Arc Radiation Characteristics of CO_2–O_2 Mixtures at 0.1–0.8 MPa and 300–30,000 K

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Abstract For high-voltage circuit breakers, it is necessary and urgent to explore SF_6 alternative gases that are environmentally friendly. CO_2 and its mixtures have been widely studied as eco-friendly insulation and arc-quenching media, but how to achieve large-capacity breaking to make it applicable to higher voltage levels is still a pressing issue. Radiation plays a crucial role in the energy dissipation process of the arc, especially under high-current conditions. Therefore, studying the radiation characteristics is beneficial for a better understanding of the breaking capacity of the arc-quenching medium. In this paper, the plasma composition of the CO_2–O_2 mixture at local thermodynamic equilibrium (LTE) is calculated using the minimization of Gibbs free energy. The radiation characteristics of the 70%CO_2–30%O_2 mixture over a pressure range of 0.1–0.8 MPa and a temperature range of 300–30,000 K are evaluated. It is found that increasing the pressure increases the number density of the gas, thus increasing the net emission coefficient. The radiation emitted by the 70%CO_2–30%O_2 mixture in the arc center is strongly absorbed within 1 mm, and the net emission coefficient of 70%CO_2–30%O_2 is higher than that of SF6 at the same pressure.

Keywords High-voltage circuit breakers · CO_2–O_2 mixtures · Arc radiation · Net emission coefficient

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1 Introduction

High-voltage circuit breakers are one of the most important and critical switchgears in the power system, playing a vital role in ensuring the safe, reliable, and stable operation of the transmission and distribution system. SF_6 is widely used as an insulation and arc-quenching medium in high-voltage circuit breakers [1]. However, SF_6 is a potent greenhouse gas and its use is restricted to a certain extent. Therefore, finding an environmentally friendly and high-performance SF_6 substitute gas is an urgent issue. Due to its low greenhouse effect, strong arc-quenching ability, and low cost, CO_2 has a high feasibility for the development and optimization of environmentally friendly high-voltage circuit breakers [2, 3]. In order to increase the voltage level and breaking capacity of circuit breakers and provide a reference for the research and optimization design of environmentally friendly high-voltage circuit breakers, it is necessary to carry out corresponding theoretical and experimental research around CO_2 and its mixed gases [4]. shows that adding a small amount of O_2 to CO_2 can significantly improve its thermal breaking performance, and at the same time eliminate the influence of carbon deposition to a certain extent. Therefore, this paper mainly studies the radiation characteristics of CO_2–O_2 mixed gas.

The arc behavior during current interruption in high-voltage circuit breakers is a complex process involving multiple physical fields. Experiments are costly and time-consuming, but with the improvement of arc models, simulation predictions of arc characteristics have become possible. The temperature of the arc plasma can reach several tens of thousands of degrees, and radiation is a very important way of energy dissipation. When simulating and analyzing arc plasma, the effect of radiation must be considered, and precise radiation coefficients are a prerequisite for reliable arc simulation. However, radiation and absorption processes in arc plasma are very complicated, with a wide range of spectral lines, so solving the radiation transport equation accurately requires a large amount of time and the computational cost is unacceptable.

At present, the calculation methods of plasma radiation characteristics mainly include net emission coefficient (NEC) method, partial characteristic method (MPC), P1 method and discrete ordinated method (DO). The MPC method assumes that in the integral of the radiation transport equation, the temperature change between the radiation source point and any point on the radiation path is always linear, because the local characteristic function used for calculation is related to the temperature and distance between two points, Therefore, it can also effectively consider the self-absorption of central radiation energy by the edge region [5]. The P1 model assumes that the plasma is a gray body, and solves the radiation transport equation into an elliptic equation, which can well deal with the influence of the plasma edge region and the vessel wall on the radiation [6]. However, because it deals with more than one equation, the calculation time is greatly increased. The DO model is based on discretizing the directional variation of radiant intensity, and the problem is solved by solving the radiative transfer equations for a set of discrete directions covering the entire 4π solid angle. Since the DO model can easily handle the incident scattering term, it outperforms other methods in computing scattered radiation problems, and it has better accuracy [7]. The NEC method proposed by Lowke [8] has been widely used as a simplified model for efficient calculation of radiation, which avoids solving the radiative transport equation. This method assumes that the arc is an isothermal and uniform sphere, which represents how much energy the plasma actually radiates outward. Fang et al. [9] compared the application of these three radiation models in circuit breaker arc plasma simulation, and pointed out that in most cases, the NEC method can effectively estimate the radiation characteristics of the central region of arc plasma.

The calculation in this paper is based on the assumption of LTE, the pressure range is 0.1–0.8MPa, and the temperature range is 300–30,000 K. First, the Gibbs free energy is minimized to calculate the plasma composition of 30%CO_2–70%O_2, and the line emission coefficient and continuous emission coefficient are calculated in the full spectrum range of the arc, and then the net emission coefficient of the mixed gas is obtained. Finally, the radiative properties of CO_2–O_2 mixed gas are evaluated. This study provides a basis for a deep understanding of the energy dissipation mechanism and arc extinguishing properties for CO_2–O_2.

2 Calculation Method

2.1 Plasma Composition

Computing the plasma composition is the first step in solving the radiation properties. The calculation of plasma composition in this paper is based on the assumption of local thermodynamic equilibrium (LTE), that is, electrons and heavy particles have the same temperature. Therefore, the composition of the plasma depends only on temperature and pressure. The ion components of the arc plasma need to satisfy the minimum Gibbs free energy, quasi-electric neutrality conditions, stoichiometric equilibrium conditions, and Dalton's law of partial pressure at the same time. This is a typical problem of constrained optimization in applied mathematics. For the convenience of solving, Lagrangian multipliers are usually used to convert the constrained optimization problem into an unconstrained problem, and then the Newton–Raphson iterative method is used to solve it.

Assuming that there are N kinds of particles in the plasma system, the Gibbs free energy can be expressed as [10]:

$$G = \sum_{i=1}^{N} n_i \mu_i \tag{1}$$

where, G is the Gibbs free energy, N is the species number of the particle, n_i is the particle number density.

The minimum Gibbs free energy method to solve the plasma particle composition must obtain the standard Gibbs free energy of each particle. The standard Gibbs free energy of a given particle can be calculated from the fitting coefficients obtained by fitting the thermodynamic parameters by the least square method.

2.2 NEC Method

In the arc plasma, various particles are in excited states or ionized states. At this time, if the energy state of electrons changes, radiation will be generated to the outside. In the high temperature region, radiation is the most important way of energy dissipation of the arc. It can be seen that the radiation will affect the properties of the plasma, so it is necessary to study the radiation characteristics.

The NEC refers to the difference between the radiation energy per unit volume and unit solid angle and the self-absorption energy at a certain position of the isotropic and isothermal plasma, which characterizes the actual outward radiation energy of the plasma. To obtain the NEC, the internal emission and absorption mechanisms of the arc plasma must be understood. Due to the very wide frequency domain range of the arc, an accurate spectral description is necessary [11].

In this work, the atomic line spectrum and continuum spectrum are considered, and the main calculation particles of radiation include: C, O, C^+, O^+, C^{++}, O^{++}, C^{+++}. NEC is obtained by line-by-line calculation.

3 Results and Discussion

3.1 Plasma Composition

Figure 1 shows the composition of 70% CO_2–30% O_2 arc plasma as a function of temperature under different pressures, and the mixing ratio refers to the initial ratio of gas mass fraction. As shown in the figure, around 2500 K CO_2 decomposes to produce CO and O_2. Therefore, the O_2 will increase slightly at this time. Subsequently, O_2 and CO begin to decompose around 4000 K and 4300 K successively, forming O atoms.

and C atoms. When the temperature is higher than 12,000 K, the molecules in the components have basically disappeared, and the plasma is mainly composed of atoms and ions. Since the content of O element in the 70% CO_2–30% O_2 mixture is greater than that of C element, although the ionization potential of C atoms is lower, the proportion of O^+ is higher than that of C^+ at high temperatures. C^{2+} ions appear earlier and have a higher proportion than O^{2+} ions at high temperatures.

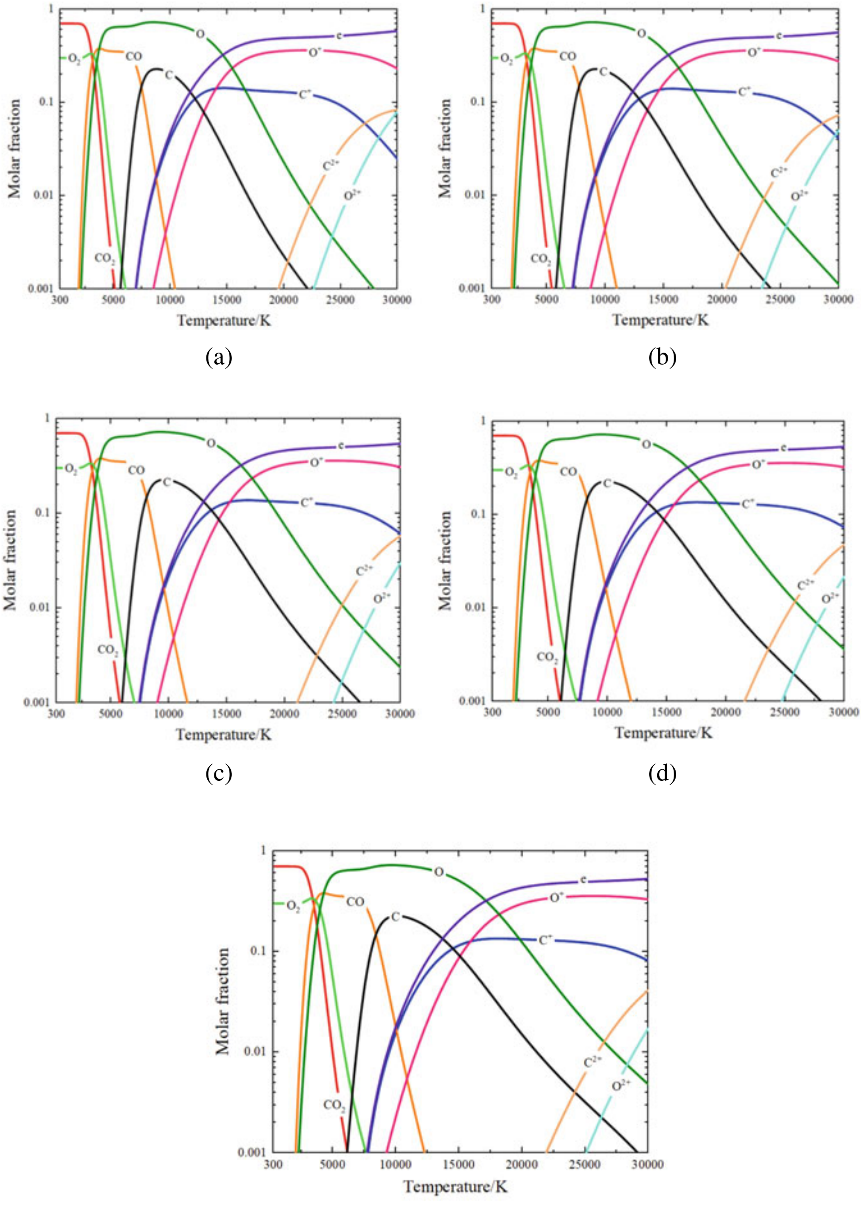

Fig. 1 Composition of 70%CO_2–30%O_2 mixture as a function of temperature. **a** P = 0.1 MPa, **b** P = 0.2 MPa, **c** P = 0.4 MPa, **d** P = 0.6 MPa, **e** P = 0.8 MPa

In this work, we mainly focus on the radiation characteristics of the arc at high temperature, so the plasma composition at high temperature directly affects the calculation results of the NECs. It is evident from Fig. 1 that increasing the pressure leads to an increase in the temperature at which dissociation and ionization occur. Therefore, an increase in pressure also changes the radiation properties, which will be discussed in the next section.

3.2 NEC Results

Figure 2 shows the NEC of 70% CO_2–30% O_2 at different pressures under optically thin conditions. The pressure is higher and the radiation is stronger. The most intuitive explanation is that the increase in pressure leads to an increase in particle number density. The change is more significant at high temperature, at 30,000 K, the NEC of 0.8MPa is an order of magnitude higher than the NEC of 0.1 MPa.

The effect of arc radius on NEC is illustrated in Fig. 3. A radius equal to 0 indicates that the arc is an optically thin plasma, and a radius not equal to 0 indicates that the attenuation of radiation during propagation is considered. The arc shape is considered as a sphere.

The NEC decreases sharply with the increase of the arc radius, which is mainly due to the strong self-absorption of the line spectrum. It can be seen that when R = 1mm, the NEC is only about 10% of that when R = 0mm, which means that most of the emissions from the central area of the arc are absorbed within 1mm. This

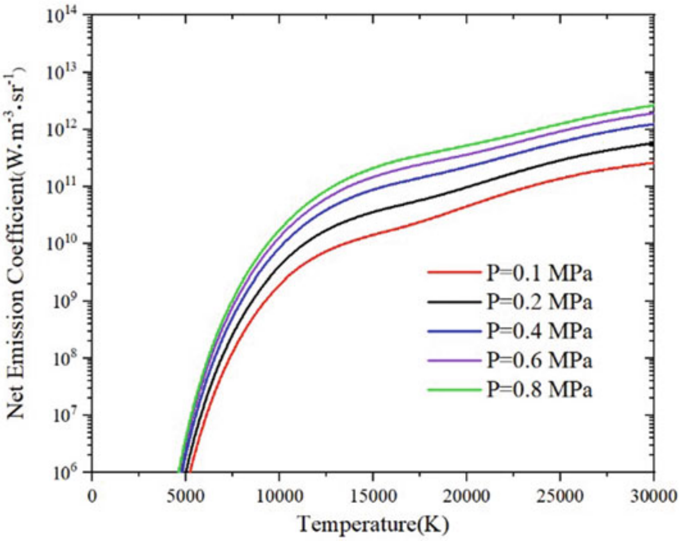

Fig. 2 NEC of 70%CO_2–30%O_2 mixture at different pressures (R = 0 mm)

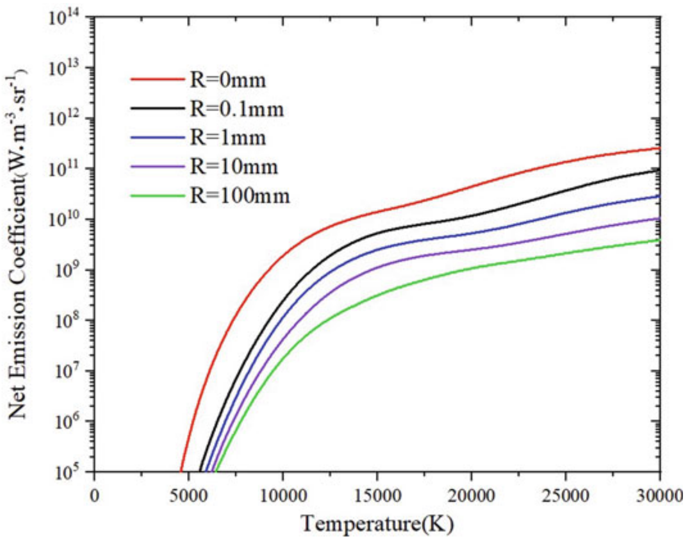

Fig. 3 NEC of 70%CO_2–30%O_2 mixture with different arc radii at 0.1 MPa

is similar to previous research conclusions of other gases. Figure 3 only shows the NEC of 70% CO_2–30%O_2 with different radii at 0.1 MPa. Of course, the degree of self-absorption of NEC coefficients is different at different pressures, but the overall trend is very similar, so results for each pressure are no longer shown.

The purpose of this paper is to evaluate its arc extinguishing ability through the radiation characteristics of 70% CO_2–30%O_2, and analyze the feasibility of using 70% CO_2–30%O_2 as an arc extinguishing medium to replace SF_6. Figure 4 compares the NEC coefficients of 70% CO_2–30%O_2 and pure SF_6, and the NEC of 70% CO_2–30%O_2 mixture holds the lead in the temperature range from 7500 to 30000 K. It can be considered that 70% CO_2–30%O_2 has a stronger radiation emission capability under optically thin conditions. At high temperatures, 70% CO_2–30%O_2 arc energy dissipation will be faster than SF_6, which is beneficial to arc extinguishing.

It is worth noting that radiation is a complex physical process. The NEC method is an excellent method to quickly evaluate the arc radiation in the high temperature area, but it cannot be well evaluated for the arc edge area, so the radiation process in the low temperature area needs more complex methods. In addition, there are many factors affecting the arc extinguishing characteristics, which require a comprehensive and objective evaluation.

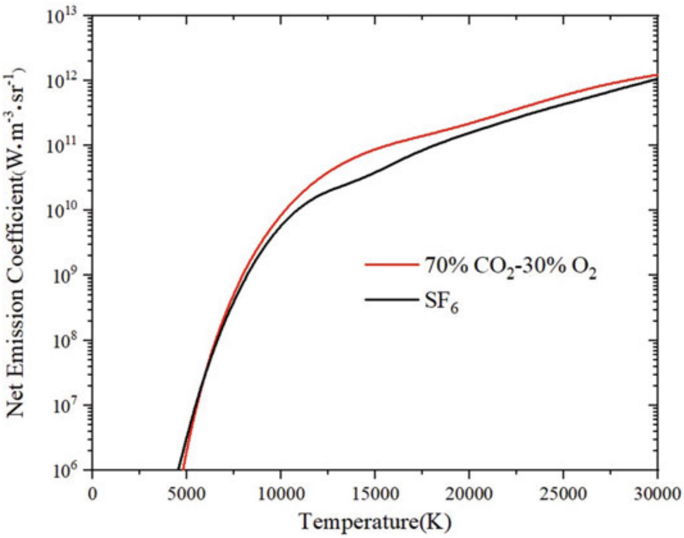

Fig. 4 NEC of 70%CO_2–30%O_2 mixture and SF_6 at 0.4 MPa

4 Conclusion

Based on LTE assumptions, this paper calculates the 0.1–0.8 MPa, 300–30,000 K 70% CO_2–30%O_2 plasma composition and NEC. The increase in pressure increases the number density of the gas, which in turn increases the radiation of the gas. Most of the energy emitted from the high temperature area of the arc center is self-absorbed within 1 mm. Compared with SF_6, 70% CO_2–30%O_2 has stronger radiation emission at 0.4 MPa, which is beneficial for arc quenching. The results of this paper provide a reference for the research on the radiation characteristics and arc extinguishing ability of 70% CO_2–30%O_2 mixture.

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