Study on Arc Extinguishing Performance of DC C4F7N/CO2 Mixed Gas

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Abstract. The arc characteristic analysis of C4F7N/CO2, CO2 and SF6 gases with volume fraction of 10%C4F7N-90% under DC condition is studied. Firstly, based on the internal physical process of arc, a two-dimensional axisymmetric arc model of C4F7N/CO2, CO2 and SF6 gas was established and calculated. The arc temperature distribution and dynamic characteristics of three gas media are compared and analyzed the results show that the temperature distribution of C4F7N/CO2 mixed gas is more similar to that of SF6 gas arc, and its radial cooling speed is faster, indicating that compared with CO2 gas, C4F7N/CO2 mixed gas has better arc-quenching characteristics, which can be used in the study of SF6 substitute gas.

Keywords: SF6 alternative gas, C4F7N/CO2 gas mixture, arc model.

1. Introduction

Sulfur hexafluoride is widely used in power systems due to its excellent insulation and arc extinguishing performance, but its greenhouse effect coefficient (GWP) is 23900 times that of CO2, and it can survive in the atmosphere for 3200 years [1]. In order to completely eliminate or reduce the impact of SF6 on the environment, scholars from various countries have begun to try to find a new type of environmentally friendly gas to replace SF6.

C4F7N is a new type of environmentally friendly gas, its GWP is 2100 times that of CO2, which is far lower than the greenhouse effect of SF6. Its ozone depletion potential (ODP) is 0 and will not damage the ozone layer. In addition, the dielectric strength of C4F7N is about twice that of SF6[2], and it is currently the most potential alternative gas. Since the liquefaction temperature of C4F7N is as high as −4.7 °C, it is not suitable for use as a gas insulating medium alone. It needs to be mixed with buffer gases such as CO2 and N2 with lower liquefaction temperature.

Li Xingwen and others studied the insulation properties of C4F7N, C5F10O and CO2 mixed gases and their application as an insulating medium under different ratios and pressures [3]. Long Yunxiang et al. conducted a steady-state Thomson method study on the ionization characteristics of C4F7N/N2 mixed gas [4]. Wuhan University conducted power frequency breakdown experiments and synergistic effect analysis for C4F7N/CO2 and C4F7N/N2 mixed gases [5]. Li Xingwen et al. studied the characteristics of the free combustion arc of C4F7N/CO2 mixed gas [6]. Lin Xin from Shenyang University of Technology and others conducted an experimental study on the arc extinguishing characteristics of C4F7N/CO2 mixed gas [7].
From the current research trend, it can be seen that the research on C$_4$F$_7$N and its mixed gas mainly stays in the experimental stage. The experimental research is often destructive, which consumes a lot of manpower and material resources, and it is impossible to rule out the influence of external conditions such as different equipment structures in the experiment influences. In order to study the characteristics of C$_4$F$_7$N/CO$_2$ mixed gas arc, it is a good choice to establish a theoretical model and simulate the process of arc development. Based on this, based on the magnetic fluid model and considering the influence of turbulence, this paper establishes a two-position axisymmetric arc model for C$_4$F$_7$N/CO$_2$, CO$_2$ and SF$_6$ gas to study arc characteristics and differences.

2. Governing equation and computational domain

2.1. Governing equation
For the gas circuit breaker breaking process, the arc in the nozzle and the surrounding airflow field can be considered to be in a local thermal equilibrium (LTE) state, so its physical process can be described by the time-averaged Navier-Stokes (RANS) equations. The NS equation consists of three conservation equations of mass, momentum and energy.

1. Mass conservation equation

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \]  \hspace{1cm} (1)

Where \( \rho \) : mass density, \( \mathbf{V} \) : gas velocity.

2. The momentum conservation equation

\[ \rho \left( \frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = \nabla \cdot \left[ -p I + \mu (\nabla \mathbf{V})^T - \frac{2}{3} \mu (\nabla \cdot \mathbf{V}) I \right] + \mathbf{J} \times \mathbf{B} \]  \hspace{1cm} (2)

Where \( p \) : pressure on the fluid cell, \( \mu \) : dynamic viscosity of fluid, \( I \) : identity matrix, \( \mathbf{J} \) : Current density, \( \mathbf{B} \) : magnetic flux density.

3. Energy equation

\[ \frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho H \mathbf{V}) = \nabla \cdot \left( \frac{\lambda}{C_p} \nabla T \right) + S_p \]  \hspace{1cm} (3)

\[ S_p = \frac{1}{\sigma} J^2 - S_{rad} + S_{\phi} \]  \hspace{1cm} (4)

\[ S_{\phi} = \frac{\partial}{\partial T} \left( \frac{k_B T}{2 q} \left( \frac{k}{C_p} + 5 \right) \right) (\nabla T \cdot \mathbf{J}) \]  \hspace{1cm} (5)

Where \( H \) : enthalpy, \( \lambda \) : thermal conductivity, \( C_p \) : specific heat at constant pressure, \( T \) : temperature, \( S_p \) : plasma heat source, \( K_B \) : boltzmann constant, \( q \) : electronic charge.

4. Gas state equation

\[ p = \rho RT \]  \hspace{1cm} (6)

Where \( R \) is the ideal gas constant, and its value has nothing to do with the gas type.
2.2. Turbulence model
This paper uses the k-ε turbulence model. In the standard k-ε model, on the basis of the Navier-Stokes equation, two transport equations that characterize the turbulence characteristics are added, which are about the turbulent kinetic energy k and the viscous diffusivity ε.

The turbulent kinetic energy equation:

$$\rho \frac{\partial k}{\partial t} + \rho (\bar{u} \cdot \nabla) k = \nabla \cdot \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + p_k - \rho \varepsilon$$

(7)

Turbulence dissipation equation:

$$\rho \frac{\partial \varepsilon}{\partial t} + \rho (\bar{u} \cdot \nabla) \varepsilon = \nabla \cdot \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + C_{\varepsilon 1} \frac{\varepsilon}{k} p_k - C_{\varepsilon 2} \rho \frac{\varepsilon^2}{k}, \varepsilon = \varepsilon_p$$

(8)

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

(9)

$$p_k = \mu_t \left[ \nabla \bar{u} \cdot \left( \nabla \bar{u} + \nabla \bar{u}^T \right) \right]$$

(10)

Where $\sigma_k$ : turbulent kinetic energy, $\varepsilon$ : turbulent energy dissipation rate.

$C_{\varepsilon 1}, C_{\varepsilon 2}, C_\mu, \sigma_k, \sigma_\varepsilon$ are the empirical constants in the turbulence model. After a large amount of experimental data analysis, these five constants are generally taken as 1.44, 1.92, 0.09, 1.0, 1.3. The physical properties of CO$_2$, SF$_6$ and 10% C$_4$F$_7$N-90% CO$_2$ mixed gas are taken from the basic database of gas discharge plasma.

2.3. Calculation area
The mathematical model of the given nozzle structure is calculated and solved by the finite element calculation method. The nozzle structure and spatial calculation area are shown in Figure 1. The detailed size information is given in the figure. HV and GND are the ground contact and the high voltage contact respectively. It is solid, the radius is 5mm, the material is copper, and the distance between the two contacts is 100mm. The nozzle material is PTFE, and the nozzle throat radius is 5mm. The gas inlet and outlet are respectively marked in the figure.

![Figure 1. Nozzle structure](image)

2.4. Boundary conditions
The arc structure of the nozzle is an axisymmetric structure. Except for the velocity, the radial components of the independent variables of the control equation are all zero. The nozzle inlet is set as the boundary condition of the air pressure inlet, the initial pressure is set to $P_0=5$atm, and the initial temperature is 293.15K. The outlet of the nozzle is set as the boundary condition of the air pressure
outlet, and the outlet pressure of the nozzle is low enough (set to 0.1 atm) to ensure that the airflow field in the nozzle is supersonic and without shock waves. The other solid surfaces (nozzle wall and electrode surface) in the model are set to have no sliding boundary conditions, that is, the vertical velocity of the surface is 0, and the surface is set to be adiabatic, that is, the heat conduction is 0. The given current value of the high-voltage contact is 1000 A, and the low-voltage contact is grounded.

3. Calculation results and analysis

Figure 3 shows the arc temperature distribution of the nozzles of SF₆, CO₂, and C₄F₇N/CO₂ mixed gases with three different media. It can be seen from the figure that the high temperature areas of the three gases are concentrated near the throat of the main nozzle. For the SF₆ arc, the maximum temperature is 21700 K, the arc diameter is the smallest, the arc radius in the throat area is 3 mm (calculated according to 4000 K isotherm), the arc core area is more obvious; the maximum temperature of CO₂ arc is lower than that of SF₆ arc, the maximum temperature is 18600 K. The arc diameter is large, the arc radius of the throat is 5 mm, and the arc core area is not obvious; after adding C₄F₇N gas, the maximum temperature of the C₄F₇N/CO₂ mixed gas arc is 18100 K, the highest temperature of the three media is the lowest, and the arc radius of the throat is 4.6 mm, compared with CO₂ arc, C₄F₇N/CO₂ mixed gas arc still has obvious high temperature area, and the arc column area is more obvious.

![Figure 2. Temperature distribution of SF₆, CO₂ and C₄F₇N/CO₂ mixed gas](image_url)

In order to observe the temperature trend of three different gases more clearly, it is necessary to study the radial temperature distribution of the three media. The radial temperature distribution of SF₆, CO₂ and C₄F₇N/CO₂ mixed gas arc at the upstream of the nozzle and at the nozzle throat is shown in Figure 2. From the radial temperature distribution diagrams of the two positions in Figure 2, it can be seen that for CO₂, SF₆ and C₄F₇N/CO₂ mixed gas, as the radius increases, the arc temperature in the center of the nozzle throat area changes the fastest, and the temperature drops rapidly. The arc has an obvious high temperature core area; for SF₆ gas arcs, the high temperature center area of the throat upstream and the nozzle is very high. Obviously, the radial temperature distribution has obvious shrinkage, the arc cooling speed is fast, and the arc radius is small. It shows that for the SF₆ arc, the radial energy transmission process plays a major role in cooling. For the CO₂ arc, compared to the other two gases, the temperature of the central axis is the lowest, but the temperature drops the most slowly in the upstream of the nozzle and the throat, especially the slowest temperature drops in the upstream of the nozzle, indicating that the energy of the CO₂ arc is not very good. The arc is transferred out through radial heat transfer, and the arc cooling rate is slow. For the C₄F₇N/CO₂ mixed gas, the central axis temperature is slightly higher than that of CO₂, and its overall radial temperature distribution trend is similar to that of CO₂, but its radial temperature decreases faster than CO₂, indicating that the addition of C₄F₇N can effectively improve the arc the radial energy transmission.
process is conducive to the arc cooling as soon as possible. The excellent breaking performance of SF\textsubscript{6} is mainly reflected in its excellent radial heat conductivity, which greatly increases the arc cooling speed and reduces the arc cooling time. From the above results, it can be shown that the C\textsubscript{4}F\textsubscript{7}N/CO\textsubscript{2} mixed gas has better arc extinguishing performance than CO\textsubscript{2}.

![Figure 3. Radial temperature distribution of SF\textsubscript{6}, CO\textsubscript{2} and C4F7N/CO\textsubscript{2} mixed gas](image)

### 4. Conclusions

Based on the magnetic fluid model and considering the influence of turbulence, this paper establishes the arc model of CO\textsubscript{2}, SF\textsubscript{6}, C\textsubscript{4}F\textsubscript{7}N/CO\textsubscript{2} mixed gas under the conditions of DC power supply, single nozzle and fixed electrode, and studies the characteristics and differences of the arc. The results show that: Compared with CO\textsubscript{2} gas, the arc radius of C\textsubscript{4}F\textsubscript{7}N/CO\textsubscript{2} mixed gas is reduced, the nozzle temperature distribution still has an obvious central area, and the arc column area is more obvious. Its radial temperature distribution is more similar to SF\textsubscript{6} gas, and the arc cooling speed is fast, showing better arc-extinguishing performance.

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