J Electr Eng Technol.2018; 13(6): 2545-2552
http://doi.org/10.5370/JEET.2018.13.6.2545

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Research on Liquefaction Characteristics of SF6 Substitute Gases

Zhikang Yuan*, Youping Tu†, Cong Wang*, Sichen Qin* and Geng Chen*

Abstract – SF_6 has been widely used in high voltage power equipment, such as gas insulated switchgear (GIS) and gas insulated transmission line (GIL), because of its excellent insulation and arc extinguishing performance. However, SF_6 faces two environmental problems: greenhouse effect and high liquefaction temperature. Therefore, to find the SF_6 substitute gases has become a research hotspot in recent years. In this paper, the liquefaction characteristics of SF_6 substitute gases were studied. Peng–Robinson equation of state with the van der Waals mixing rule (PR-vdW model) was used to calculate the dew point temperature of the binary gas mixtures, with SF_6, C_3F_8, c-C_4F_8, CF_3I or C_4F_7N as the insulating gas and N_2 or CO_2 as the buffer gas. The sequence of the dew point temperatures of the binary gas mixtures under the same pressure and composition ratio was obtained. $SF_6/N_2 < SF_6/CO_2 < C_3F_8/N_2 < C_3F_8/CO_2 < CF_3I/N_2 < CF_3I/CO_2 <$ c-$C_4F_8/N_2 < C_4F_7N/N_2 <$ c-$C_4F_8/CO_2 < C_4F_7N/CO_2$. SF_6/N_2 gas mixture showed the best temperature adaptability and C_4F_7N/CO_2 gas mixture showed the worst temperature adaptability. Furthermore, the dew point temperatures of the SF_6 substitute gases at different pressures and the upper limits of the insulating gas mole fraction at -30 ℃, -20℃ and -10℃ were obtained. The results would supply sufficient data support for GIS/GIL operators and researchers.

Keywords: SF_6 substitute gases, GIS and GIL, Peng-Robinson equation of state, van der Waals mixing rule, dew point temperature.

1. Introduction

SF_6 has been widely used in high voltage power equipment, such as gas insulated switchgear (GIS) and gas insulated transmission line (GIL), because of its excellent insulation and arc extinguishing performance. However, SF_6 faces two serious environmental problems: greenhouse effect and high liquefaction temperature. As a greenhouse gas, the global warming potential (GWP) of SF_6 is 23900 and the life in the atmosphere is about 3200 years [1-3]. In Kyoto Protocol, SF_6 was identified as one of the six prime contributors to the greenhouse effect. On the other hand, as a heavy gas with large molecular weight, the liquefaction temperature of SF_6 is high. It is easy to liquefy under the conditions of high pressure and low temperature, which is not suitable for use in high and cold regions. Therefore, to find the SF_6 substitute gases has become a research hotspot in recent years [2-6].

To solve the problems above, the use of SF_6 mixed gas is a feasible way. Binary gas mixtures, SF_6/N_2 and SF_6/CO_2, showed better performance in greenhouse effect and liquefaction characteristics, and kept good insulation and arc extinguishing performance [7-10]. In the long run, however, the use of SF_6 mixed gas cannot stop the emission of SF_6 to the environment. To find a gas or gas mixture that could replace SF_6 is a better way. Considering that there is no a single gas that can completely replace SF_6 up to now, most of the research is concentrated on the binary gas mixtures with C_3F_8, c-C_4F_8, CF_3I or C_4F_7N as the insulating gas and N_2 or CO_2 as the buffer gas at present. And the insulation and arc extinguishing performance of the gas mixtures under different pressure have been discussed in a large number of articles [5-6, 11-16]. As the pressure rises, the dew point temperature of the gas mixtures become higher, which means the gas mixtures would condense to form liquid at a higher temperature. The operation temperature of GIS and GIL is from -30 ℃ to 50℃ according to article [17]. The dew point temperature of the gas mixtures should also meet the operating requirements of the high voltage equipment.

At present, there are few studies on the liquefaction characteristics of SF_6 substitute gases. The relationship between the liquefaction temperature of SF_6 and the pressure is shown in article [18-19], but no gas mixture is involved. A method to calculate the dew point temperature of the gas mixture is mentioned in article [16, 20-23]. However, the method only takes the influence of the insulating gas into account, ignoring the effect of the buffer gas. The calculated results show a large error. Another calculation method was mentioned in article [24]. However, no mixing rule was used, which means the gases in the binary system are taken into consideration separately.

In this paper, Peng-Robinson equation of state [25] with the van der Waals [26] mixing rule (PR-vdW model) was

† Corresponding Author: State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, China. (typ@ncepu.edu.cn)
* State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, China.
Received: January 10, 2018; Accepted: March 27, 2018

used to calculate the dew point temperature of the binary gas mixtures, with SF_6, C_3F_8, c-C_4F_8, CF_3I or C_4F_7N as the insulating gas and N_2 or CO_2 as the buffer gas, under the conditions of different pressures and different composition ratios. The results would supply an essential data base for the binary gas mixtures using in GIS and GIL, and promote the application of SF_6 substitute gases.

2. Calculation Model

Peng-Robinson equation of state with the van der Waals mixing rule (PR-vdW model) would be introduced at first in this chapter. Then, the dew point temperature of pure SF_6 would be calculated by this model. The accuracy of the model would be verified by comparing the calculated results with the data supplied by National Institute of Standards and Technology (NIST).

Peng-Robinson equation of state was shown in Eq. (1).

$$p = \frac{RT}{v-b} - \frac{a(T)}{v(v+b)+b(v-b)} \tag{1}$$

In Eq. (1), p represents pressure. R is gas constant, R = 8.314 J · mol^{-1} · K^{-1}. T is temperature, the unit is K. v is mole volume. $a(T)$ is energy parameter and b is covolume parameter. The expressions of $a(T)$ and b were shown in Eq. (2) and (3), respectively.

$$a(T) = 0.457235\frac{R^2T_c^2\alpha(T)}{p_c} \tag{2}$$

$$b = 0.077796\frac{RT_c}{p_c} \tag{3}$$

In Eq. (2), p_c is the critical pressure. T_c is the critical temperature. $\alpha(T)$ was shown in Eq. (4).

$$\alpha(T) = \left(1+(0.3746+1.5423\omega-0.2699\omega^2)(1-T_r^{0.5})\right)^2 \tag{4}$$

$$T_r = \frac{T}{T_c} \tag{5}$$

In Eq. (4), ω is the acentric factor. In this paper, critical parameters and acentric factors of SF_6 and the substitute gases were shown in Table 1. However, the critical parameter and acentric factor of C_4F_7N were under the protection of the contract, so they were not listed in Table 1.

Table 1. Critical parameters and acentric factors of SF_6 and the substitute gases

Gas	T_c/K	p_c/MPa	ω
SF_6	318.72	3.755	0.210
C_3F_8	345.02	2.640	0.317
c-C_4F_8	388.38	2.778	0.355
CF_3I	396.44	3.953	0.180
CO_2	304.13	7.377	0.224
N_2	126.19	3.396	0.037

van der Waals mixing rule was shown in Eq. (6) and (7).

$$a = \sum_i\sum_j x_i x_j a_{ij} \tag{6}$$

$$b = \sum_i x_i b_{ii} \tag{7}$$

In the mixing rule, the interaction between two components follows the rules shown in Eq. (8) and (9).

$$a_{ij} = (1-k_{ij})\sqrt{a_{ii}a_{jj}} \tag{8}$$

$$b_{ij} = \frac{\left(b_{ii}+b_{jj}\right)}{2} \tag{9}$$

In the equations above, i and j represent the components in the binary mixtures. x_i and x_j are the mole fractions of the components. a_{ii} and a_{jj} are the energy parameters of the components. b_{ii} and b_{jj} are the covolume parameters of the components. a_{ii} and b_{ij} are the interaction parameters between the com $a(T) = 0.457235\frac{R^2T_c^2\alpha(T)}{p_c}$ ponents. k_{ij} is the adjustable parameter

The fugacity coefficient of component i (ϕ_i) was shown in Equantion (10).

$$\ln\phi_i = \frac{b_i}{b}(Z-1) - \ln(Z-B) - \frac{A}{2\sqrt{2}B}\left(\frac{2\sum_{j=1}^{m}x_j a_{ij}}{a} - \frac{b_i}{b}\right)\ln\left(\frac{Z+\left(1+\sqrt{2}\right)B}{Z+\left(1-\sqrt{2}\right)B}\right) \tag{10}$$

In Eq. (10), $B = \frac{bp}{RT}$, $A = \frac{ap}{\left(RT\right)^2}$, $Z = \frac{pv}{RT}$.

The fugacity of component i (f_i) was shown in Eq. (11).

$$f_i = x_i p \phi_i \tag{11}$$

When the phases were in equilibrium, the fugacities of the vapor and liquid were consistent, as shown in Eq. (12).

$$f_i^V = f_i^L \tag{12}$$

Which means

$$\alpha_i\phi_i^V = \beta_i\phi_i^L \tag{13}$$

In Eq. (13), α_i represents the mole fraction of component i in the vapor phase. β_i represents the mole fraction of component i in the liquid phase. The mole fraction of

Table 2. Measured and calculated data of SF_6 vapor pressure

P/MPa	T_{NIST}/K	T_{cal}/K	ΔT/K
0.30	229.89	229.77	0.12
0.40	237.34	237.29	0.05
0.50	243.57	243.49	0.08
0.60	248.94	248.82	0.12
0.70	253.62	253.51	0.11
0.80	257.81	257.73	0.08

component i in vapor and liquid phase would be figured out at specified temperature and pressure by solving Eq. (13).

The dew point temperature of pure SF_6 was calculated by PR-vdW model. The calculated results (T_{cal}) were shown in Table 2. In Table 2, the experimental results (T_{NIST}) supplied by National Institute of Standards and Technology were also listed [27]. The absolute deviation between the calculated value and the reference value was calculated according to Eq. (14) and the results were shown in Table 2. It exhibited that all the absolute deviations were less than 0.12.

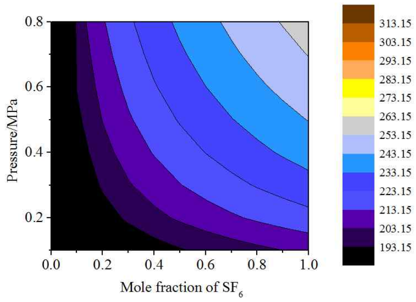
$$\Delta T = \left| T_{NIST} - T_{cal} \right| \quad (14)$$

3. Results

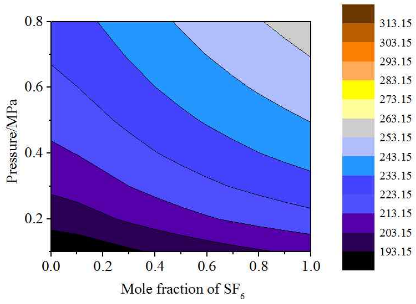
In this chapter, the dew point temperature of the SF_6 substitute gases under the pressure of 0.1~0.8MPa were exhibited.

The dew point temperature of SF_6 binary gas mixtures were calculated and shown in Fig. 1. Fig. 1(a) exhibited the results of SF_6/N_2 and Fig. 1(b) exhibited the results of SF_6/CO_2. The results showed that the dew point temperature increased with the increase of the mole fraction of SF_6 in the gas mixture under certain pressure. On the other hand, when the mole fraction of SF_6 was fixed, the dew point temperature of the gas mixture would increase gradually with the increase of the pressure. The highest dew point temperature of the SF_6 gas mixtures was 257.73K(-15.42℃) when the mole fraction of SF_6 is 1 under 0.8MPa. The lowest dew point temperatures of SF_6/N_2 and SF_6/CO_2 gas mixtures were 77.43K (-195.72℃) and 185.06K (-88.09℃), respectively, when the mole fraction of SF_6 was 0 under 0.1MPa. SF_6/N_2 gas mixture showed lower dew point temperature than SF_6/CO_2 gas mixture under the same pressure and SF_6 mole fraction.

The dew point temperature of C_3F_8 binary gas mixtures were calculated and shown in Fig. 2. Fig. 2(a) exhibited the results of C_3F_8/N_2 and Fig. 2(b) exhibited the results of C_3F_8/CO_2. The results showed that the dew point temperature increased with the increase of the mole fraction of C_3F_8 in the gas mixture under certain pressure. On the other hand, when the mole fraction of C_3F_8 was fixed, the dew point temperature of the gas mixture would increase gradually with the increase of the pressure. The highest dew point temperature of the C_3F_8 gas mixtures was 294.87K (21.72℃) when the mole fraction of C_3F_8 is 1 under 0.8MPa. The lowest dew point temperatures were in accordance with SF_6 gas mixtures. C_3F_8/N_2 gas mixture showed lower dew point temperature than C_3F_8/CO_2 gas mixture under the same pressure and C_3F_8 mole fraction.

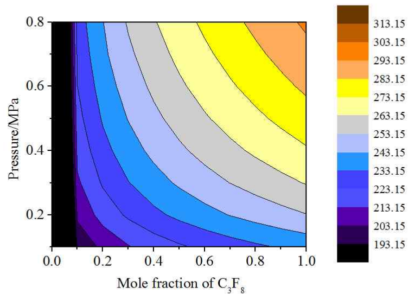


(a) SF_6/N_2

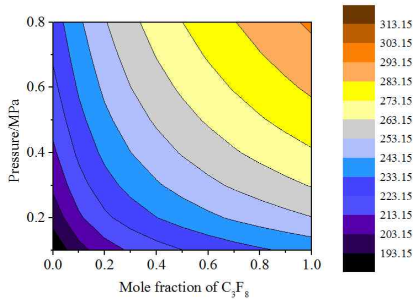


(b) SF_6/CO_2

Fig. 1. Dew point temperature of SF_6 gas mixture

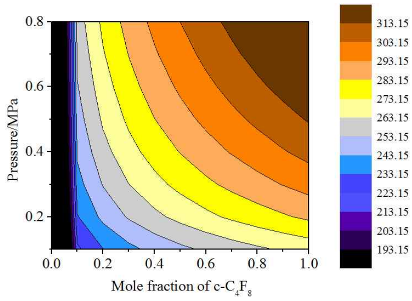


(a) C_3F_8/N_2

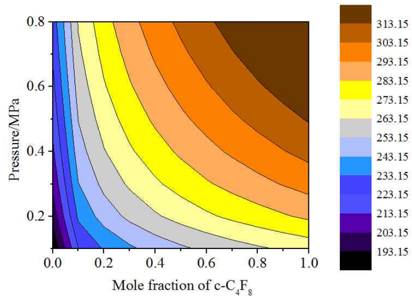


(b) C_3F_8/CO_2

Fig. 2. Dew point temperature of C_3F_8 gas mixture

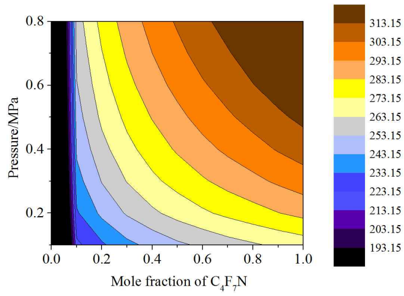


(a) c-C_4F_8/N_2

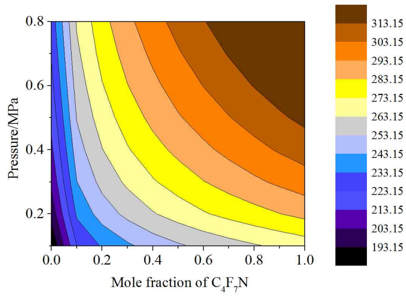


(b) c-C_4F_8/CO_2

Fig. 3. Dew point temperature of c-C_4F_8 gas mixture

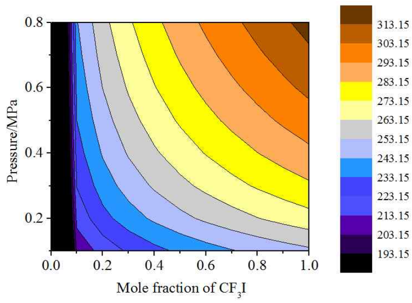


(a) C_4F_7N/N_2

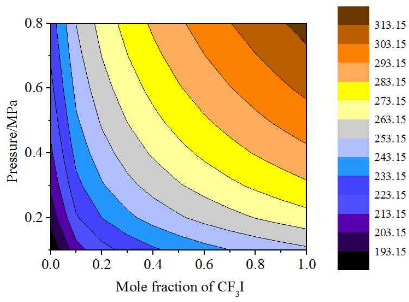


(b) C_4F_7N/CO_2

Fig. 5. Dew point temperature of C_4F_7N gas mixture



(a) CF_3I/N_2



(b) CF_3I/CO_2

Fig. 4. Dew point temperature of CF_3I gas mixture

The dew point temperature of c-C_4F_8 binary gas mixtures were calculated and shown in Fig. 3. Fig. 3(a) exhibited the results of c-C_4F_8/N_2 and Fig. 3(b) exhibited the results of c-C_4F_8/CO_2. The results showed that the dew point temperature increased with the increase of the mole fraction of c-C_4F_8 in the gas mixture under certain pressure. On the other hand, when the mole fraction of c-C_4F_8 was fixed, the dew point temperature of the gas mixture would increase gradually with the increase of the pressure. The highest dew point temperature of the c-C_4F_8 gas mixtures was 331.40K (58.25℃) when the mole fraction of c-C_4F_8 is 1 under 0.8MPa. The lowest dew point temperatures were in accordance with SF_6 gas mixtures. c-C_4F_8/N_2 gas mixture showed lower dew point temperature than c-C_4F_8/CO_2 gas mixture under the same pressure and c-C_4F_8 mole fraction.

The dew point temperature of CF_3I binary gas mixtures were calculated and shown in Fig. 4. Fig. 4(a) exhibited the results of CF_3I/N_2 and Fig. 4(b) exhibited the results of CF_3I/CO_2. The results showed that the dew point temperature increased with the increase of the mole fraction of CF_3I in the gas mixture under certain pressure. On the other hand, when the mole fraction of CF_3I was fixed, the dew point temperature of the gas mixture would increase gradually with the increase of the pressure. The highest dew point temperature of the CF_3I gas mixtures was 316.66K (43.51℃) when the mole fraction of CF_3I is 1 under 0.8MPa. The lowest dew point temperatures were in accordance with SF_6 gas mixtures. CF_3I/N_2 gas mixture showed lower dew point temperature than CF_3I/CO_2 gas mixture under the same pressure and CF_3I mole fraction.

The dew point temperature of C_4F_7N binary gas mixtures were calculated and shown in Fig. 5. Fig. 5(a) exhibited the results of C_4F_7N/N_2 and Fig. 5(b) exhibited the results of C_4F_7N/CO_2. The results showed that the dew point temperature increased with the increase of the mole fraction of C_4F_7N in the gas mixture under certain pressure. On the other hand, when the mole fraction of C_4F_7N was fixed, the dew point temperature of the gas mixture would increase gradually with the increase of the pressure. The highest dew point temperature of the C_4F_7N gas mixtures was 333.39K (60.24℃) when the mole fraction of C_4F_7N is 1 under 0.8MPa. The lowest dew point temperatures were in accordance with SF_6 gas mixtures. C_4F_7N/N_2 gas mixture showed lower dew point temperature than C_4F_7N/CO_2 gas mixture under the same pressure and C_4F_7N mole fraction.

The calculated results of the SF_6 substitute gases showed that the dew point temperature of the gas mixture with N_2 was significantly lower than that with CO_2 under the same pressure and composition ratio, which meant that the gas mixture with N_2 were more difficult to liquefy. Under the same pressure and composition ratio, the sequence of the dew point temperatures of the binary gas mixtures was shown as follows: $SF_6/N_2 < SF_6/CO_2 < C_3F_8/N_2 < C_3F_8/CO_2 < CF_3I/N_2 < CF_3I/CO_2 <$ c-$C_4F_8/N_2 < C_4F_7N/N_2 <$ c-$C_4F_8/CO_2 < C_4F_7N/CO_2$. SF_6/N_2 gas mixture showed the best temperature adaptability and C_4F_7N/CO_2 gas mixture showed the worst temperature adaptability. Furthermore, it was found that the isotherms of the gas mixtures, with C_3F_8, CF_3I, c-C_4F_8 and C_4F_7N as the insulating gas, became more and more dense when the mole fraction of the insulating gas decreased, which meant that the change of the dew point temperature caused by the change of the mole fraction of the insulating gas would be more significant.

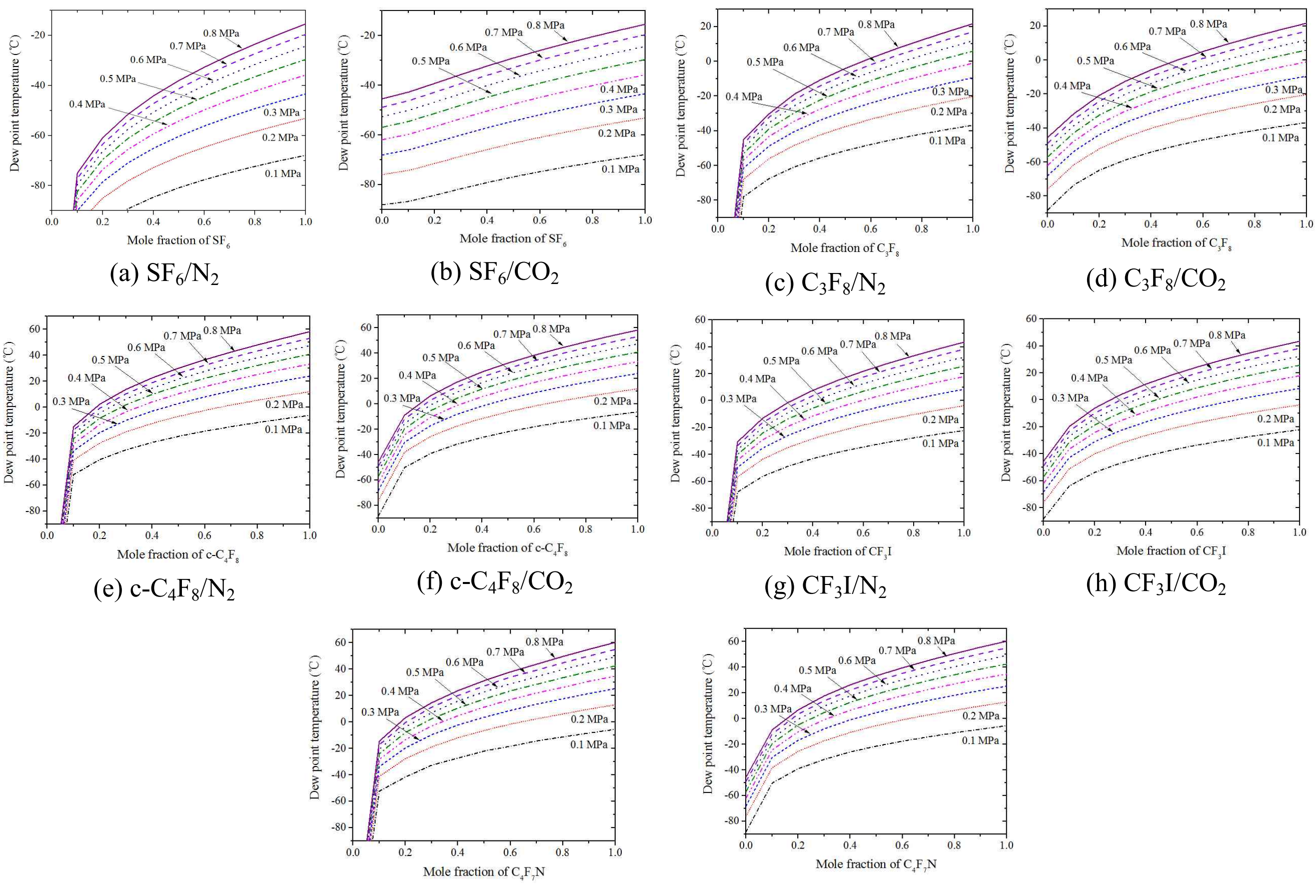
4. Discussion and Application

The dew point temperatures of the SF_6 substitute gases at different pressures were shown in Fig. 6.

On the other hand, the upper limits of the insulating gas mole fraction were shown in Table 3, Table 4 and Table 5, respectively, when the environment temperature was -30℃, -20℃ and -10℃. "--" meant the gas mixture would not liquefy under the condition no matter what the mole fraction of the insulating gas was. If the mole fraction of the insulating gas was higher than the advised value in the table, the gas mixture might liquefy and lead to insulation failure in GIS/GIL. The data supplied above would provide sufficient data support for GIS/GIL operators and researchers.

5. Conclusion

In this paper, the liquefaction characteristics of SF_6 substitute gases were studied, and the following



(a) SF_6/N_2 (b) SF_6/CO_2 (c) C_3F_8/N_2 (d) C_3F_8/CO_2 (e) c-C_4F_8/N_2 (f) c-C_4F_8/CO_2 (g) CF_3I/N_2 (h) CF_3I/CO_2 (i) C_4F_7N/N_2 (j) C_4F_7N/CO_2

Fig. 6. Dew point temperatures of the SF_6 substitute gases at different pressures

Table 3. The upper limit of insulating gas mole fraction in the gas mixture at -30℃

Insulating gas	Buffer gas	Pressure (MPa)							
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80
SF_6	N_2	--	--	--	--	0.990	0.844	0.738	0.657
	CO_2	--	--	--	--	0.984	0.760	0.595	0.469
C_3F_8	N_2	--	0.691	0.473	0.364	0.295	0.254	0.221	0.202
	CO_2	--	0.662	0.424	0.302	0.231	0.181	0.146	0.115
c-C_4F_8	N_2	0.349	0.181	0.125	0.099	0.096	0.094	0.092	0.090
	CO_2	0.334	0.166	0.102	0.085	0.072	0.061	0.051	0.042
CF_3I	N_2	0.725	0.373	0.255	0.194	0.163	0.139	0.119	0.103
	CO_2	0.709	0.338	0.212	0.153	0.111	0.088	0.073	0.060
C_4F_7N	N_2	0.350	0.183	0.127	0.099	0.096	0.094	0.092	0.090
	CO_2	0.331	0.165	0.101	0.085	0.072	0.061	0.051	0.042

Table 4. The upper limit of insulating gas mole fraction in the gas mixture at -20℃

Insulating gas	Buffer gas	Pressure (MPa)							
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80
SF_6	N_2	--	--	--	--	--	--	0.990	0.885
	CO_2	--	--	--	--	--	--	0.985	0.817
C_3F_8	N_2	--	--	0.696	0.536	0.438	0.373	0.325	0.290
	CO_2	--	--	0.663	0.484	0.376	0.301	0.251	0.208
c-C_4F_8	N_2	0.561	0.288	0.196	0.156	0.126	0.104	0.098	0.097
	CO_2	0.549	0.271	0.178	0.132	0.099	0.088	0.078	0.070
CF_3I	N_2	--	0.560	0.381	0.291	0.239	0.199	0.178	0.160
	CO_2	--	0.531	0.342	0.248	0.189	0.153	0.123	0.099
C_4F_7N	N_2	0.555	0.287	0.197	0.155	0.125	0.103	0.098	0.097
	CO_2	0.537	0.267	0.176	0.131	0.098	0.088	0.078	0.069

Table 5. The upper limit of insulating gas mole fraction in the gas mixture at -10℃

Insulating gas	Buffer gas	Pressure (MPa)							
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80
SF_6	N_2	--	--	--	--	--	--	--	--
	CO_2	--	--	--	--	--	--	--	--
C_3F_8	N_2	--	--	0.982	0.760	0.622	0.530	0.463	0.411
	CO_2	--	--	0.980	0.727	0.573	0.469	0.393	0.337
c-C_4F_8	N_2	0.863	0.445	0.302	0.234	0.190	0.165	0.145	0.129
	CO_2	0.858	0.426	0.282	0.207	0.168	0.138	0.114	0.097
CF_3I	N_2	--	0.808	0.552	0.422	0.344	0.290	0.255	0.226
	CO_2	--	0.794	0.518	0.380	0.295	0.241	0.198	0.171
C_4F_7N	N_2	0.844	0.435	0.296	0.232	0.187	0.162	0.143	0.126
	CO_2	0.839	0.415	0.277	0.203	0.156	0.137	0.113	0.096

conclusions were obtained.

1. Peng-Robinson equation of state with the van der Waals mixing rule (PR-vdW model) was used to calculate the dew point temperatures of the binary gas mixtures, with SF_6, C_3F_8, c-C_4F_8, CF_3I or C_4F_7N as the insulating gas and N_2 or CO_2 as the buffer gas. The sequence of the dew point temperatures of the binary gas mixtures, under the same pressure and composition ratio, was shown as follows: $SF_6/N_2 < SF_6/CO_2 < C_3F_8/N_2 < C_3F_8/CO_2 < CF_3I/N_2 < CF_3I/CO_2 <$ c-$C_4F_8/N_2 < C_4F_7N/N_2 <$ c-$C_4F_8/CO_2 < C_4F_7N/CO_2$. SF_6/N_2 gas mixture showed the best temperature adaptability and C_4F_7N/CO_2 gas mixture showed the worst temperature adaptability.
2. The dew point temperatures of the SF_6 substitute gases at different pressures and the upper limits of the insulating gas mole fraction at -30℃, -20℃ and -10℃ were obtained. The results would supply sufficient data support for GIS/GIL operators and researchers.

Acknowledgements

The authors are grateful for the financial and technical support of the National Basic Research Program of China (973 Program) (2014CB239502) and the Fundamental Research Funds for the Central Universities (2018MS005).

References

[1] R. Watson, “Common themes for ecologists in global issues,” *Journal of Applied Ecology*, vol. 36, no. 1, pp. 1-10, 1999.

[2] J. Devins, "Replacement gases of SF6," *IEEE Transactions on Electrical Insulation,* vol. 15, no. 2, pp. 81-86, 1980.

[3] L. Christophorou, J. Olthoff, R. Brunt, "Sulfur hexafluoride and the electric power industry," *IEEE Electrical Insulation Magazine*, vol. 13, no. 5, pp. 20-24, 1997.

[4] N. Malik, A. Qureshi. "A review of electrical breakdown in mixtures of SF6 and other gases," *IEEE Transactions on Electrical Insulation*, vol. 14, no. 1, pp. 1-13, 1979.

[5] D. Xiao, "Development prospect of gas insulation based on environmental protection," *High Voltage Engineering*, vol. 42, no. 4, pp. 1035-1046, 2016.

[6] X. Li, H. Zhao, "Review of research progress in SF_6 substitute gases," *High Voltage Engineering*, vol. 42, no. 6, pp. 1695-1701, 2016.

[7] Y. Qiu, "Dielectric strength of SF_6/N_2 and SF_6/CO_2 gas mixtures," *Journal of Xi'an Jiaotong University*, vol. 19, no. 3, pp. 9-16, 1985.

[8] H. Uhm, Y. Byeon, K. Song, E. Choi, H. Ryu and J. Lee, "Analytical investigation of electrical breakdown properties in a nitrogen-SF6 mixture gas," *Physics of Plasmas*, vol. 17, no. 11, pp. 1291-1298, 2010.

[9] Y. Tu, Z. Yuan, B. Luo, C. Wang, X. Zeng and X. Dong, "Calculation on dew temperatures of binary gas mixtures SF_6/N_2 and SF_6/CO_2 under 0.4~0.8 MPa gas pressures," *High Voltage Engineering*, vol. 36, no. 5, pp. 1446-1450, 2015.

[10] P. Osmokrovic, M. Stojkanovic, K. Stankovic, M. Vujisic and D. Kovacevic, "Synergistic effect of SF_6 and N_2 gas mixtures on the dynamics of electrical breakdown," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 19, no. 2, pp. 677-688, 2012.

[11] B. Wu, D. Xiao, Z. Liu, L. Zhang and X. Liu, "Analysis of insulation characteristics of c-C_4F_8 and N_2 gas mixtures by Monte Carlo method," *Journal of Physics D-Applied Physics*, vol. 39, no. 19, pp. 4204-4207, 2006.

[12] Z. Yuan, Y. Tu, C. Wang, Y. Zhao, X. Dong, "Experimental research on (vapor + liquid) equilibria for the {trifluoroiodomethane (CF_3I) + carbon dioxide (CO_2)} system from 243.150 to 273.150 K," *Journal of Chemical Thermodynamics*, no. 101, pp. 49–53, 2016.

[13] L. Chen, P. Widger, M. Kamarudin, H. Griffiths and A. Haddad, "CF_3I Gas Mixtures: Breakdown Characteristics and Potential for Electrical Insulation," *IEEE Transactions on power delivery*, vol. 32, no. 2, pp. 1089-1097, 2017.

[14] M. Hikita, S. Ohtsuka, S. Okabe and G. Ueta, "Breakdown Mechanism in C_3F_8/CO_2 Gas Mixture under Non-uniform Field on the Basis of Partial Discharge Properties," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 16, no. 5, pp. 1413-1419, 2009.

[15] H. Zhao, X. Li, and H. Lin, "Insulation Characteristics of c-C_4F_8-N_2 and CF_3I-N_2 Mixtures as Possible Substitutes for SF_6," *IEEE Transactions on power delivery*, vol. 32, no. 1, pp. 254-262, 2017.

[16] S. Zhao, D. Xiao, H. Zhang and Y. Deng, "Discharge Characteristics of CF_3I/N_2 Mixtures under Lightning Impulse and Alternating Voltage," *High Voltage Engineering*, vol. 24, no. 5, pp. 2731-2737, 2017.

[17] H. Koch, *Gas-insulated transmission lines(GIL)*, 1st ed., John Wiley & Sons Inc, New Jersey, 2012.

[18] Y. Deng, D. Xiao, J. Chen, "Insulation Performance of CF_3I-N_2 Gas mixtures as alternative for SF_6 in GIS/C-GIS," *High Voltage Engineering*, vol. 39, no. 9, pp. 2288-2293, 2013.

[19] H. Katagiri, H. Kasuya, H. Mizoguchi and S. Yanabu, "Investigation of the performance of CF_3I gas as a possible substitute for SF_6," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 15, no. 5, pp. 1424-1429, 2008.

[20] Y. Deng and D. Xiao, "The effective ionization coefficients and electron drift velocities in gas mixtures of CF_3I with N_2 and CO_2 obtained from Boltzmann equation analysis", *Chinese Physics B*, vol. 22, no. 3, pp. 035101, 2013.

[21] Y. Deng and D. Xiao, "Analysis of the insulation characteristics of CF_3I gas mixtures with Ar, Xe, He, N_2, and CO_2 using Boltzmann equation method," *Japanese Journal of Applied Physics*, vol. 53, no. 9, pp. 3253-3259, 2014.

[22] W. Xing. "Basic study on c-C_4F_8/N_2 Gas mixtures substituting using For SF_6 in electrical apparatus," PhD diss., Chinese Academy of Sciences, pp. 27-28, 2011.

[23] L. Zhang, "Study on insulation characteristics of c-C_4F_8 and its gas mixtures substituting SF_6," PhD diss., Shanghai Jiao Tong University, pp. 77-79, 2007.

[24] H. Zhao, X. Li and H. Lin, "Insulation Characteristics of c-C_4F_8-N_2 and CF_3I-N_2 Mixtures as Possible Substitutes for SF_6," *IEEE transaction on power delivery*, vol. 32, no. 1, pp. 254-262, 2017.

[25] D. Peng, D. Robinson, "A new two-constant equation of state," *Industrial and Engineering Chemistry Research Fundamentals*, vol. 15, no. 1, pp. 59-64, 1976.

[26] T. Kwak and G. Mansoori, "Van der waals mixing rules for cubic equations of state. Applications for supercritical fluid extraction modelling," *Chemical Engineering Science*, vol. 41, no. 5, pp. 1303-1309, 1986.

[27] E. Lemmon, M. Huber, M. Mclinden, Reference Fluid Thermodynamic and Transport Properties (REFPROP), NIST Standard Reference Database 2.3, version 9.0. Thermophysical Properties Division, National Institute of Standards and Technology: Boulder, USA, 2010.

Zhikang Yuan He was born in Quzhou, Zhejiang Province, China, in 1992. He received the B.Sc. degree in electrical engineering from North China Electric Power University, Beijing, in 2014. Currently, he is a Ph.D. candidate in electrical engineering at North China Electric Power University. His research interests include electrical insulation materials and high voltage engineering.

Youping Tu She was born in Ningbo, Zhejiang, China, in 1966. She received her B.Sc. and M.Sc. degrees from the Department of Electrical Engineering, Chongqing University in Chongqing, China, respectively in 1988, and in 1991. Currently, she is a professor in the Department of Electrical Engineering at North China Electric Power University in Beijing, China. From 1991 to 1994, she worked in the computer application field in Hangzhou Heat Power Plant, Zhejiang Province, China. During 1994, she was a research assistant in the Department of Precision Instrument and Mechanics, Tsinghua University in Beijing, China. From 1994 to 1995, she worked in Ludao Company in Beijing, China. She was a lecturer from 1995 to 2003, and an associate professor from 2004 to 2010 in the Department of Electrical Engineering at North China Electric Power University in Beijing, China. Her research interest includes insulation technology, overvoltage and protection for power system. She is the author of more than 100 technical papers.

Cong Wang He was born in Ganzhou, Jiangxi Province, China, in 1980. He obtained his B.Sc. and M.Sc. degrees from the Department of Electrical Engineering, North China Electric Power University in Beijing, China, respectively in 2002, and in 2012. Currently, he is a senior engineer in the Department of Electrical Engineering, North China Electric Power University in Beijing, China. His research interests include properties of the dielectric material, gas discharge and online monitoring of electrical equipment.

Sichen Qin He was born in Xi'an, Shaanxi Province, China, in 1993. He received the B.S. degree in electrical engineering and automation from North China Electric Power University in 2015. Now he is working for Ph.D. in High voltage and insulation technology in North China Electric Power University, Beijing, China.

Geng Chen He was born in Baoding, Hebei Province, China, in 1990. He received the B.Sc. degree in agricultural electrification and automation from Agriculture University of Hebei, Baoding, China, in 2014. Currently, he is a Ph.D. candidate in North China Electric Power University, Beijing, China. His research interests include dielectric materials, insulation technology and design optimization of GIL.