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

**Yuan Gao[1], Yanjie Ni[1] and Baoming Li[1,2]**

[1] National Key Laboratory of Transient Physics, Nanjing University of Science and Technology, Nanjing 210094, Jiangsu, China

Email: gynjust@163.com

## INTRODUCTION

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. 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. 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. 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.

## CALCULATION MODEL

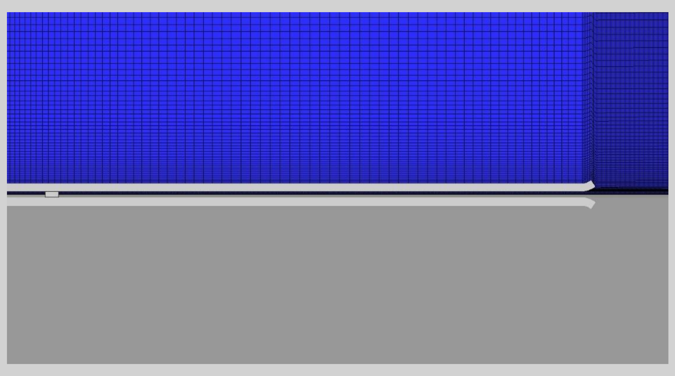

Figure 1 Geometric model of flow field of railgun(model 1)

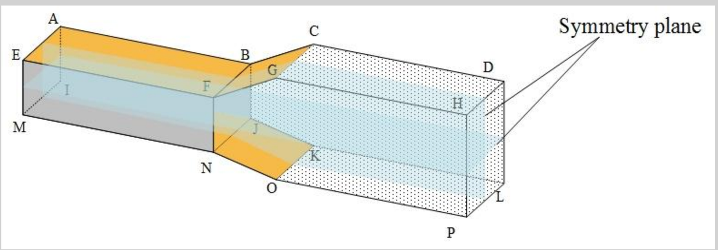


Figure 2 Calculation domain of muzzle arc(model 2)

**TABLE.1** Boundary conditions(model 2)

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

## CALCULATION EQUATIONS

### Calculation Equation

$$\frac{\partial(\rho u)}{\partial t} + \mathrm{div}(\rho v_i \vec{v}) = \mathrm{div}(\mu\,\mathrm{grad}\,u) - \frac{\partial p}{\partial x} + S_i$$

$$\frac{\partial(\rho T)}{\partial t} + \mathrm{div}(\rho \vec{v} h) = \mathrm{div}(\lambda\,\mathrm{grad}\,h) + \frac{\partial p}{\partial t} + S_T$$

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho \vec{v}) = S_m$$

$$\frac{\partial(\rho Y_i)}{\partial t} + \nabla(\rho \mathbf{v} Y_i) = -\nabla \cdot J_i + R_i + S_i$$

$$S_\mathrm{T} = \omega Q = -k\exp\left(\frac{E}{RT}\right) j_\mathrm{o} j_\mathrm{i} \frac{\rho^2}{W_\mathrm{o} W_\mathrm{i}} Q$$

In the model 1 of dynamic model, the model equation is the basic governing equation of fluid mechanics. The component model was used, and the source term of energy equation is given by Arrhenius formula.

$$\boldsymbol{S} = \boldsymbol{J} \times \boldsymbol{B}$$

$$S_T = \frac{\boldsymbol{J}^2}{\sigma} - 4\pi\varepsilon_n + \frac{5}{2}\frac{k_B}{e c_p}(\boldsymbol{J} \cdot \mathrm{grad}\,T)$$

$$\mathrm{div}(\sigma\,\mathrm{grad}\,\varphi) = 0$$

$$\boldsymbol{J} = -\sigma\,\mathrm{grad}\,\boldsymbol{\varphi}$$

$$\mathrm{div}(\mathrm{grad}\,A_i) = -\mu j_i$$

$$\boldsymbol{B} = \nabla \times \boldsymbol{A} + \boldsymbol{B}_i$$

In the model (2) of arc plasma, the source term in the flow field equation is obtained by coupling Maxwell equations. Equations are defined by user defined scalar (UDS) of FLUENT, and the others are coupled by user defined function (UDF) codes.

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.

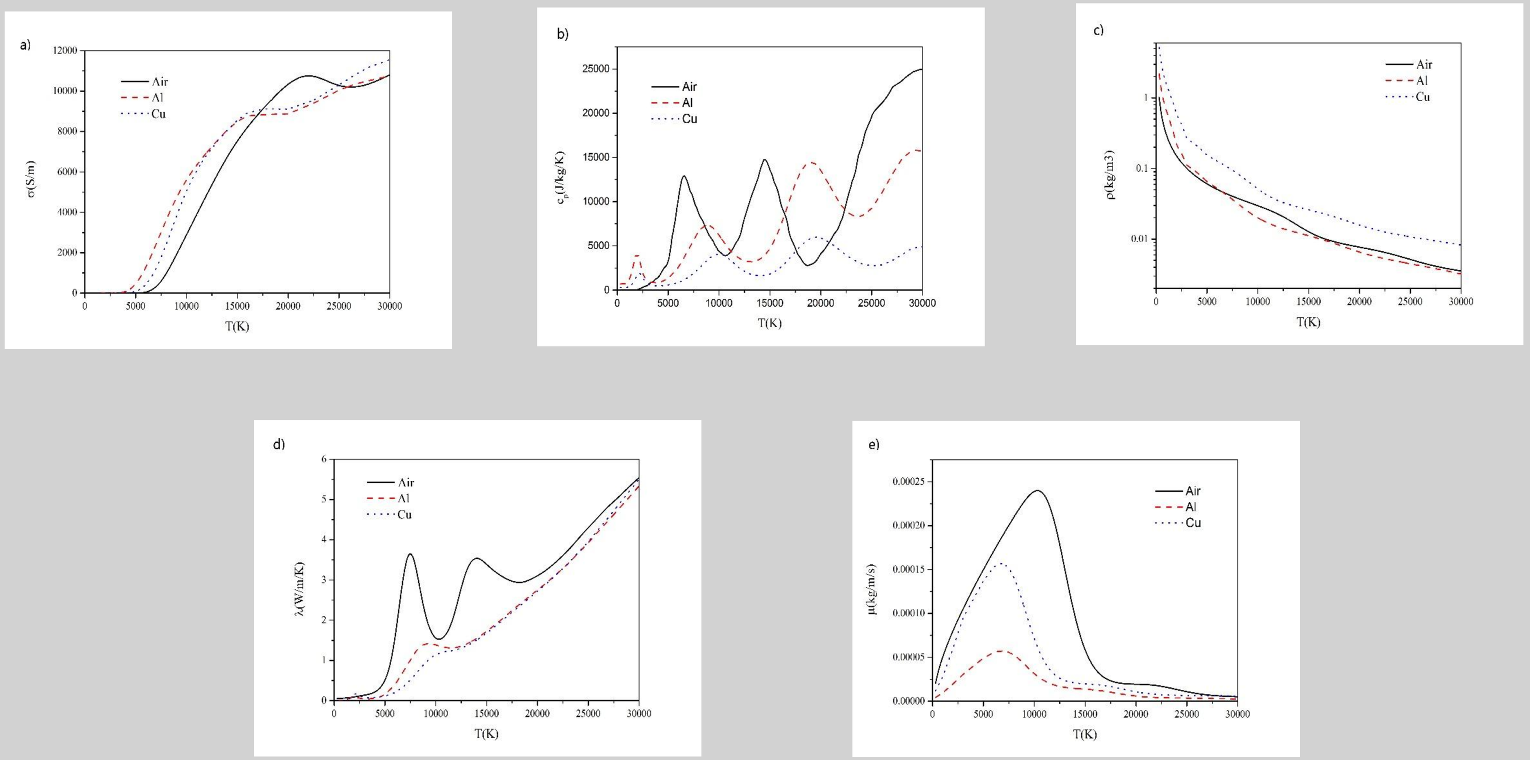

Figure 3 Physical parameters of plasma, a): Electric conductivity; b): Specific heat; c): Mass density; d): Thermal conductivity; e): Viscosity

## RECULT AND DISCUSSION

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 , 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.

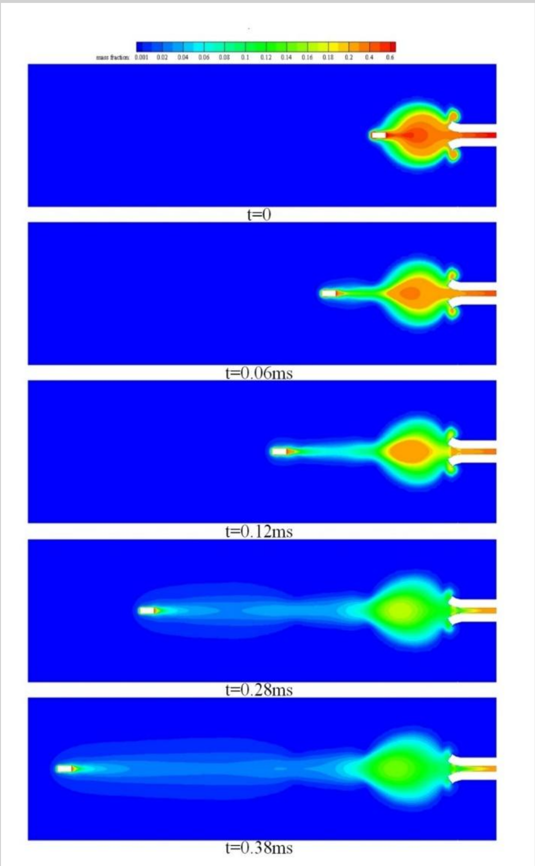


Figure 4Metal vapor distribution in muzzle area

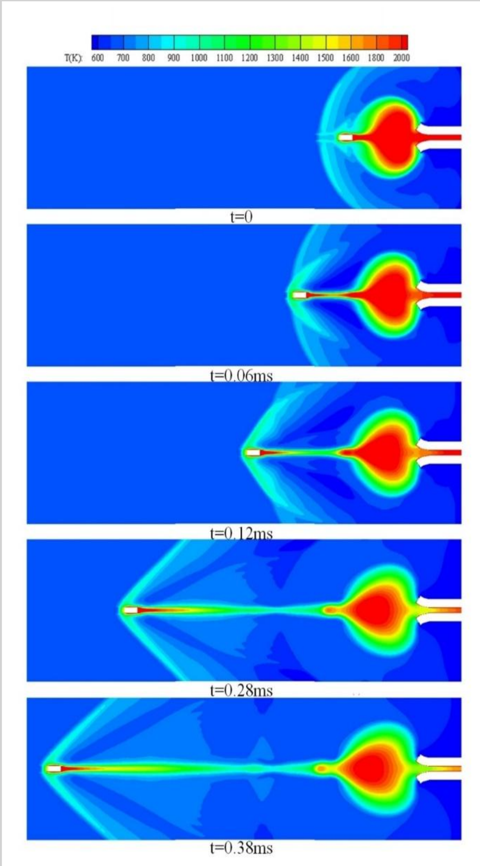


Figure 5 Temperature distribution in muzzle area


Figure 6 High speed acquisition results of railgun muzzle flame

Figure 6 is from He Y's paper, 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.

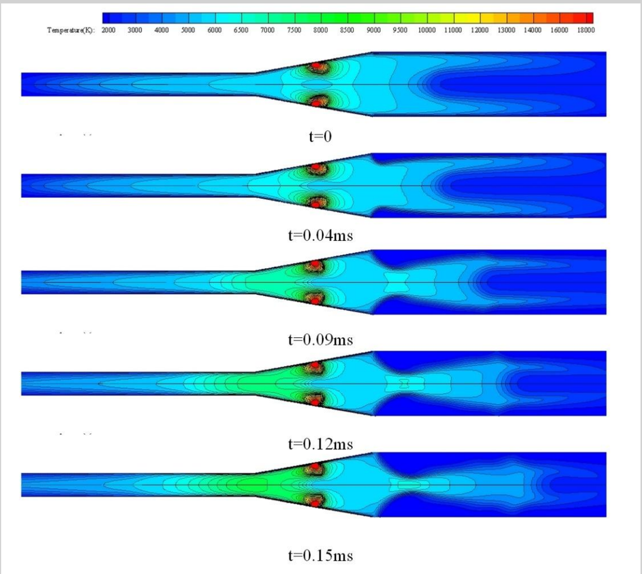


Figure 9 Cloud chart of flow field with arc in muzzle

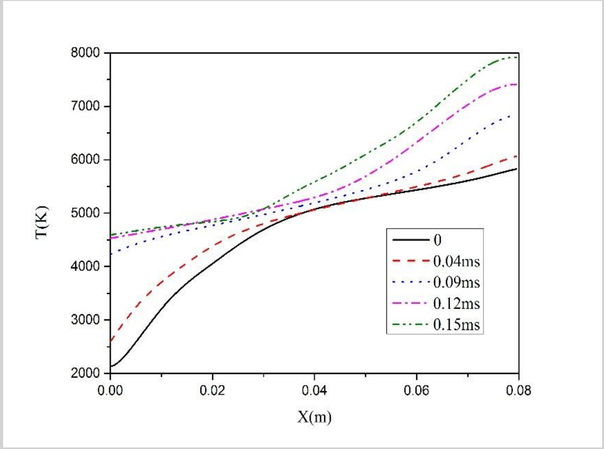


Figure 10 Temperature curve on axis of bore at different time

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. 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.

## CONCLUSION

In this paper, the 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. The conclusions are as follows:

- 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.
- 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.
- 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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