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STUDY ON PRE-ARC PROCESS AND MICROSCOPIC PARAMETERS OF SF6 MIXTURE GAS CIRCUIT BREAKER

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ABSTRACT

The use of SF_6/N_2 or SF_6/CO_2 mixture gas as a potential alternative to SF_6 has attracted wide attention due to the easy availability of N_2 and CO_2, stable chemical and physical properties, non-toxicity, non-flammability, and non-combustion. In this paper, the simulation study of the arc formation process in the circuit breaker is carried out from a microscopic point of view. The simulation is based on the gas dynamics equation considering the complex collisions between charged particles and neutral molecules and obtaining the time-varying law of the micro-parameters such as the electron density and average electron energy in the arc forming process of SF_6/N_2 and SF_6/CO_2 mixture gas. The results can help us understand the characteristics of the mixture gas arc from the microscopic level, and provide a theoretical basis for the design and manufacture of the new circuit breaker.

Keywords: SF6/N2 mixture gas, SF6/CO2 mixture gas, microscopic parameter, arc, circuit breaker

1. INTRODUCTION

SF_6 gas is widely used in high voltage level as insulation and arc extinguishing medium. However, due to its high greenhouse effect, SF_6 has been listed as one of the six restricted gases [1]. Therefore, it is of great significance to find new gases with insulating properties comparable to SF_6 and low greenhouse effect index.

At present, most scholars adopt experimental methods to analyze insulation properties of mixture gases by measuring the breakdown voltage and other parameters[2]. Experimental method can reflect the electric strength of the mixture gases, but it cannot explain the complicated breakdown phenomena and it can be affected by the external influences. The establishment of an effective mathematical model for the simulation of mixture gas is another effective means to solve this problem [3]. When the gas is broken down, the temperature of the ionization channel rises due to the impact of charged particles, and the electrical breakdown turns into a stable thermal breakdown, and finally forms a steady arc. In this process, when the breakdown channel is cold before the start of thermal ionization, the process is called the pre-arc process which is the basis of arc generation[4]. Therefore, in this paper, a simplified micro-arc model of the circuit breaker is established. The SF_6/N_2 and SF_6/CO_2 mixture gases are taken as the research objects to simulate and analyze the dynamic pre-arc process.

2. SIMULATION MODEL

2.1 Mathematical models and assumptions

In this paper, a mathematical model was established based on the following assumptions: (1) After the contacts separate, the gas is evenly distributed; (2) The photoionization is ignored; (3) The diffusion motion of heavy ions and electrons are neglected, and only the migration motion is considered.

The mathematical model is based on the Boltzmann equation of gas dynamics as shown in equation (1) - (4).

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$$\frac{\partial}{\partial t}(n_e) + \nabla \cdot [-n_e(\mu_e \cdot E) - D_e \cdot \nabla n_e] = R_e \quad (1)$$

$$\frac{\partial}{\partial t}(n_\varepsilon) + [-n_\varepsilon(\mu_\varepsilon \cdot E) - D_\varepsilon \cdot \nabla n_\varepsilon] + E \cdot \Gamma_e = S_{en} \quad (2)$$

$$\Gamma_e = -(\mu_e \cdot E)n_e - \nabla(D_e n_e) \quad (3)$$

$$S_{en} = \sum_{j=1}^{p} x_j k_j N_n n_e \Delta\varepsilon_j \quad (4)$$

Where: n_e is electron density; R_e is the electron source; Γ_e is the electron flux; μ_e is electron mobility; D_e is electron diffusivity; n_ε is electron energy density; μ_ε is electron energy mobility; D_ε is electron energy diffusivity; S_{en} is the energy loss or gain due to an inelastic collision; x_j is the mole fraction of the target substance in the reaction; k_j is the rate coefficient; N_n is the total neutral particle density; $\Delta\varepsilon_j$ is the energy loss from reaction j.

2.2 Calculation model and parameter settings

The circuit breaker is simplified into a two-dimensional axisymmetric model shown in Fig. 1 where A is static contact and B is moving contact with the radium r=20mm and the spacing z=5mm.

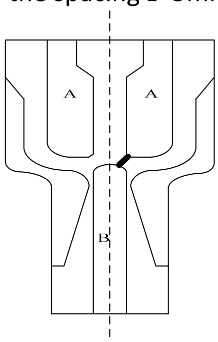


Fig 1 Simplified model of circuit breaker

The pre-arc processes of SF_6/N_2 and SF_6/CO_2 mixture gases under the same initial conditions were simulated. The Initial electron and inon number density are $10^{13}/m^2$ separately; Initial average electron energy is 5.8eV; temperature is 273K; secondary electron emission coefficient is 0.25; electron mobility is 4×10^{24}/（v·m·s）.

2.3 Gas collision equation and collision cross section

The pre-arc process is microscopically explained as the process of gas ionization. The time of this process is extremely short, and the collisions frequency of charged particles and neutral particles are very high. The collision equations and corresponding cross sections of SF6 and N2 are shown in Fig. 2 and Fig. 3.

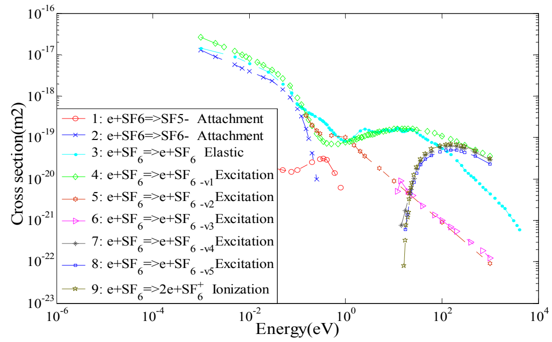


Fig 2 SF_6 gas collision cross section

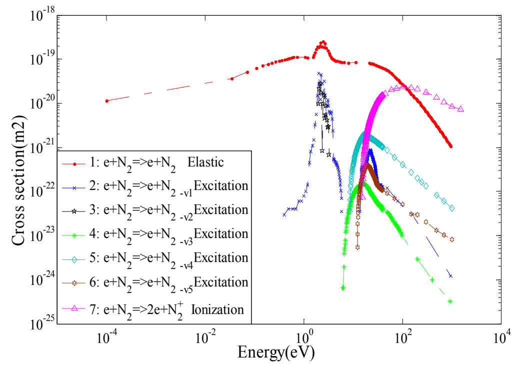


Fig 3 N_2 gas collision cross section

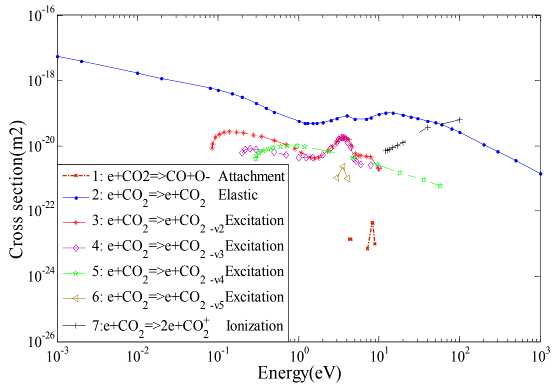


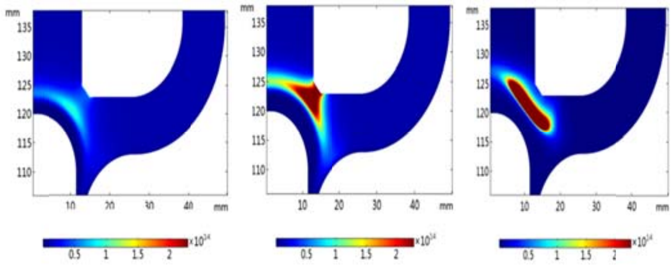
Fig 4 CO_2 collision cross section

Among them, SF_6^+, SF_5^-, SF_6^-, N_2^+, CO_2^+ represent heavy ions; SF6s represents SF6 excited state molecules; N_2s represents N_2 in excited state molecules; CO_2s represents CO_2 in excited state molecules. The energy required for the initial effective collision of SF_6 gas is lower than that of N_2 and CO_2. As the energy increases, when N_2 and CO_2 also reach the energy that can collide effectively, the effective collision probability of N_2 is greater than that of SF_6 and CO_2, but the ionization energy of the CO_2 molecule (about 3.75eV) is lower than that of the N_2 molecule (about 15.6eV).

3. ANALYSIS OF MICROSCOPIC PARAMETERS OF SF_6/N_2 AND SF_6/CO_2 MIXTURE GASES

3.1 Electron density distribution in the dynamic pre-arc process of mixture gas

Fig 5-6 shows the dynamic change process of electron density in the arc channel formation process of SF_6/N_2 and SF_6/CO_2 mixture gases when the SF_6 content is 20%. At the initial stage of arc formation, local plasma is formed by the collision ionization of particles between contacts, and the initial electron concentration is $10^{13}/m^3$.



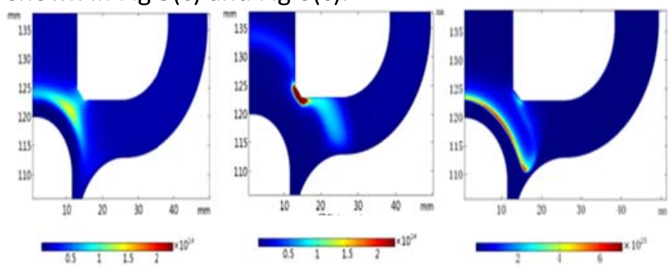
(a) t=2.96ns (b) t=25.2ns (c) t=80.5ns

Fig 5 Electron density of SF6/N2 mixture

After the contacts are disconnected, the electrons and ions between the electrodes are evenly distributed, and the net space charge is zero. As the voltage between the electrodes gradually increases, the electrons move from the cathode to the anode due to the influence of the electric field, colliding with the neutral molecules and ionizes, which doubles the number of space electrons. Because of the low ionization energy of CO_2, the number of electrons generated by ionization is more under the same conditions. Therefore, the electron density of the SF_6/CO_2 mixture gas is higher than that of the SF_6/N_2 mixture gas, and the arc development speed is faster, as shown in Fig 5(a) and Fig 6 (a).

Along with the occurrence of impact ionization, a part of electrons are continuously absorbed near the anode, also the concentration and density of electron in the near anode region are reduced, while large-scale electron avalanche has not formed yet, space charges are insufficient, and the number of new electrons is less, which hinders ionization collision as shown in Fig 5(b). At this time, due to the rapid development of SF_6/CO_2 mixture gas, a large amount of electrons have been absorbed by the anode, and the ions move slower than electrons and stay in the space forming space charge, which distort the electric field in the anode region. Finally, the direction of electric field intensity near-anode region changed. Under the action of the reverse electric field, large scale electrons are isolated to form an anode sheath, as shown in Fig 6(b).

Then, the neutral particles outside the anode sheath collide with a large number of electrons, and the high charge density center develops from the anode to the cathode. When the collision occurs to a certain extent, the electron energy decreases, and the electrons are accelerated in the direction of the electric field, and cannot stay near the cathode. The number of positive ions in this region is much more than the number of electrons, forming a cathode sheath, as shown in Fig 5(c) and Fig 6(c).



(a) t=2.96ns (b) t=25.2ns (c) t=80.5ns

Fig 6 Electron density of SF6/CO2 mixture

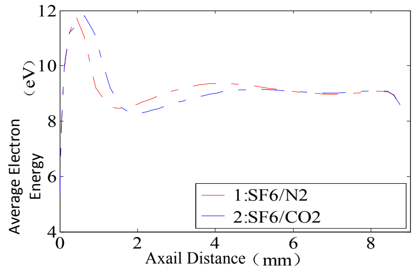
The thickness of the cathode sheath in SF_6/CO_2 mixture gas is about 1.6 mm, and the electron density is up to 2.38×10^{16} ($1/m^3$). For SF_6/N_2 mixture gas, the thickness of the cathode sheath is about 1.5 mm, and the electron density is at most 2.26×10^{16} ($1/m^3$).

3.2 *The average electron energy change of the mixture gas in dynamic pre-arc process*

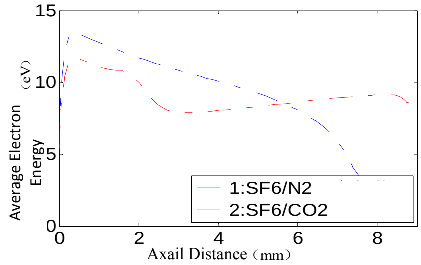
Fig 7 shows the change of average electron energy of SF_6/N_2 and SF_6/CO_2 mixture. As shown in Fig 8(a), at the initial discharge, electrons move from the cathode to the anode, and the electric field intensity near the cathode is the highest, with higher electron density and higher electron energy. The average electron energy near the cathode of SF_6/CO_2 mixed gas is higher than that of SF_6/N_2 mixture gas, and the maximum near the cathode is 12eV.At 0.3μs, the velocity of the electron near the anode increases and the average energy of the electron also increase, while the energy of the electron near the anode decreases. As the electron distorts the electric field, the SF_6/CO_2 mixture gas distorts the electric field to a greater extent. In this distorted electric field, the change of the average electron energy is also greater than that of the SF_6/N_2 mixed gas.At 0.6μs, due to the rapid development of the SF_6/CO_2 arc, the electron energy drops lower at the anode and reaches a maximum of 19.3ev at the cathode.

3.3 *Heavy ions analysis in the mixture gas in dynamic pre-arc process*

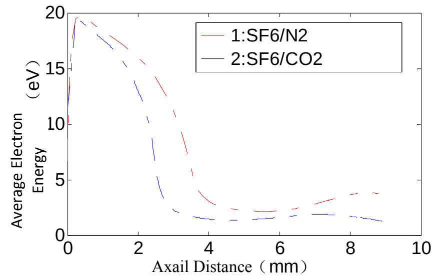
Fig 8-9 shows the axial distribution of ion density in the dynamic process of SF_6/N_2 and SF_6/CO_2 mixture gas. Due to the low SF6 gas content, N2+ and CO2+ positive ions are the most abundant positive ions in the discharge process.



(a) t=0.5nm



(b) t=0.3μm



(c) t=0.6μm

Fig 7 Average electron energy

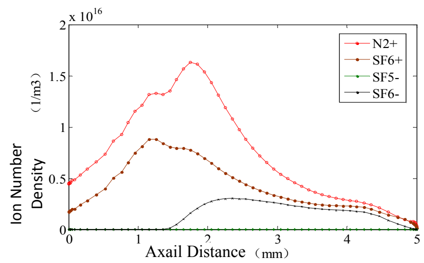


Fig 8 Heavy ion number density distribution in SF6/N2

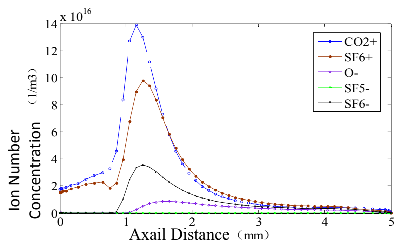


Fig 9 Heavy ion number density in SF6/CO2

The concentration of SF_6^+ ions in the mixture gas is lower than N_2^+ and CO_2^+, indicating that even a small amount of SF_6 gas plays an important role in the ionization process. The concentration of SF_5^- particles in the two mixture gases is lower than that of SF_6^-, because the reaction rate of SF_6^- ion formation is higher than that of SF_5^-. The number density of O^- ions generated in SF_6/CO_2 mixture gas is much lower than that of SF_6^- ions, which also indicates that CO_2 adsorption plays a certain role in the arc development of mixture gas, but it is not obvious.

4. CONCLUSION

A simplified model of circuit breaker is established to analyze the dynamic pre-arc process of SF_6/N_2 and SF_6/CO_2 mixture gases in this paper and the following conclusions are obtained:

1) In the pre-arc development process, the electron density of SF_6/CO_2 mixture gas is higher than that of SF_6/N_2, and the arc develops faster.

2) In the initial phase, the average electron energy of SF6/CO2 is lower than that of SF_6/N_2, while in the later phase, it is higher than that of SF_6/N_2.

3) The average electron energy of SF_6/CO_2 mixture is higher than that of SF_6/N_2. In mixture gases, even a small amount of SF_6 gas can play a significant role in arc development.

4) The simulation study in this paper provides a theoretical basis for the search for SF6 replacement gas. It's possible to use SF6/N2 and SF6/CO2 mixture gas instead of pure SF6 gas.

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