Study on Arc Extinguishing Capability of HFO-1336mzz(E)/CO_2 as SF_6 Substitute Gas

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Abstract SF_6 gas is mostly used in medium and high voltage power equipment due to its great insulation and arc extinguishing performance. However, large amounts of SF_6 gas can have a serious greenhouse effect. This article studies the arc extinguishing performance of HFO-1336mzz (E)/CO_2 mixture to evaluate its feasibility as an environmentally friendly gas to replace SF_6 in medium voltage switchgear. Based on the theory of local thermodynamic equilibrium, the physical parameters of HFO-1336mzz(E)/CO_2 were calculated by Gibbs energy minimization method, which provided important data support for the basic input parameters of simulation for arc burning simulation. Two-dimensional magnetohydrodynamic simulation model was established, and the load current breaking process was simulated under the pneumatic load switch structure. The temperature field distribution in the arc extinguishing room of HFO-1336mzz(E)/CO_2 and SF_6 gas were compared during the arc burning process. The results provide a key reference for the application of HFO-1336mzz(E)/CO_2 as arc extinguishing medium in medium voltage switchgear.

Keywords HFO-1336mzz(E)/CO_2 · Arc extinguishing performance · Magnetohydrodynamic · Physical parameter

1 Introduction

SF_6 was widely used in various switchgear since the 1960s due to its excellent arc extinguishing performance, insulation performance, self-recovery, thermal conductivity and stability, greatly promoting the development and application of high-voltage electrical equipment [1, 2]. In the field of medium voltage equipment, SF_6

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has gradually replaced the power equipment with compressed air or high pressure nitrogen as the insulating medium. Because of its superior insulation performance, using it as an insulating medium can reduce the charging pressure of medium voltage equipment and reduce the volume of equipment, in line with the miniaturization of power equipment, safe and reliable technology and use requirements.

However, the widely used SF_6 gas not only promotes the development of related industries, but also brings serious environmental problems. The Global Warming Potential (GWP) of SF_6 is about 25,200 times that of CO_2, and its atmospheric life is over 3000 years. In the Kyoto Protocol signed by over 100 countries in 1997, SF_6 is clearly stipulated as one of the six greenhouse gases that are limited in emission [3, 4]. Under the Protocol, governments of all countries are required to formulate and carry out a series of SF_6 emission policies, but SF_6 gas is still continuously discharged into the atmosphere.

In the past few decades, a series of emission reduction measures for SF_6 gas have been adopted in the power industry, such as gas recovery and gas leak detection. But these measures can not fundamentally avoid the SF_6 gas application in power equipment. Therefore, finding gas media with electrical performance and safety and environmental protection close to SF_6 is a recent hot topic. Research on SF_6 substitute gas at home and abroad has not been interrupted. Alternative gases that have been proposed include conventional gases (dry air, CO_2, N_2, etc.) and their mixtures with SF_6 [5–7], fluorocarbon compounds and their halogenates (c-C_4F_8, CF_3I, etc.) [8–10], other fluorine-containing compounds (C_4F_7N, $C_5F_{10}O$, HFO-1234ze(E), HFO-1336mzz(Z), etc.) [11–14]. However, these alternative gases have their own advantages and disadvantages.

This paper proposes high insulation gas HFO-1336mzz (E) as a substitute gas for SF_6 for medium voltage switchgear. At present, HFO-1336mzz(E) is mainly studied as a new type of heat pump working medium and refrigerant. The GWP value of this gas was 18, and Ozone Depletion Potential was 0, indicating low toxicity. At the same time, its atmospheric life is about a few days to a few weeks, good environmental performance. However, the liquefaction temperature of HFO-1336mzz(E) is relatively high, about 7.58 °C, and buffer gas has to be added in practical application [15, 16]. This paper selects CO_2 as the buffer gas. Preliminary study shows that HFO-1336mzz(E) gas mixture can achieve the insulation level comparable to SF_6, suitable for medium voltage switchgear. At present, some researchers have carried out preliminary studies on the insulation properties of HFO-1336mzz(E) gas mixture. However, the arc extinguishing performance of HFO-1336mzz(E) gas and its mixture remains to be further verified. Therefore, this paper carries out a systematic simulation study on the arc extinguishing performance of SF_6 and HFO-1336mzz(E)/CO_2 mixture in 12 kV load switch.

2 Simulation Model

As a kind of switch equipment with simple structure, convenient installation and maintenance, safe and reliable, and reasonable economic and technical indexes, medium voltage load switch has been widely used in 10–35 kV power supply system, especially in the urban distribution network. Load switch is a kind of switching appliance with simple arc extinguishing device, which can close, break and carry normal load of line or specified overload current, and has certain short-circuit closing capacity. According to different arc extinguishing medium or mode, load switches are mainly divided into gas production type, pressure type, vacuum type and SF_6 type. The four kinds of load switches have different structures and different performance. In this paper, the pneumatic load switch with strong arc extinguishing performance is selected, which has an obvious disconnect point. Its working principle is to compress the gas in the arc extinguishing chamber through the relative motion between the piston and the cylinder in the gas chamber when the contacts are separated, so that the pressure of the gas increases gradually. The gas is blown out by the arc in the process of gas flow in the nozzle. The performance of breaking small current is good, and the arc extinguishing effect is stable. In this paper, the pneumatic load switch structure with strong arc extinguishing performance is selected as the simulation research object. Pneumatic load switch is composed of moving arc contact, static arc contact, nozzle, pneumatic type, piston and so on. The nozzle material is PTFE.

Figure 1 shows the simulation model of load switch. The arc extinguishing media studied are SF_6 and HFO-1336mzz(E)/CO_2. The inflation pressure is 0.1 and 0.12 MPa, the outlet pressure is set as the aeration pressure of the chamber, and the ambient temperature is 300 K.

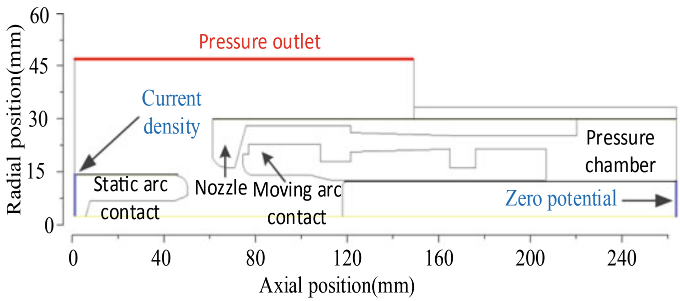


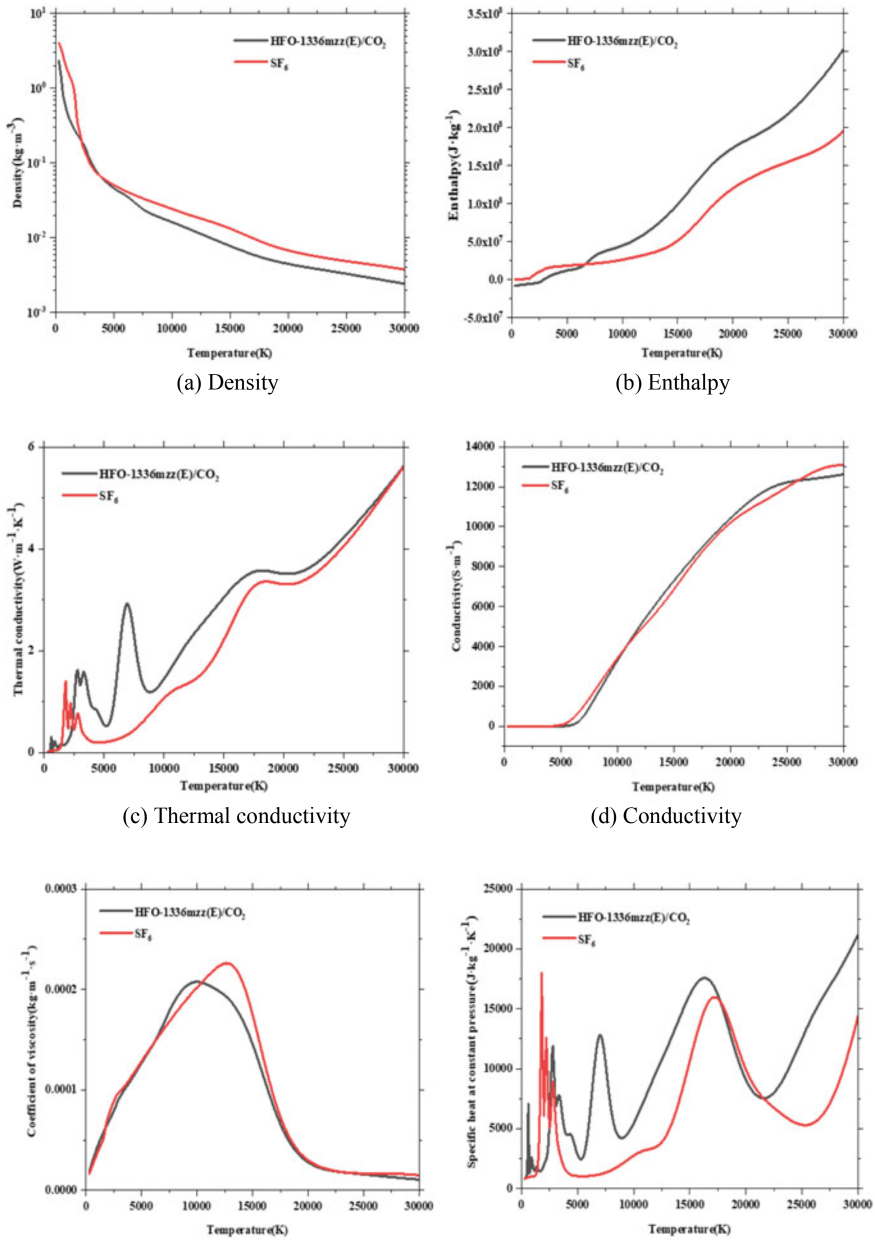
Fig. 1 Simulation model of the load switch

3 Physical Parameter

Physical parameters are the key data reflecting gas properties. Understanding the physical parameters of gas is beneficial to systematically compare the inherent microscopic properties of gas medium, and qualitatively evaluate the arc extinguishing ability of medium from the microscopic point of view. Since the physical parameters of arc plasma at high temperature are difficult to be directly measured by experiments, based on the theory of local thermodynamic equilibrium, the plasma components of SF_6 and HFO-1336mzz(E)/CO_2 in the range of 300–30,000 K are calculated by Gibbs free energy minimization method. Furthermore, the physical properties of arc plasma are calculated, including thermodynamic properties and transport coefficients. The calculated physical parameters, as the basic input parameters of arc magnetohydrodynamic simulation, provide important data support for arc ignition simulation.

Figure 2 shows the comparison of physical parameters between HFO-1336mzz(E)/CO_2 and SF_6 at 0.1 MPa. At temperatures above 5000 K, the density of SF_6 is higher than the mass density of the HFO-1336mzz(E) gas mixture, due to the fact that the mass of S atoms is higher than the mass of C and O. The change of enthalpy with temperature is related to density, and the higher the density, the lower the enthalpy. The thermal conductivity in the arc reflects the ability of the arc to transfer the energy from the arc core area to the edge area and the outside of the arc. Higher thermal conductivity in the arc burning stage can accelerate the energy dissipation rate, which is conducive to the recovery of the strength of the post-arc medium. In general, the thermal conductivity of HFO-1336mzz(E) gas mixture is higher than that of SF_6 in the temperature range of 2500 K to 20,000 K, so it can be considered that HFO-1336mzz(E) gas mixture has better thermal conductivity during arc burning. In the temperature range below 10,000 K, the conductivity of HFO-1336mzz(E) gas mixture is slightly lower than SF_6, but above 10,000 K, the conductivity of HFO-1336mzz(E) gas mixture is higher than SF_6. This indicates that HFO-1336mzz(E) gas mixture has lower electrical conductivity in the post-arc stage. If analyzed only from the perspective of electrical conductivity, HFO-1336mzz(E) gas mixture is more conducive to the establishment of gap insulation strength and less prone to post-arc breakdown than SF_6 in the post-arc stage. The viscosity coefficient of the gas mixture has a peak value with little difference from SF_6, but the peak value corresponds to different temperatures, and the gas mixture peaks at lower temperatures.

Therefore, HFO-1336mzz(E) gas mixture should have a certain degree of arc extinguishing ability, and only from the conductivity, thermal conductivity parameters, HFO-1336mzz(E) gas mixture should have better energy dissipation ability in the recovery stage of post-arc medium. However, the behavior of arc plasma is very complex and difficult to predict. It is not accurate to evaluate the specific arc extinguishing ability of gas mixture only based on the calculated physical parameters. Therefore, it is necessary to further combine the actual switch structure and



(a) Density (b) Enthalpy

(c) Thermal conductivity (d) Conductivity

(e) Coefficient of viscosity (f) Specific heat at constant pressure

Fig. 2 Comparison of physical parameters between SF_6 and HFO-1336mzz(E)/CO_2 mixture the related governing equations in the arc development process to carry out more comprehensive simulation calculation of arc burning.

4 Simulation Result Analysis

Figure 3 shows the arc temperature distribution of SF_6 and mixed gas during arc ignition. When the arc burning reaches 1 ms, the contact spacing gradually expands. At this time, the load current is 523.7 A, and the arc begins to expand. At the same time, it can be observed that the high-temperature gas of the mixed gas arc further expands outward, but the radius of SF_6 arc is not much different. It is worth noting that the highest temperature of mixed gas arc is 13,800 K, lower than the highest temperature of SF_6 gas arc 15,400 K, which indicates that SF_6 gas arc combustion is more intense. When the arc is fired to 4 ms, the current increases to A peak of 890.9 A. At this stage, the energy injected into the arc increases significantly, and the arc will rapidly expand and further extend into the gas region. Although the current increases, the arc temperature remains basically unchanged. When the nozzle and movable contact continue to move, the gas is compressed, so the gas will continue to blow from the pressure chamber towards the arc core. At the same time, it can be seen that the axial diffusion rate of the mixed gas arc is greater than SF_6, indicating that the energy dissipation rate of the mixed gas is stronger. The arc temperature is still SF_6 with a maximum of 16,900 K. When the arc burning reaches 8 ms, the current attenuates to 275.3 A, the input energy of arc decreases, and the arc is in a weakened state of contraction. In addition, the compression effect of the mixed gas arc is more obvious, the high temperature area of the arc is more concentrated near the axis, and the arc becomes thinner and longer. The arc temperature is also lowered. The arc temperature of the mixed gas is only 14,400 K, which is 1400 K lower than SF_6, which is conducive to avoiding arc reignition.

5 Conclusion

This paper studies the arc extinguishing characteristics of HFO-1336mzz(E)/CO_2 as the extinguishing medium in 12 kV load switch, and compares it with SF_6. According to the arc temperature distribution, when the axial diffusion rate of HFO-1336mzz(E)/ CO_2 arc is greater than SF_6 and the current is faster than zero, the arc temperature of HFO-1336mzz(E) /CO_2 arc is 1400 K lower than SF_6, which is conducive to avoiding arc reignition. It can be concluded that HFO-1336mzz(E)/CO_2 can be used as an environmental protection gas arc extinguishing medium in 12 kV load switch.

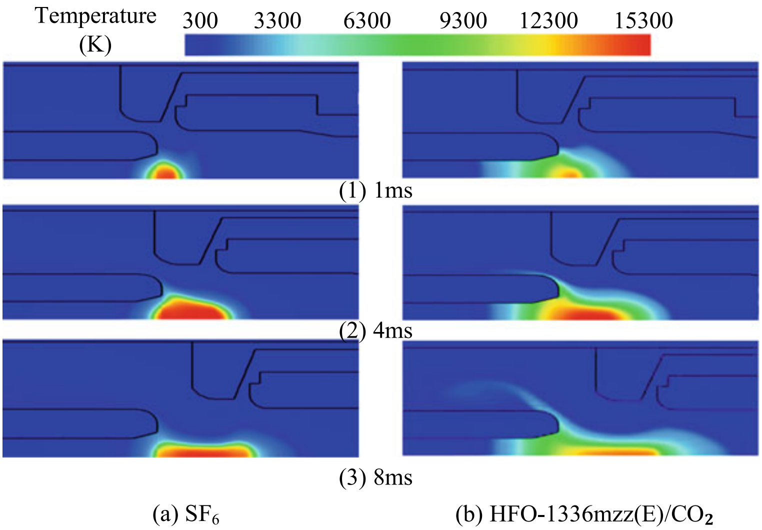


Fig. 3 Distribution of arc temperature during arcing period in SF_6 and HFO-1336mzz(E)/CO_2 mixture

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References

1. Li X, Zhao H (2016) Review of research progress in SF_6 substitute gases. High Voltage Eng 42(6):1695–1701 (in Chinese)
2. Rabie M, Franck CM (2018) Assessment of eco-friendly gases for electrical insulation to replace the most potent industrial greenhouse gas SF_6. Environ Sci Technol 52(2):369–380
3. Zhang B, Wang K et al (2023) Insulation Characteristics of HFO-1336mzz(E) and its mixtures as eco-friendly alternatives to SF_6 for medium-voltage switchgears. IEEE Trans Dielectr Electr Insul 30(2):536–545
4. Zhang B, Yao Y et al (2022) Study of the dielectric breakdown strength of CO_2–O_2 mixtures by considering ion kinetics in a spatial–temporal growth avalanche model. J Appl Phys 132(9):093302
5. Guo Z, Liu S et al (2019) Study of the arc interruption performance of CO_2 gas in high-voltage circuit breakers. IEEE Trans Plasma Sci 47(5):5742–2751
6. Stoa-Aanensen NS, Runde M, Jonsson E (2016) Empirical relationships between air-load break switch parameters and interrupting performance. IEEE Trans Power Delivery 31(1):278–285
7. Wada J, Ueta G, Okabe S (2013) Evaluation of breakdown characteristics of CO_2 gas for non-standard lightning impulse waveforms-breakdown characteristics in the presence of bias voltages under non-uniform electric field. IEEE Trans Dielectr Electr Insul 20(1):112–121
8. Chen L, Widger P, Kamarudin MS et al (2016) CF_3I Gas mixtures: breakdown characteristics and potential for electrical insulation. IEEE Trans Power Delivery 32(2):1089–1097

9. de Urquijo J, Juárez AM, Basurto E et al (2007) Electron impact ionization and attachment, drift velocities and longitudinal diffusion in CF_3I and CF_3I–N_2 mixtures. J Phys D Appl Phys 40:2205–2209
10. Katagiri H, Kasuya H (2008) Investigation of the performance of CF_3I gas as a possible substitute for SF_6. IEEE Trans Dielectr Electr Insul 15(5):1424–1429
11. Zhang B, Xiong J et al (2022) Pulsed Townsend measurement of electron swarm parameters in C_4F_7N-CO_2 and C_4F_7N–N_2 mixtures as eco-friendly insulation gas. J Appl Phys 131(3):033304
12. Hao M, Zhang B et al (2022) Electron swarm parameters and dielectric strength of C_5F_{10O} and its mixtures with CO_2 and dry air. J Phys D: Appl Phys 55(12):125205
13. Hösl A, Pachin J, Eguz E et al (2020) Positive synergy of SF_6 and HFO1234ze(E). IEEE Trans Dielectr Electr Insul 27(1):322–324
14. Nechmi HE, Beroual A, Girodet A et al (2016) Fluoronitriles/CO_2 gas mixture as promising substitute to SF_6 for insulation in high voltage applications. IEEE Trans Dielectr Electr Insul 23(5):2587–2593
15. Xiao S, Han P, Li Y (2021) Insulation performance and electrical field sensitivity properties of HFO-1336mzz(E)/CO_2: a new eco-friendly gas insulating medium. IEEE Trans Dielectr Electr Insul 28(6):1938–1948
16. Katsuyuki T, Junichi I, Konstantinos K (2017) Thermodynamic properties of HFO-1336mzz(E) (trans−1,1,1,4,4,4−hexafluoro−2−butene) at saturation conditions. Int J Refrig 82:283–287