Modification of DC Flashover Voltage at High Altitude on the Basis of Molecular Gas Dynamics

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Abstract – The effect of altitude on thermal conduction, surface temperature, and thermal radiation of partial arc was investigated on the basis of molecular gas dynamics to facilitate a deep understanding of the pollution surface discharge mechanism. The DC flashover model was consequently modified at high altitude. The validity of the modified DC flashover model proposed in this paper was proven through a comparison with the results of high-altitude simulation experiments and earlier models. Moreover, the modified model was found to be better than the earlier modified models in terms of forecasting the flashover voltage. Findings indicated that both the thermal conduction coefficient and the surface thermodynamics temperature of partial arc had a linear decrease tendency with the altitude increasing from 0 m to 3000 m, both of which dropped by approximately 30% and 3.6%, respectively. Meanwhile, the heat conduction and the heat radiation of partial arc both had a similar linear decrease of approximately 15%. The maximum error of DC pollution flashover voltage between the calculation value according to the modified model and the experimental value was within 6.6%, and the pollution flashover voltage exhibited a parabola downtrend with increasing of pollution.

Keywords: Flashover, High altitude, Molecular gas dynamics, Energy balance model, Radiation

1. Introduction

The distribution of primary energy is reasonably and fully utilized in China because the abundant natural resources in the western region are transported to the eastern region through the UHV transmission lines that are being gradually put into operation. However, the terrain of China in the west is higher than that in the east, and regions in which the altitude exceeds 1000 m account for over 2/3 of the whole land [1]. Owing to the rarefied air, cold climate, and different pollution degrees in high-altitude areas, electric insulation performance lower than that in plain areas. This condition threatens the safe operation of electric power systems.

To conduct an in-depth study on the physical mechanism of the pollution surface discharge and to identify basic measures to solve pollution flashover, M El-A Slama [2] conducted a systematic study on earlier pollution flashover models [3, 4] and found that the characteristic constant depended on the equivalent circuit parameters and the heat characteristics of the discharge channel. The effect of the insulated surface on gas discharge was investigated by Fusheng Guo [5], and the development model of the

streamer at arc head was built. Wenxia Sima [6] proposed a DC radial development model along the pollution surface with consideration of the effect of energy radiation on flashover during arc development. In addition, the force on the arc development along the surface was analyzed, and a force analysis-based calculation model of arc velocity was proposed [7]. However, these studies did not consider the effect of atmospheric parameters on insulator surface discharge characteristics under contamination conditions, and research on how these models can be correctly remains insufficient [8,9]. In particular, a significant difference is observed when the correction coefficient of pollution flashover voltage is determined at high altitudes [10-13].

In this study, the effect of altitude on the thermal conduction, surface temperature, and thermal radiation of a partial arc was investigated on the basis of the arc energy balance model with consideration of radiation and gas molecular dynamics. The modified DC flashover model at high altitude was proposed and compared with other modified models in terms of the expression of thermal conduction and radiation of partial arc. The process of pollution surface discharge at high altitude was comprehensively investigated from a microcosmic perspective, which facilitated a deeper understanding of the physics parameters of surface discharge. This finding also has academic significance and engineering application value for discovering the discharge mechanism under complex conditions and for preventing flashover accidents.

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2. Arc Energy Balance Model Considering Radiation

Once the dry band is formed, most of the applied voltage is applied to it. The discharge at the location in which the electric field is concentrated between the electrode and insulation boundary is enhanced, and several steamers form a large discharge domain. When the charged particle grows to a specific concentration range, the volume force effect of plasma is enhanced, and the charged particles concentrate in the cylinder channel [14]. The high-concentration charged particles can enhance collision and composition in the channel, where a large amount of heat and light are sent, and a bright partial arc is formed. With the development of discharge, the arc is gradually extended forward across the dry band, and flashover is formed at the end. In this study, the Obenaus flat model was adopted, as shown in Fig. 1.

Fig. 1. Flat plate model of the polluted insulator

High-temperature radiation is an important mode of heat transmission. Arc temperature can reach 5000 K to 14000 K from its production to flashover [15]. Thus, the effect of the arc heat radiation is especially important to maintain heat balance. A high-temperature object will radiate energy outward by sending an electromagnetic wave without any medium while the radiation and absorption of the gas is occurring internally, which is irrelevant to the shape [16].

In this work, the partial arc is equal to a resistance that can send out radiation. With the enhanced discharge, the arc heat radiation is gradually enhanced. Based on the conservation of energy law and ignoring the effect of convection, total power is equal to the arc radiation, arc heat transmission, and the surplus pollution layer heat loss powers, which satisfies the energy conservation Eq. (1):

$$UI = F_{\lambda} \varepsilon \delta T_s^4 \cdot 2\pi r x + K \frac{dT_s}{dr} \cdot 2\pi r x + r_c (L - x) I^2 \quad (1)$$

where T_s is the arc surface temperature; r_c is the equivalent resistivity of the residual pollution layer, streamer, and air; x is the arc length; L is the insulating plate length; ε is the grey body factor, $\varepsilon \in (0, 1)$; F_{λ} is the blackbody radiation, which is function of the product of wavelength and arc surface temperature [17]; δ is the Stefan-Boltzmann Constant, $\delta = 5.6705 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$; and K is the arc thermal-conductivity coefficient.

Suppose that the heat conduction loss is caused by the heat production of arc plasma resistance, Eq. (1) can be

expressed as (2):

$$UI = F_{\lambda} \varepsilon \delta T_s^4 \cdot 2\pi r x + \frac{I^2}{\sigma(T_c)} x + r_c (L - x) I^2 \quad (2)$$

where T_c is the arc center temperature, and $\sigma(T_c)$ is the arc conductivity.

During the development process, the arc current and radius meet the empirical Eq. [18] (3):

$$r = \sqrt{\frac{I}{1.45\pi}} \quad (3)$$

Substituting Eq. (3) into the first term on the right in Eq. (2). The term of radiation energy can be expressed as (4):

$$F_{\lambda} \varepsilon \delta T_s^4 \cdot 2\pi r x = C \sqrt{I} x \quad (4)$$

where $c = (4\pi/14500)^{1/2} F_{\lambda} \varepsilon \delta T_s^4$, which is defined as the arc radiation constant to characterize the radiation capacity sent forth to the surrounding and is the function of electromagnetic radiation wavelength, gray body factor, and arc surface temperature.

Substituting the Eq. (4) into Eq. (2), the critical flashover voltage can be obtained:

$$U_c = C^{2/3} L r_c^{1/3} \quad (5)$$

3. Effect of Altitude on the Heat Exchange of Partial Arc

3.1 Effect of altitude on the thermal conduction of partial arc

The contact area of two gases A and B , which are in contact with each other at different temperatures ($T_A < T_B$), is dS , as shown in Fig. 2. The average thermal motion energy of gas molecules of A is lower than that of B from a molecular dynamics perspective. The exchange between parts A and B is caused by thermal motion. Some gas molecules with high kinetic energy are transported from

Fig. 2. Sketch map of heat exchange in gas

B to A , whereas others with low kinetic energy are transported from A to B , such that heat conduction is formed macroscopically.

Suppose that the gas molecule density and the average velocity of A and B are n_A , n_B , v_A , and v_B , respectively, which can be similarly regarded as $n_A v_A = n_B v_B = nv$. The irregular movement of gas molecules is simplified to move parallel to the x , y , and z -axes, and the number of gas molecules transported between A and B at dt in arbitrary volume is obtained by:

$$dN = \frac{1}{6} n v dS dt \quad (6)$$

The energy transferred between A and B at dt can be expressed as:

$$\Delta Q = \frac{a+b+2c}{2} k (T_A - T_B) \quad (7)$$

where a , b , and c are the translation freedom, rotation freedom, and vibration freedom of gas molecules, respectively; and k is the Boltzmann constant.

The constant-volume specific heat of the gas is expressed as follows:

$$c_v = \frac{(a+b+2c)Nk}{2M} \quad (8)$$

where M is the gas quality, and N is the number of molecules.

Substituting Eq. (8) into Eq. (7), we can obtain the energy transferred between A and B for one gas molecule at dt as follows:

$$\Delta Q = c_v m (T_A - T_B) \quad (9)$$

Based on Eqs. (6) and (9), the total energy transferred between A and B at dt can be obtained by:

$$dQ = \frac{1}{6} \rho v c_v (T_A - T_B) dS dt \quad (10)$$

where $\rho = nm$ is the gas molecule density, and m is the gas molecule quality.

Hence, the heat energy transported is proportional to the temperature difference, contact area of the two parts of gases, and the transport time [19]. The average velocity of gas molecules with temperature T is:

$$v = \sqrt{\frac{8kT}{\pi m}} \quad (11)$$

Substituting Eq. (11) into Eq. (10) and compare it with the macroscopic thermal conductivity coefficient, we

obtain the thermal conductivity coefficient at low air pressure, which is expressed as follows:

$$\frac{n}{n_0} = \frac{p}{p_0} \times \frac{273+t_0}{273+t} \quad (12)$$

The atmospheric pressure, temperature, and relative air density changed consistently with increments of altitude [20], as shown in Table 1. The normal condition is $t = 20^\circ\text{C}$, $p_0 = 101.3\text{ kPa}$, and the modified method can be referred to GB311.2 83 or IEC60-1 73 under non-standard conditions. Thus, the relationship among relative air density, pressure, and temperature is expressed as follows:

$$\frac{n}{n_0} = \frac{p}{p_0} \times \frac{273+t_0}{273+t} \quad (13)$$

Given that no relationship exists between the temperature and the constant-volume specific heat of ideal gas, the ratio of thermal conduction coefficient at low pressure and atmospheric pressure can be obtained as:

$$\frac{K}{K_0} = \frac{p}{p_0} \cdot \sqrt{\frac{T_0}{T}} \quad (14)$$

According to Eq. (14) and Table 1, the variations of air thermal conduction coefficient with respect to the altitude is obtained as shown in Fig. 3. The thermal conduction coefficient of air obviously exhibited a linear decrease with increments in altitude, and a higher altitude resulted in a larger drop in the heat conduction coefficient. The thermal conduction coefficient dropped by 30% when the altitude increased from 0 m to 3000 m.

Table 1. Variations of air pressure, relative air density, and temperature with the increments of altitude

Altitude (H/m)	0	1000	2000	3000
Air pressure (p/kPa)	101.3	89.7	79.4	70.4
Relative air density	1	0.901	0.812	0.732
Temperature ($T/^\circ\text{C}$)	20	14	8	2

Fig. 3. Relationship between thermal conductivity coefficient and altitude

Fig. 4. Relationship between arc thermal conductivity value and altitude

Supposing that the temperature gradient dT/dr of the arc edge is constant, and considering the thermal conduction formula and the variations of the arc radius with the air pressure [8], the ratio of the arc thermal conduction under low air pressure and under atmospheric pressure at the same current can be expressed as follows:

$$\frac{Q_1}{Q_{10}} = \left(\frac{p}{p_0}\right)^{0.535} \sqrt{\frac{T_0}{T}} \quad (15)$$

The thermal conduction capacity of the arc exhibited a linear decrease with increments in altitude, which agrees with the variations of arc thermal conduction with altitude, as shown in Fig. 4. The thermal conduction value of the arc dropped to approximately 85% of the atmospheric pressure when the altitude rose to 3000 m. This drop indicates that the thermal conduction capacity of the arc was reduced at low pressure, and a small amount of energy from the power supply can maintain the forward movement of the arc.

3.2 Effect of altitude on the partial arc surface temperature

The currents through the arcs under a standard atmosphere and low air pressure are I_0 and I , respectively. For the same pollution and applied voltage, the arc radius and current meet the relationship as follows [8, 21]:

$$r_0 = \sqrt{\frac{I_0}{1.45\pi}} \quad (16)$$

$$r = \left(\frac{p}{p_0}\right)^{-0.465} \sqrt{\frac{I}{1.45\pi}} \quad (17)$$

According to Eqs. (16) and (17), the ratio of the current density at this two kind conditions can be expressed as follows:

$$\frac{j}{j_0} = \left(\frac{p}{p_0}\right)^{0.93} \quad (18)$$

By combining Eq. (18) with the micro expression of the current density in Eq. (19) and supposing that the electrons in the arc having the same velocity, the ratio of the arc current density at low air pressure and atmospheric pressure can be expressed as Eq. (20):

$$j = n_e e v_e \quad (19)$$

$$\frac{j}{j_0} = \frac{n_e}{n_{e0}} \quad (20)$$

Therefore, by comparing Eqs. (18) and (20), the ratio of the arc electron density in the two cases can be expressed as follows:

$$\frac{n_e}{n_{e0}} = \left(\frac{p}{p_0}\right)^{0.93} \quad (21)$$

Given that the collision frequency in the plasma is proportional to the neutral background gas density and that the main collision is electron to neutral particle, the collision frequency between the electron and gas neutral particles can be considered proportional to the neutral gas molecules at room temperature:

$$\gamma_{em} = 6.3 \times 10^{-9} n \quad (22)$$

where γ_{em} is the collision frequency of electron to neutral gas molecules, and n is the neutral gas molecule concentration.

The energy loss of the collision between the electrons and gas molecules per time is ΔE , which is completely converted into the molecule dynamic energy. The energy of the electron can be expressed as follows:

$$\Delta E = E e \lambda_e = \frac{E e k T}{\sqrt{2\pi} d^2 p} \quad (23)$$

where E is the applied electrical field, λ_e is the main free path of electron, and d is the effective diameter of the arc molecule.

Given that most air molecules are binary molecules, the average molecule dynamic energy of air molecule is proportional to the thermodynamic temperature:

$$\Delta E = \frac{7}{2} k \Delta T \quad (24)$$

Given that arc surface temperature is significantly higher than that of the surroundings, the temperature difference between the arc and the surroundings is approximate to arc surface temperature, viz. $\Delta T \approx T_s$. The energy loss of electron per unit and the gas molecule temperature meets the relationship:

$$n_e \gamma_{em} \Delta E = n \frac{7}{2} k T_s \quad (25)$$

Considering Eqs. (23) to (25), we can express the gas molecule thermodynamic temperature on the arc surface caused by electron collision as follows:

$$T_s = \frac{\sqrt{2} n_e \gamma_{em} E e T}{7 \pi d^2 n k} \quad (26)$$

The ratio of gas molecule thermodynamic temperature at low air pressure and the atmospheric pressure caused by electron collision can be expressed as follows:

$$\frac{T_s}{T_{s0}} = \frac{n_e \gamma_{em} n_0 T p_0}{n_{e0} \gamma_{em0} n T_0 p} \quad (27)$$

where T_{s0} , n_{e0} , γ_{em0} , and n are the gas molecule thermodynamic temperature on the arc surface caused by electron collision, the electron density in the arc, the collision frequency of electron with neutral gas molecule, and the neutral gas molecule density, respectively, at temperature T_0 and air pressure p_0 . Moreover, T_s , n_e , γ_{em} , and n are those at temperature T and air pressure p .

Substituting Eqs. (21) and (22) into Eq. (27), we obtain Eq. (28):

$$\frac{T_s}{T_{s0}} = \left(\frac{p}{p_0}\right)^{-0.07} \cdot \frac{T}{T_0} \quad (28)$$

The relationship between the gas molecule thermodynamic temperature on the arc surface caused by electron collision and altitude is shown in Fig. 5, where the gas molecule thermodynamic temperature on the arc surface exhibits a linear decrease with increments of altitude. However, the temperature of the arc surface did not change significantly. When the altitude was 3000 m, the arc surface temperature only dropped by approximately 3.6%.

Fig. 5. Relationship between altitude and arc surface temperature caused by electron collision

3.3 Effect of altitude on the radiation of partial arc

Although the thermodynamic temperature generated by the electron collision on the arc surface dropped about 3.6%, the arc radiation dropped significantly because arc radiation constant is proportional to the biquadratic order of arc temperature. Supposing that the radiation function and grey body factor of arc are constant, the arc thermal radiation satisfies the following equations:

$$\frac{U}{U_0} = \left(\frac{p}{p_0}\right)^m \quad (29)$$

$$\frac{Q_2}{Q_{20}} = \frac{C}{C_0} \quad (30)$$

$$\frac{Q_2}{Q_{20}} = \left(\frac{p}{p_0}\right)^{-0.28} \left(\frac{T}{T_0}\right)^4 \quad (31)$$

According to Eq. (31), the variation of the arc radiation energy with different altitudes is shown in Fig. 6. The thermal radiation capacity of the arc exhibited a linear decrease trend with increments of altitude, which is similar to the trend of thermal conduction capacity. In addition, the thermal radiation of arc dropped for approximately 85% when the altitude was 3000 m.

Fig. 6. Relationship between arc thermal radiation value and altitude

4. Modification of DC Flashover Voltage at High Altitude and Models Comparison

Both the thermal conduction and radiation of the arc exhibited a linear decrease as shown in Figs. 4 and 6, which indicated that a smaller applied power can maintain the arc movement. Hence, the flashover voltage can be reduced at low pressure.

The most important engineering concern is the flashover voltage. Thus, the effect of low pressure on the flashover voltage is investigated in this study. The above research stated that both the thermal conduction and the thermal radiation of the arc exhibited the same linear downtrend with increments of altitude, and the external energy

Fig. 7. Relationship between critical flashover voltages and altitudes with different m values

exchange of arc can be substituted by the variation of thermal radiation. Based on the model proposed in this paper, the critical flashover voltage at low pressure meets the following equation:

$$\frac{U}{U_0} = \left(\frac{p}{p_0}\right)^{-0.28} \cdot \left(\frac{T}{T_0}\right)^4 \quad (32)$$

Early studies [1, 13] show that the DC pollution flashover voltage at low pressure satisfies the following relationship:

$$\frac{U}{U_0} = \left(\frac{p}{p_0}\right)^m \quad (33)$$

where U and U_0 are the DC flashover voltages with altitudes H and zero, respectively; p and p_0 are the air pressure values with altitudes of H and zero, respectively; and m is the air pressure (altitude) influence characteristic exponent.

According to Eqs. (32) and (33), the change relation of negative polarity critical flashover voltage and the altitude with different m value is shown in Fig. 7. The critical flashover voltages obtained from the different models all exhibited linear decrements with increments of altitude. Moreover, the model proposed in this study reflects that the critical flashover voltage is not only associated with pressure, but also with the temperature in the corresponding altitude, which is significant for the deep understanding of the pollution flashover mechanism at low pressures.

5. High Altitude Simulation Experiment

5.1 Specimens

The experiment was conducted with the use of the common toughened glass flat model, and three glass flats with the size of $20\text{ cm} \times 20\text{ cm} \times 1\text{ cm}$. A column-plate electrode was used to be consistent with the electric field

Fig. 8. Schematic diagram of the specimen

structure of the Obenaus model. On the left is a cylindrical copper high voltage electrode with a height and diameter 5 cm, and the distance of the high voltage electrode surface to the left and right ends are both 7.5 cm. On the right is the rectangular grounding electrode with length, width, and height of 2, 20, and 0.2 cm, respectively. A ruler was stuck to the side of the glass plate to observe the distance of the arc development anytime. The upright and bottom views of the sample are shown in Figs. 8 (a) and 8 (b).

5.2 Experiment equipment

5.2.1 Main experiment equipment

The main performance parameters of the regulator were as follows: rated capacity of 100 kVA, input voltage of 380 V, and output voltage of 400 V. The main performance parameters of the transformer were as follows: rated capacity of 200 kVA, rated current of 1 A, and input and output voltages of 0 V to 400 V and 0 kV to 200 kV, respectively. The DC power was supplied by silicon stack rectification. The dynamic voltage fall was lower than 5% when the leakage current was 1 A, and the voltage ripple coefficient was lower than 3% during the flashover, both of which all meet the requirement of DC pollution testing power of IEC 61245 [23]. The main experiment equipment is shown in Fig. 9.

The experiment power source was introduced to the laboratory through a wall bushing, and the applied voltage and leakage current were collected synchronously using a NI USB-6525 data acquisition card. In the acquisition process, the applied voltage was measured using a resistance voltage divider with the attenuation ratio of 1:10000, and the leakage current was realized by measuring the $1\ \Omega$ non-inductance resistor, which is in series between the grounding electrode and the earth. Protection resistances R_1 and R_2 were applied to prevent the current from

(a) Regulator control cabinet

(b) Regulator

(c) Capacitor

(d) Standard DC divider

Fig. 9. Main experiment equipment

becoming too large in the experiment. R1 is 5 k Ω , and R2 is water resistance with conductivity lower than 5 $\mu\text{S}\cdot\text{cm}^{-1}$.

5.2.2 Equipment of high altitude simulation and experiment wiring diagram

The high altitude condition was simulated by controlling the pressure of a sealed container to validate the proposed calculation model of critical flashover voltage at high altitude. The sealed container and steam generator used in the experiment are shown in Fig. 10. The sealed container is made of stainless steel with a height and diameter of 765 and 800 mm, respectively. The humidity can be controlled from 30% to 100%, and the pressure can be controlled from 30 kPa to 101.3 kPa. The power of the sealed

(a) Closed container

(b) Steam generator

Fig. 10. The closed container and steam generator

Fig. 11. Schematic diagram of high altitude experiment circuit

container is 9 kW, and the total spray water volume can be controlled from 0 to 12.9 kg/h. The specimen, sealed container, and experiment wiring diagram are shown in Fig. 11.

5.2.3 Experiment results and analysis

In order to study the statistic condition and the variation of critical flashover voltage, 10 times of flashover experiment have been carried out with different pollution degree and air pressure respectively. The interval of two test is 5 minutes. Take the value of error below 10% with average value as an effective test value, and the final critical flashover voltage is the average value of all the effective test values.

The variations between pollution flashover voltage and altitude with the different pollution degrees were calculated according to the practical condition of engineering, and a simulation experiment was conducted. Figs. 12-14, and 15 are the critical flashover voltage comparisons of calculations and experiments with altitudes of 0, 1000, 2000, and 3000 m, respectively. The critical flashover voltage exhibited a parabola decrease trend with increments of pollution degree, and the calculation value of critical flashover voltage was consistent with that of the experiment, especially when

Fig. 12. Calculated value and experimental value of critical flashover voltage at 0 m

Fig. 13. Calculated value and experimental value of critical flashover voltage at 1000 m

Fig. 14. Calculated value and experimental value of critical flashover voltage at 2000 m

Fig. 15. Calculated value and experimental value of critical flashover voltage at 3000 m

the altitude was at 0 and 3000 m, and the maximum error was only approximately 2.9%. And the maximum error at 1000 and 2000 m, was less than 6.6%.

6. Conclusion

The effect of altitude on the arc thermal conduction, arc surface temperature, arc thermal radiation, and DC flashover

voltage was investigated on the basis of the arc energy balance flat model with consideration of the radiation and the molecular gas dynamics. The main conclusions are as follows:

- (1) The arc thermal conduction coefficient exhibited a linear decrease trend with increments of altitude. The thermal conduction coefficient dropped by approximately 30% when the altitude increased from 0 m to 3000 m, whereas the arc thermal conduction dropped only by approximately 15%.
- (2) Both the arc surface thermodynamics temperature and the arc thermal radiation capability exhibited linear decreases with increments of altitude. The arc surface thermodynamics temperature dropped by approximately 3.6% when the altitude increased from 0 m to 3000 m, whereas the arc thermal radiation dropped by approximately 15%, which is the same as the case of arc thermal conduction.
- (3) The DC flashover voltage is a function of pressure and temperature at high altitude and satisfied the relationship: $U/U_0 = (p/p_0)^{-0.28} (T/T_0)^4$.
- (4) With increments of altitude, the maximum error of DC flashover voltage between the calculation value obtained from the proposed model and the experiment value was less than 6.6%.

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