) = \text{div}(\mu \text{grad} u) - \frac{\partial p}{\partial x} + S_i$$  \hspace{1cm} (1)

$$\frac{\partial (\rho T)}{\partial t} + \text{div}(\rho \vec{v} h) = \text{div}(\lambda \text{grad} h) + \frac{\partial p}{\partial t} + S_T$$  \hspace{1cm} (2)

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho \vec{v}) = S_m$$  \hspace{1cm} (3)

$$\frac{\partial (\rho Y_i)}{\partial t} + \nabla (\rho \vec{v} Y_i) = -\nabla \cdot J_i + R_i + S_i$$  \hspace{1cm} (4)

$$S_T = \omega Q = -k \exp\left(\frac{E}{RT}\right)j_i j_i \frac{\rho^2}{W_i W'_i} Q$$  \hspace{1cm} (5)

In the model (b) of arc plasma, the source term in the flow field equation is obtained by coupling Maxwell equations. Equations (6) and (8) are defined by user defined scalar (UDS) of FLUENT, and the others are coupled by user defined function (UDF) codes. Where $J$ is the current density, $B$ is the magnetic field intensity, $\phi$ is the electric potential, $A$ is the magnetic vector potential. The plasma physical parameters are electrical conductivity $\sigma$, net emission coefficients $e$, Boltzmann constant $k_b$, and constant pressure specific heat capacity $c_p$. The physical parameters of mixed plasma are obtained by linear interpolation [9].

$$S = J \times B$$  \hspace{1cm} (6)

$$S_T = \frac{J^2}{\sigma} - 4\pi e + \frac{5}{2} k_b (J \cdot \text{grad} T)$$  \hspace{1cm} (7)

$$\text{div}(\sigma \text{grad} \phi) = 0$$  \hspace{1cm} (8)

$$J = -\sigma \text{grad} \phi$$  \hspace{1cm} (9)

$$\text{div}(\text{grad} A_i) = -\mu j_i$$  \hspace{1cm} (10)

$$B = \nabla \times A + B_i$$  \hspace{1cm} (11)

In the launching process of the railgun with copper rail and aluminum armature, the metal vapor plasma in the bore and the muzzle area is mainly composed of copper ion, aluminum ion and air ion, and its physical parameters are as shown in the figure 3.
3. Boundary conditions

In dynamic mesh model (a), the boundary of airflow field is set as standard atmospheric pressure. Considering the heat generated by current transition and sliding friction, the in-bore of railgun is in high temperature state of 2500K, and the temperature of armature wall is set to 2500K. Because the temperature of the armature tail is higher than the boiling point and the simulation time is very short [10], the mass generation rate $S_m$ of its tail adjacent element is temporarily set as a constant in this

Figure 3. Physical parameters of plasma, a): Electric conductivity; b): Specific heat; c): Mass density; d): Thermal conductivity; e): Viscosity.
Mass fraction of copper on the rail wall near the armature is set to 1, and the mass fraction of aluminum on armature wall is set to 1. The data on the coupling interface is transferred by interpolation.

| Species       | V | T     | P     |
|---------------|---|-------|-------|
| BCGF          |   | arc: $-\alpha \frac{\partial V}{\partial n} = g(x)$ | 2500K | --   |
| BJIA/ABFE     |   | else: $\partial V / \partial n = 0$ | 2500K | --   |
| GCDH/DLKJBC   | Al/Air/Cu | $\partial V / \partial n = 0$ | 2000K | $f(t,x)$ |
| AIME          | Al/Air/Cu | $\partial V / \partial n = 0$ | 1200K | 0.5atm |
| DLPH          | Al/Air/Cu | $\partial V / \partial n = 0$ | 1200K | $f(t)$ |

In arcing model (b), the setting of temperature boundary conditions mainly refers to the parameters and calculation results of model (a). The gas boundary conditions is set as function $f(t,x)$ of time and position. For electric field boundary conditions, the current is 400A, and the current density at the root of arc obeys Poisson distribution $g(x)$ [11].

4. Result and discussion

4.1. Numerical results of metal flame at muzzle

The metal vapor of the railgun is ejected from the muzzle with high speed, and it is in a high temperature state. Figure 4 shows the mass fraction of metal vapor at the muzzle during launching, and figure 5 shows the temperature distribution of the corresponding muzzle flow field. At the initial stage, there is a lot of metal vapor in the expansion wave, which forms a high temperature flow field. With the projectile moving at high speed and rushing out the initial expansion wave, due to the gas viscosity and the high temperature state of the armature itself, part of the metal vapor moves with the armature along the launching direction, which forms a light band composed of metal vapor after the armature. According to Arrhenius theory, the calculated peak value of the temperature field of metal vapor combustion is more than 3000K [4], which is close to the spectral measurement results of J J Weimier and describes the metal flame in the process of armature ejection to a certain extent.
Figure 4. Metal vapor distribution in muzzle area.

Figure 5. Temperature distribution in muzzle area.

Figure 6. High speed acquisition results of railgun muzzle flame.
Figure 6 is from He Y's paper [5], which is the result of high-speed video recording of muzzle area during launching of small-diameter aluminum armature. It can be seen that the initial expansion wave mainly composed of metal vapor and the metal vapor light band at the back of armature obviously exist in the launching process. The front end of the initial expansion wave (position p) moves along the launching direction, and the light band of the metal flame is narrow because of the air contraction of the projectile tail. This is close to the numerical results in figure 4 and figure 5.

4.2. Pressure in muzzle area

Figure 7. Pressure of muzzle flow field during armature movement.

As mentioned in the definition of boundary conditions in the previous paper, this paper simulates the backflow of gas at the muzzle by fitting the bore pressure boundary conditions during armature movement. Figure 7 is the pressure curve of the gas wall of the muzzle in the set simulation time. It can be seen that the pressure near the muzzle is the highest, and it tends to decrease gradually on the boundary. Moreover, with the gas flowing back, the pressure at the muzzle gradually rises. The pressure on the boundary changes with time, and there is a difference according to the pressure at different positions, so it is necessary to set the gas boundary condition in the arc model as a function of time and position $f(t, x)$, and the setting result is shown in figure 8.

Figure 8. Boundary pressure distribution of arc model at initial time.
4.3. Arc in muzzle area

Because the moving speed of armature is much faster than that of sound, the air pressure in bore is much lower than that of atmosphere. The pressure difference between the inside and outside of the muzzle makes the gas in the muzzle move towards the bore, and the arc plasma in the muzzle area is also moving at high speed under the influence of Lorentz force, which makes the temperature and flow of the muzzle flow field more complex. Figure 9 is the simulation result of the development process of the muzzle flow field in 0.15ms. At the initial moment, there is a high temperature air mass produced by the arc combustion between the two rails of the muzzle. At the arc root, the plasma temperature is more than 28000K, and the movement speed is vertical to the wall. Under the influence of arc plasma, the temperature in the muzzle region is over 6000K. Affected by the backflow phenomenon, the arc shape gradually began to change, and at the time of 0.04ms, it had a tendency to move towards the bore, which made the temperature of the bore rise sharply. At the time of 0.15ms, the bore temperature is close to 8000K. In the process of simulation, the shape of arc root has not changed much, so the position of arc root is assumed to be fixed in this paper.

Figure 9. Cloud chart of flow field with arc in muzzle.
Figure 10. Temperature curve on axis of bore at different time.

Figure 10 shows the temperature curve at different times on the axis of the bore during the backflow process. The temperature near the muzzle is higher than the others, which is affected by the arc radiation. With the advance of backflow, the arc deflects to the bore. The high temperature gas moves to the bore, and the temperature on the axis increases significantly. In 0.15ms, the temperature of the in-bore surface is more than 4500k, which is also far greater than the boiling point of the rails and armature materials. It can be considered that in this process, the metal vapor moves towards the in-bore in the state of gas.

4.4. Influence of arc on backflow

Figure 11. Velocity distribution in the region of the muzzle arc.

The effect of arc combustion on the flow field is mainly reflected in radiation heat transfer and high-speed plasma flow. Figure 11 is the velocity distribution cloud chart of the muzzle position at the initial time. Since the magnetic field generated by the rail current in the bore is considered in this paper, the movement direction of the arc plasma is not perpendicular to the wall where the arc root is located. In the overall shape, the arc is inclined to the outside of the muzzle, and the maximum speed is 1100m / s. Figure 12 shows the velocity distribution in x direction on the arc root line, with a peak
value close to 800m / s. That is to say, there is momentum component in x direction in the hole breakdown arc plasma, which will affects the movement of gas from outside to inside to some extent.

![Figure 12. X-direction velocity distribution curve.](image1)

![Figure 13. Arc force on the axis of the bore.](image2)

In order to further discuss the influence of breakdown arc on the muzzle flow field, figure 13 shows the Lorentz force \( J \times B \) in x direction applied to the ions on the bore axis at different times. With the arc burning and the gas flowing back from the bore, the whole shape of the arc moves to the bore, which makes the ion temperature in the bore rise and the magnetic field change, so that the Lorentz force of the plasma changes. It can be seen in the figure that the peak value of Lorentz force on the axis of bore increases gradually with time, and the position of the maximum value develops towards bore, which shows that with the change of the breakdown arc shape, the arc in the muzzle region can promote the high temperature gas return into the bore.

5. Conclusion
In this paper, the method of coupled dynamic and static grid boundary is used to simulate the armature movement. Combined with the multi-component transport equation and the treatment of the source
term of the component combustion energy equation, a model is established to simulate the metal vapor flow field in the muzzle area during the armature launching process. Based on MHD theory, the flow field of multi-component plasma with arc in muzzle region is modeled and simulated. In this paper, the characteristics of metal vapor movement in the muzzle and the effect of arc on the backflow phenomenon are analyzed. The conclusions are as follows:

1) In the launching process of the railgun, the metal vapor generated in the movement process in the bore will form a high temperature flow field in the muzzle area, and there is a trend of movement towards the armature and in the bore.

2) The arc plasma has a certain velocity component in the direction of armature exit for the railgun with opening angle for muzzle, which to a certain extent restrains the gas outside the bore moving directly to the inner bore.

3) With the phenomenon of backflow, the breakdown arc deflects the inner bore, and the axial component of arc force points to the bore, which intensifies the backflow of high temperature gas at muzzle.

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