doi:10.14311/ppt.2019.3.231
Plasma Physics and Technology **6**(3):231–234, 2019

EXPERIMENTAL INVESTIGATION ON THE ARC CHARACTERISTICS AND ARC QUENCHING CAPABILITIES OF $C_5F_{10}O$-CO_2

Z. Guo[a], F. Tang[b], Q. Lv[b], X. Li[a,*], B. Zhang[a], S. Jia[a], R. Huang[b]

[a] *State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, Xi'an, Shaanxi, 710049, China*
[b] *Shenzhen Power Supply Bureau, Shenzhen 518020*
[*] `xwli@mail.xjtu.edu.cn`

Abstract. $C_5F_{10}O$-CO_2 mixtures are possible alternatives to SF_6 - which has a high global warming potential - as the interruption medium in gas circuit breakers. This paper experimentally studies the arcing characteristics of $C_5F_{10}O$-CO_2 mixture, with an experimental model with viewing windows, and measures the arc voltage, current and emission spectrum. The arc evolution process is captured with a high speed camera through an inspection window. The two-dimensional distribution of arc is obtained and analyzed by the inverse transformation of Abel. The results show that, the $C_5F_{10}O$-CO_2 mixture arc is more volatile than SF_6 gas, and adding $C_5F_{10}O$ into CO_2 improves the stability of the arc, and significantly reduces the arc temperature.

Keywords: arc, $C_5F_{10}O$, inverse transformation of Abel, temperature.

1. Introduction

Exploring environmentally friendly gases that can replace SF_6 or partially replace SF_6 is an important research topic in this field due to the strong greenhouse effect of SF_6. Recently, two new fluorinated compounds, perfluoronitriles (PFN) (e.g. C_4F_7N or $(CF_3)_2CFCN$), perfluoroketones (PFK) (e.g. $C_5F_{10}O$ or $CF_3COCF(CF_3)_2$), draws great attentions in leaps and are considered as very promising SF_6 substitutes [1, 2]. In the past few years, the investigations on the dielectric strength (DS) of gas mixtures based on C_4F_7N and $C_5F_{10}O$ are carried out dramatically by various researchers. The results show that a small quantity of these gases mixed with CO_2 or dry air increases the DS of the gas mixture tremendously to be close to the DS of pure SF_6 [3, 4]. The arc interruption capability of these gas mixtures are also investigated through simulations as well as experiments [5].

This paper aims at the arcing characteristic of $C_5F_{10}O$-CO_2 mixtures. Based on a detachable experimental model with observation window, the arcing characteristics in the free-burning arc of $C_5F_{10}O$-CO_2 mixtures were studied experimentally. The emission spectrum along the radial direction of the arc was recorded by a spectrometer. The arc temperature distribution along the radial direction of the arc were obtained by Abel inverse transformation.

2. Experimental set up

The experiments are carried out with a detachable experimental prototype with an observation window, as shown in Fig. 1. The electrodes are made of copper. The electrode diameter is 10 mm and the distance between the electrodes is continuously adjustable. The electrode distance of the experiment is fixed to 10 mm.

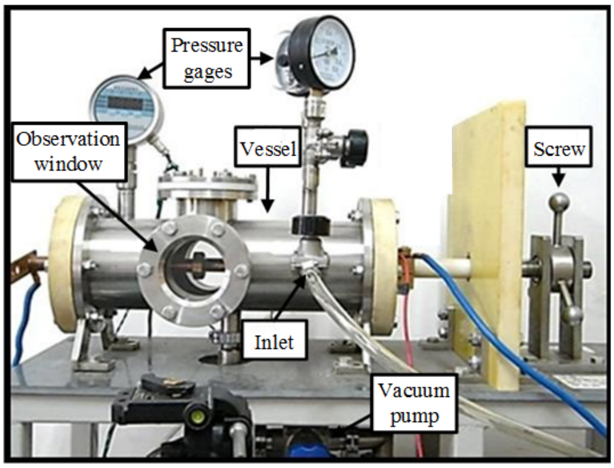


Figure 1. Geometry of the test prototype.

In this experiment, a copper wire with a diameter of 0.1 mm is pre-connected between the electrodes to start the arc. To ensure the stability and reliability of the experiment, the copper wire is connected to the center of the two electrodes and kept as parallel as possible to the axis.

The short-circuit current is provided by a capacitor bank circuit with an oscillating frequency of 50 Hz. The sketch of the test circuit is shown in Fig. 2. The discharge circuit is connected with a thyristor switch. Since the thyristor switch only allows the forward current, a diode in parallel with the thyristor switch is adopted to obtain a cycle of current. A DG535 signal generator is used to control the thyristor switch and the operating mechanism of the GCB model in order to inject the current and trigger the spectrometer. The arc voltage and current were measured using a high voltage probe (P6015A, Tektronix) and a Rogowski

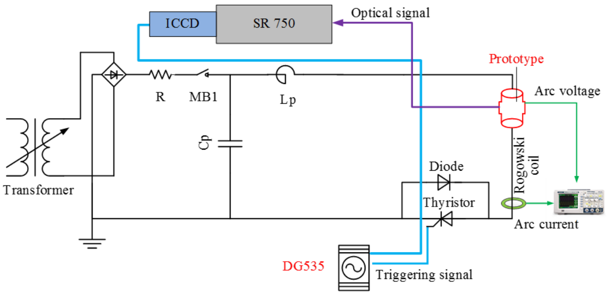


Figure 2. Sketch of the test circuit.

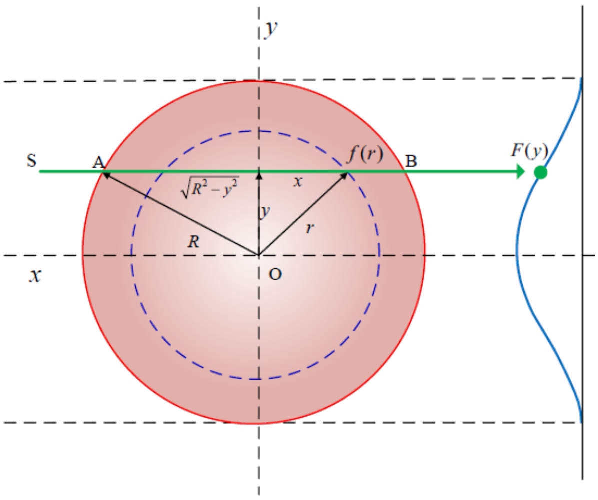


Figure 3. Schematic diagram of Abel inverse transformation.

coil respectively. The measurement data was recorded using a digital oscilloscope. The spectral information of the arc plasma was measured using a spectrometer (SR750, Andor) and an ICCD (iStar DH734, Andor).

In this paper, the arc temperature was evaluated by the Boltzmann slope method. Three lines of Cu I 521.8 nm, Cu I 515.32 nm and Cu I 510.55 nm and was used to obtain the copper atom excitation temperature. Assuming that the arc region is an axisymmetric region, in order to obtain the spatial distribution of the arc temperature, the radial temperature distribution of the arc is obtained by inversion of the Abel inverse transform. As shown in Fig. 3, the $f(r)$ represents the profile of the intensity of spectral line; the r represents the radial distance from the arc center; the R represents the radius of the arc.

As can been seen from the picture, the intensity of spectral lines is an integral of the emission coefficient along the measurement direction.

$$f(y) = \int_{-\sqrt{R^2-y^2}}^{\sqrt{R^2-y^2}} f(x)\mathrm{d}x \tag{1}$$

The distribution of emission coefficient is assumed to be symmetrical, then the relation between intensity and emission coefficient can be changed into:

$$f(y) = \int_y^R f(r)\frac{r\mathrm{d}r}{\sqrt{r^2-y^2}} \tag{2}$$

After the Abel inverse:

$$f(y) = -\frac{1}{\pi}\int_r^R f'(r)\frac{\mathrm{d}y}{\sqrt{y^2-r^2}} \tag{3}$$

$f(r)$ is expressed by three cubed spline function from discrete experiment data.

Under the LTE condition, the excitation of the atom obeys the Boltzmann equation. The arc temperature can be calculated by two different spectral line emitted from a same ion, the double-line method, and the formula is shown below.

$$\frac{I_1}{I_2} = \frac{A_1 g_1 \lambda_2}{A_2 g_2 \lambda_1}\exp\left(-\frac{E_1-E_2}{kT}\right) \tag{4}$$

where E represents energy levels; k represents the Boltzmann constant; g represents the statistical weight; A represents the transition probability; λ represents wave length; ε represents the emission coefficient, obtained from the line intensity by means of Abel inversion.

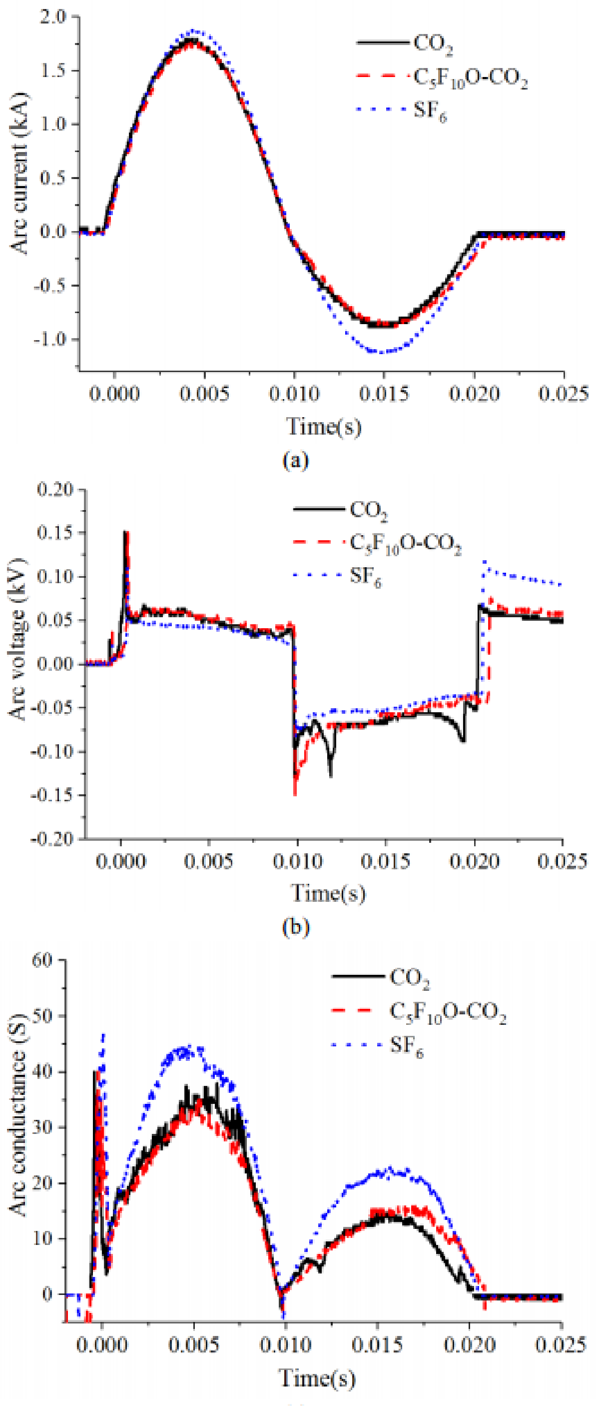
The gas scheme used in this experiment includes: CO_2, 28% $C_5F_{10}O$–72% CO_2 and SF_6 gas. The gas pressure is 0.1 MPa, and the expected short-circuit current is 1.6 kA. Among them, the ratio of 28% $C_5F_{10}O$–72% CO_2 gas mixture corresponds to a gas liquefaction temperature of -5°C at 0.1 MPa.

3. Experimental results

Fig. 4 shows the arc current, arc voltage and arc conductance waveforms of a 28% $C_5F_{10}O$–72% CO_2 mixed gas and CO_2 and SF_6 under free-burning arc situation. It can be seen from the current waveform that the peak current of SF_6 is the highest, and the currents of CO_2 and 28% $C_5F_{10}O$–72% CO_2 gas mixture are close. It can be seen from the voltage waveforms that the arc voltage of the SF_6 gas arcing process is the lowest and most stable, and the stability of CO_2 is the worst. There are many violent fluctuations during the second current half-wave period, while the stability of 28% $C_5F_{10}O$–72% CO_2 gas mixture is better than pure CO_2. Fig. 4(c) shows the arc conductance of several gases under free-burning arc situation. It can be seen that the arc conductance of SF_6 is the highest, while the arc conductance of CO_2 and 28% $C_5F_{10}O$–72% CO_2 mixed gas is relatively close.

Overall, from the arc voltage, current and conductance waveforms of CO_2, SF_6 and 28% $C_5F_{10}O$–72% CO_2 gas mixture, it can be seen that the arc of SF_6 gas is more stable, thus the arc voltage of SF_6 arc changes more gently, and is lower than CO_2 and $C_5F_{10}O$–72% CO_2 gas mixture, which makes the current amplitude of SF_6 arc higher than CO_2 and $C_5F_{10}O$–72% CO_2 gas mixture.

Fig. 5 shows the results of the spectral measurement of a 28% $C_5F_{10}O$–72% CO_2 gas mixture, in which the



(a)

(b)

(c)

Figure 4. Comparison of simulation result with experiment result.

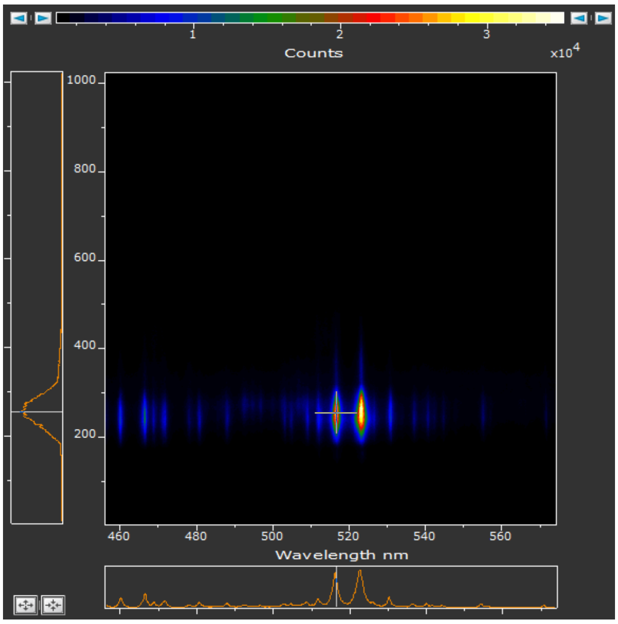


Figure 5. The results of the spectral measurement of 28% $C_5F_{10}O$–72% CO_2 gas mixture.

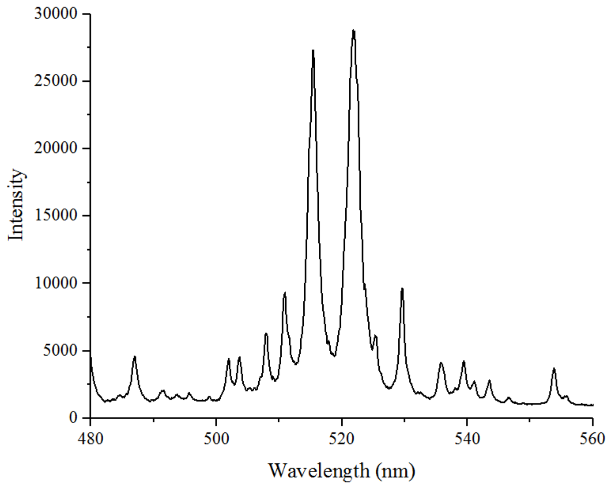


Figure 6. The spectral distribution of the arc center.

horizontal axis corresponds to the wavelength and the vertical axis corresponds to the vertical distribution. Fig. 6 shows the spectral distribution of the arc center. It can be seen that the three lines of Cu I 521.8 nm, Cu I 515.32 nm and Cu I510.55 nm are obvious.

Fig. 7 shows the radial distribution of the arc temperature at the current peak of the first half-wave in the free-burning arc of CO_2, 28% $C_5F_{10}O$–72% CO_2 and SF_6 gas. It can be seen that the temperature of the arc core is between 14000 K and 20000 K. The arc core temperature of the CO_2 gas arc is the highest, about 20000 K. The arc core temperature of 28% $C_5F_{10}O$–72% CO_2 is about 16200 K, while the SF_6 arc core temperature is about 14900 K, which is much lower than the other two gases. In addition, the arc diameter of CO_2 arcis about 13 mm, and the arc is thinner than the other two gases. The SF_6 and 28% $C_5F_{10}O$–72% CO_2 arc diameters are approximately 23 mm and 16 mm, respectively. Therefore, the addition of $C_5F_{10}O$ gas to the CO_2 gas can significantly lower the arc temperature and make the arc diameter larger, which corresponds to the stability of the aforementioned arc voltage.

4. Conclusions

Based on a detachable experimental model with observation window, the free-burning arc characteris-

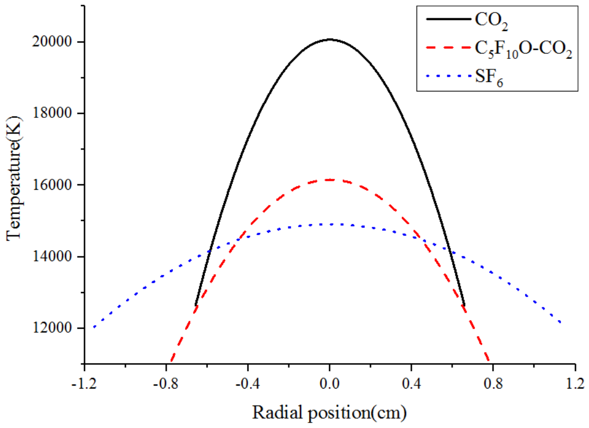


Figure 7. The radial distribution of the arc temperature at the current peak of the first half-wave in the free-burning arc of CO_2, 28% $C_5F_{10}O$–72% CO_2 and SF_6 gas.

tics of 28%$C_5F_{10}O$–72%CO_2 gas mixtuere and CO_2 were studied and compared with that of SF_6. The emission spectrum of the arc was measured. The two-dimensional distribution of arc temperature was obtained by Abel inverse transformation. Compared with the SF_6, the arc voltage fluctuation of CO2 and 28%$C_5F_{10}O$–72%CO_2 mixed gas is more severe and higher, and the current amplitude is smaller. After the addition of $C_5F_{10}O$ to CO_2 gas, the stability of the arc is improved.The addition of $C_5F_{10}O$ gas to the CO_2 gas can significantly reduce the arc core temperature.

References

[1] J. K. Olthoff, R. J. Van Brunt, and L. G. Christophorou. Sulfur hexafluoride and the electric power industry. *IEEE Electr. Insul. Mag.*, 13(5):20–24, 1997. `doi:10.1109/57.620514`.

[2] H. Zhao, A. B. Murphy, and X. Li. SF_6-alternative gases for application in gas-insulated switchgear. *J. Phys. D: Appl. Phys.*, 51(15):153001, 2018. `doi:10.1088/1361-6463/aab314`.

[3] H. Lin, X. Li, and H. Zhao. Dielectric properties of Fluoronitriles/CO_2 and SF_6/N_2 mixtures as a possible SF_6-substitute gas. *IEEE Trans. Dielectr. Electr. Insul.*, 28(4):1332–1339, 2018. `doi:10.1109/tdei.2018.007139`.

[4] C. M. Franck and M. Rabie. Comparison of gases for electrical insulation: Fundamental concepts. *IEEE Trans. Dielectr. Electr. Insul.*, 25(2):649–656, 2018. `doi:10.1109/TDEI.2018.006900`.

[5] P. Stoller, C. Doiron, D. Tehlar, P. Simka, and N. Ranjan. Mixtures of CO_2 and $C_5F_{10}O$ perfluoroketone for high voltage applications. *IEEE Trans. Dielectr. Electr. Insul.*, 24(5):2712–2721, 2017. `doi:10.1109/TDEI.2017.006383`.