Simulation on the Characteristics of Rotating Vacuum Arc Plasma

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Abstract. Making electrodes rotate with the rotating speeds from 1°/ms to 10°/ms during the breaking process is a new method and technology to improve the breaking capacity in the vacuum circuit breaker. In this paper, a 3-D two-temperature magnet-hydro-dynamic (MHD) model is established, and the centrifugal force is added into the momentum conservation equation to simulate and analyze the rotating vacuum arc plasma. From the simulation results in different rotating speeds, it can be seen that: the ion and electron temperatures, the plasma density distribution, the plasma pressure and the heat flux density of anode all decrease, which have an effective influence in the breaking process of vacuum circuit breaker and the new technology can be a new method to improve the breaking capacity.

Keywords: Vacuum arc · Magnet hydro dynamic model · Rotating arc · Numerical simulation

1 Introduction

Vacuum circuit breaker (VCB) is widely used in many fields, such as electroplate, pulsed power technology and modern power system, and the phenomena of vacuum arc (VA) are of great significances. Many scholars have researched and analyzed the VA, such as studying and establishing a two-dimensional VA HMD model [1], researching the arc characteristics of double-break VCB [2, 3], exploring the VA with the methods of simulation and experiment [4], designing a new structure VCB and analyzing the arc characteristics [5–8].

Nowadays, to improve the voltage level and breaking capacity of VCB is an essential topic. Exerting rotating speed in the contacts in the breaking process is a new method and technology to improve the breaking capacity. In this paper, by adding the centrifugal force term to the momentum equation of the 3-D VA MHD model, the arc with different rotating speeds can be simulated, and the plasma characteristics, such as: ion and electron temperature, plasma density, plasma pressure and the heat flux density in different rotating speeds can be studied and anlyzed.

J. He et al. (Eds.): *The proceedings of the 16th Annual Conference of China Electrotechnical Society*, LNEE 891, pp. 531–539, 2022.
https://doi.org/10.1007/978-981-19-1532-1_56

2 The Model of Rotating Vacuum Arc

2.1 Physical Model and Basic Assumption

VA is composed of cathode sopts zone, arc column zone and anode sheath. The arc column is between cathode spots zone and anode sheath, which is the main area of VA. In this paper, the arc column zone is selected for simulation. The physical model of low current VA is shown in Fig. 1. In this paper, the electrode radius $R_0 = 25$ mm, gap distance $d = 10$ mm, arc current $I_0 = 500$ A, cathode spots radius $r_0 = 7.5$ mm. The basic assumption in this model is essential [9].

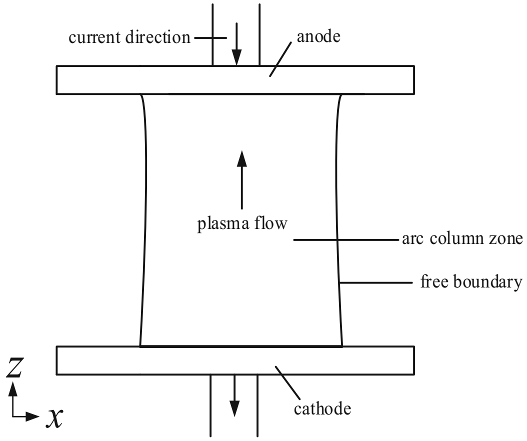

Fig. 1. Physical model of low current vacuum arc

2.2 Mathematical Model

The 3-D two-temperature VA MHD model has been established [10]. What's more, the rotating arc model needs to add the centrifugal force into the momentum conservation equation.

Momentum balance:

$$div(\rho_i \vec{u} \vec{u}_x) = -\frac{\partial p_i}{\partial x} - \frac{\partial (n_e k T_e)}{\partial x} + (\vec{j} \times \vec{B})_x + F_x \tag{1}$$

$$div\,(\rho_i \vec{u} \vec{u}_y) = -\frac{\partial p_i}{\partial y} - \frac{\partial (n_e k T_e)}{\partial y} + (\vec{j} \times \vec{B})_y + F_y \tag{2}$$

$$div(\rho_i \vec{u} \vec{u}_z) = -\frac{\partial p_i}{\partial z} - \frac{\partial (n_e k T_e)}{\partial z} + (\vec{j} \times \vec{B})_z \tag{3}$$

Equation (1), (2) and (3) are the momentum balance. In the equation, ρ_i is ion mass density, u is ion velocity, u_k is ion velocity in k-direction (k = x, y, z), n_e is electron number density, k is Boltzmann constant, T_e is electron temperature, j is current density, B is magnetic flux density, $\vec{j} \times \vec{B}$ is the Lorentz forcre and the F_x and F_y are the centrifugal force.

$$F_x = m_i n_i \omega^2 x \tag{4}$$

$$F_y = m_i n_i \omega^2 y \tag{5}$$

In the Eq. (4) and (5), n_i is ion number density, ω is angular velocity, and x and y are the distance from ion position to the rotation center along x and y direction.

3 Boundary Condition

3.1 Cathode Side

In this paper, the VA with the current of 500 A is simulated. The boundary condition of fluid field is the same with 200 A [9] and the magnetic field along x and y at cathode side:

$$B_x = \begin{cases} \frac{\mu_0 j_0 \, (y - y_0)}{2} & r \; < \; r_0 \\ \frac{\mu_0 I_0 \, (y - y_0)}{2\pi r^2} & r \; \geq \; r_0 \end{cases} \tag{6}$$

$$B_y = \begin{cases} -\frac{\mu_0 j_0 \, (x - x_0)}{2} & r < \; r_0 \\ -\frac{\mu_0 I_0 \, (x - x_0)}{2\pi r^2} & r \geq r_0 \end{cases} \tag{7}$$

B_x and B_y are the magnetic field along x and y direction, μ_0 is vacuum magnetic permeability, j_0 is average current density, x_0 and y_0 are the center positon of arc, $x_0 = 10$ mm, $y_0 = 6$ mm, r is the distance from arc center to the ion position, $r = \sqrt{(x - x_0)^2 + (y - y_0)^2}$.

3.2 Anode Side

As the fluid is supersonic flow, the flow field parameters at the anode boundary need not be set. In the energy conservation equation, the anode boundary condition is set as adiabatic condition:

$$\frac{\partial T_e}{\partial z} = 0 \tag{8}$$

3.3 Radial Boundary

Boundary conditions of magnetic along x and y direction at radial boundary:

$$B_x = \frac{\mu_0 I_0 \, (y - y0)}{2\pi r^2} \tag{9}$$

$$B_y = -\frac{\mu_0 I_0 \, (x - x0)}{2\pi r^2} \tag{10}$$

The boundary condition in the flow field is set as adiabatic condition:

$$\frac{\partial T_e}{\partial n} = 0 \tag{11}$$

4 Simulation Results and Analysis

In this paper, the electrode radius $R_0 = 25$ mm , gap distance $d = 10$ mm, arc current $I_0 = 500$ A, cathode spot radius $r_0 = 7.5$ mm, the coordinates of the arc center are $x_0 = 10$ mm, $y_0 = 6$ mm.

Figure 2 and Fig. 3 shows the ion temperature and electron temperature. The maximum value area of them are both in the center of arc, the anode temperature is higher than the cathode temperature, and the electron temperature is higher than the ion temperature. This is because the mass of electron is much less than that of ions, so electrons can obtain more kinetic energy under the influence of electric field force, and this energy will be converted into heat energy during collision, so the electron temperature is higher than that of ions.

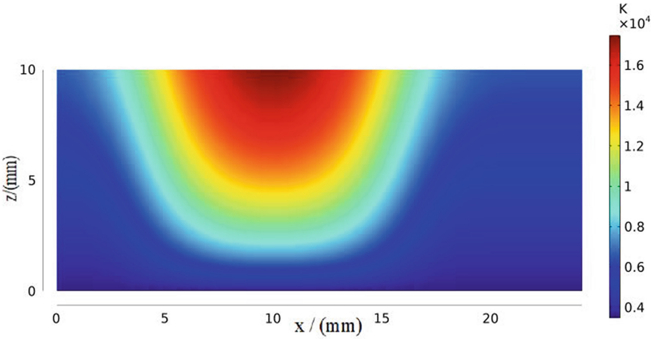

Fig. 2. Ion temperature

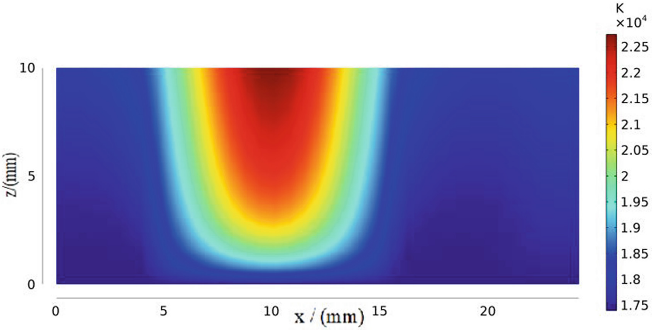

Fig. 3. Electron temperature

The variation of ion temperature and electron temperature with different rotation speed is shown as Fig. 4 and Fig. 5. With the increase of rotation speed, both of the them decrease. This is because the rotating arc reduces the plasma density, and the current density and collision frequency of particles also decrease. As a result the temperature of them both have a certain decline.

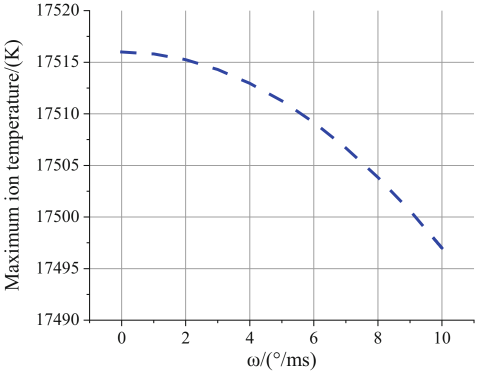

Fig. 4. Maximum ion temperature in different rotation speeds

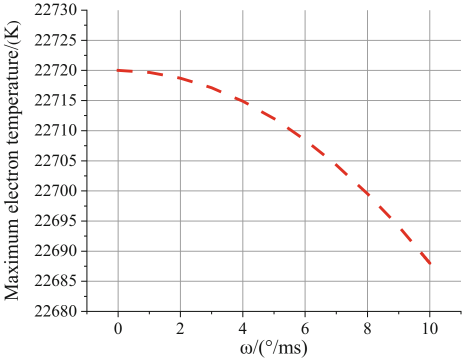

Fig. 5. Maximum electron temperature in different rotation speeds

The plasma density distribution is shown in Fig. 6. Because the ion mass is much greater than the electron mass, and the plasma mass flow is mainly the ion flow, so the plasma density here is actually ion density. The centrifugal force of rotation arc will

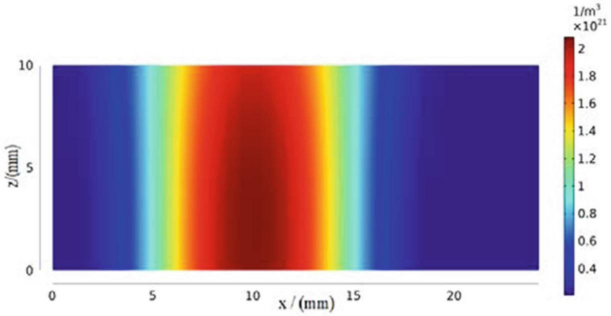

Fig. 6. Plasma density distribution

decrease the plasma density along *x* and *y* direction. The plasma density at cathode side in different rotation speeds is shown in Fig. 7.

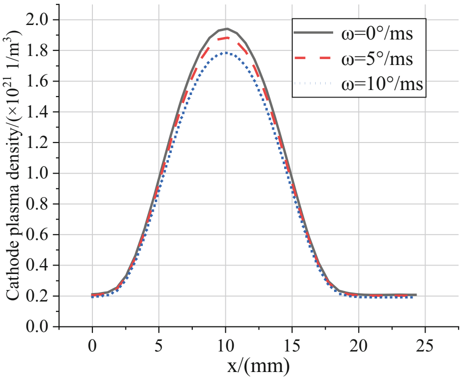

Fig. 7. Cathode plasma density in different rotation speeds

The VA is considered as an ideal gas, so the plasma satisfies the ideal-gas equation. The plasma pressure, shown in Fig. 8, is a parameter that reflects the plasma density and plasma temperature. To study the influence of rotating arc on plasma pressure, take the arc center ($x = 10$ mm, shown in Fig. 8) as the analysis object, research the plasma pressure from cathode side to anode side. The analysis results are shown in Fig. 9, and the plasma pressure decreases with the increase of rotating speed, which have the same trend as the variation of plasma density, electron temperature and ion temperature. It is proved that rotating arc can change the plasma characteristics.

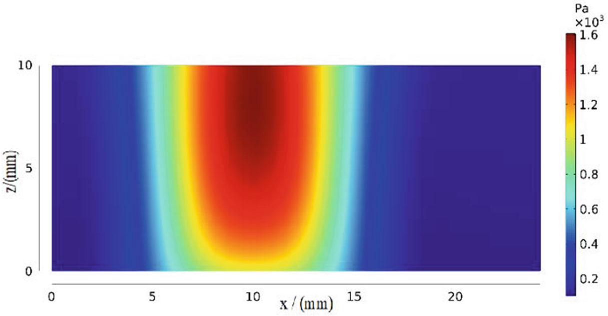

Fig. 8. Plasma pressure

When the contacts of VCB is separating, the energy of arc is mainly dissipated by flowing into the anode. The continuous input of strong energy will increase the anode temperature, leading to the melting and evaporation of contact materials, and changing the characteristics of arc plasma. The distribution of heat flux density to anode is an important parameter, which is related to the breaking condition. Figure 10 shows the

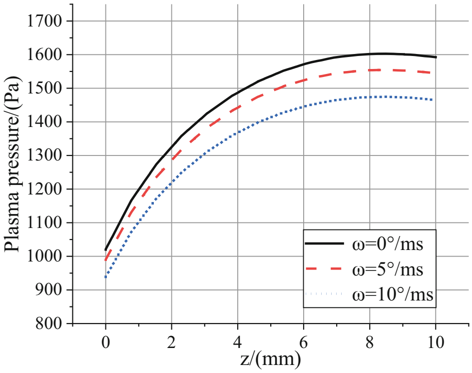

Fig. 9. Plasma pressure along z direction in different rotating speed

distribution of heat flux density to anode and Fig. 11 reflects the situation of different rotation speed about it. In the figures, S is heat flux density, S_e is electron flux density and the S_i is ion flux density.

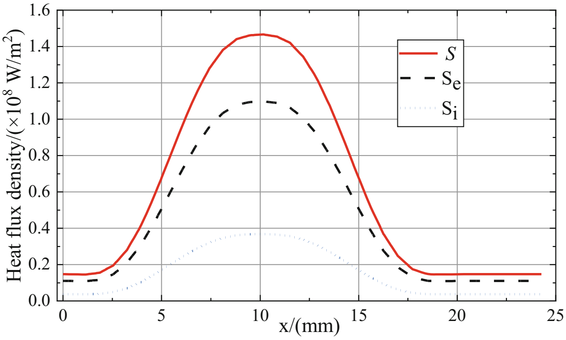

Fig. 10. Distribution of heat flux density to anode

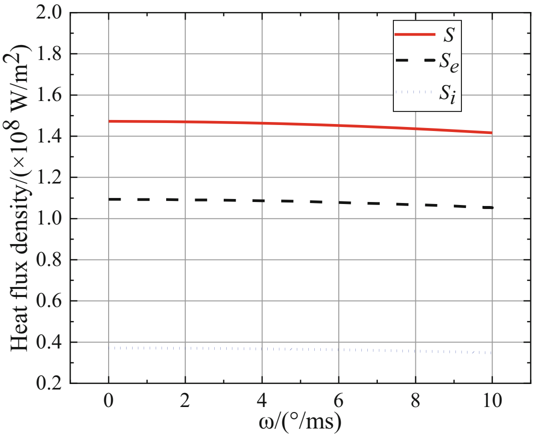

Fig. 11. Maximum heat flux density to anode in different rotation speed

5 Summary

In this paper, a new method to improve the breaking capacity of VCB and its simulation model are proposed. Through the rotation arc model and simulation results, the relation between different rotation speeds and plasma characteristics can be researched and concluded. With the increase of rotation speed, the ion and electron temperature, the plasma density, the plasma pressure and the heat flux density all decline, which has an effective influence in the breaking process of VCB.

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