Process parameters selection of insulator contamination cleaning by dry ice

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Abstract. The dry ice cleaning was applied to the charged cleaning of the insulators in the power distribution room. On the basis of the system parameters optimization experiments of the insulator dry ice cleaning, setting the air pressure to 0.6 MPa and the dry ice flow rate to 2.5 kg/min, the process parameters optimization experiments of the insulator dry ice cleaning were carried out, and the optimal cleaning process parameters of the insulator were obtained through experiments. Using multi-physics simulation software Comsol to analyze the force distribution of external surface of the insulator when spraying dry ice at different distances and different angles in the dry ice cleaning, the experiment results were verified and the following conclusions were obtained: the cleaning angle and cleaning distance of the nozzle are affecting dry ice cleaning effect. The main process factors of the cleaning effect are most effective when the nozzle cleaning angle is from 15° to 25° and the cleaning distance is from 18 cm to 24 cm.

1. Introduction

In the long-term run of insulators and wall bushings in power distribution rooms, a certain degree of pollution accumulation will be formed on the surface, and it is easy to cause pollution flashover in humid climate conditions [1-3]. At present, the commonly used anti-pollution measures in China include: regular manual cleaning, strengthening insulation configuration, adding auxiliary umbrella skirt, adjusting the outer insulation creepage distance, and coating the surface of the insulator with anti-pollution flash organic coating [4]. Among them, cleaning the surface of the insulator is the main anti-pollution measure, which can effectively prevent the insulator from flashing accidents and ensure the safe and stable operation of the power system [5].

Cleaning the external insulation surface of the power system is mainly divided into power-off cleaning and charged cleaning. Power-off cleaning is mainly manual cleaning, and charged cleaning is mainly charged water cleaning, electrochemical cleaning and mechanical cleaning. Dry ice cleaning technology is to make liquid carbon dioxide into dry ice particles and spray them onto the surface of the object to be cleaned by mixing with dry air, using the impact force generated by high-speed movement of dry ice particles, combined with the low temperature characteristics of dry ice itself and the thermal expansion caused by sublimation. The scale, oil stains and residual impurities on the surface to be cleaned are quickly removed, and the objects not damaged [6]. Dry ice cleaning technology is a new type of charged cleaning technology, which has obvious advantages compared...
with other charged cleaning technology [7], and has broad application prospects [8,9].

The factors affecting the cleaning effect of insulator dry ice can be divided into four categories: 1) System factors: including the compressed air supply pressure provided by the air compressor and the dry ice flow rate controlled by the dry ice machine [10]. It is necessary to study the effect of the compressed supply pressure and dry ice flow rate on the cleaning effect and thereby determine the optimal combination of compressed air supply pressure and dry ice flow rate; 2) Process factors: including cleaning angle and cleaning distance, it is necessary to study the influence of cleaning angle and cleaning distance on the cleaning effect and thus determine the optimal combination of cleaning distance and cleaning angle; 3) Object factors: including the pollution level of the insulator surface and the degree of pollution adhesion, it is necessary to study the influence of the pollution level and the pollution adhesion on the cleaning effect; 4) Time factors: the effect of the length of dry ice cleaning time.

In the system parameter optimization experiments of the insulator dry ice cleaning made by our team, by changing the compressed air pressure and dry ice flow rate, the following conclusions are obtained: the cleaning effect is optimal when the compressed air pressure is 0.6 MPa and the dry ice flow rate is 2 to 2.5 kg/min. In the case where the system parameters are determined, the influence of the cleaning angle and the cleaning distance on the cleaning effect is particularly important. In 2016, Gao et al [11] adopted the variable-controlling approach, using ESDD and NSDD of the insulator cleaned by dry ice as the basis for judging the cleaning effect. By changing the compressed air pressure, dry ice snow flow rate, cleaning angle and cleaning time, they studied the influence of these parameters on the cleaning effect. In 2018, Chen et al [12] studied the influence of dry ice flow rate, compressed air pressure, cleaning angle, nozzle speed and contaminant adhesions on the cleaning effect under conditions that the cleaning distance fixed to 15cm and the cleaning time fixed to 30 s through the variable-controlling approach. In the past, the research of process parameters were carried out by using the variable-controlling approach to study their respective effects. In fact, the two process parameters of cleaning angle and cleaning distance interact with each other, so combined parameters experiments should be done to obtain the best process parameters. And these studies lack the internal theoretical analysis and simulation verification. Based on the system parameters optimization experiments of dry ice cleaning, the dry ice cleaning optimization experiments were carried out to study the influence of the cleaning distance and cleaning angle on the dry ice cleaning effect and the best range of cleaning angle and cleaning distance is obtained. Besides, Comsol software was used to study the influence of the injection angle and the injection distance on the surface force distribution of the insulator, using which the optimization experiments were verified.

2. Process factors analysis of insulator dry ice cleaning
In the dry ice cleaning technology, high-speed movement of dry ice produces impact force [13]. The fracture of the insulator fouling layer mainly depends on the impact force of dry ice particles [14]. Changing the process parameters of the insulator dry ice cleaning will affect the impact force of the dry ice particles. The influence of the process parameters of the insulator dry ice cleaning on the impact force is as follows:

- Cleaning angle: define the cleaning angle of the nozzle as the angle between the dry ice nozzle and the horizontal direction. The cleaning angle directly affects the vertical component of the impact force of the dry ice particles on the fouling layer. The larger the vertical impact force component, the stronger the striking force, the better the cleaning effect; the smaller the vertical impact force component, the weaker the striking force, and the worse the cleaning effect.

- Cleaning distance: define the nozzle cleaning distance as the distance between the dry ice nozzle and the surface of the object to be cleaned. The cleaning distance directly affects the kinetic energy and scattering surface size of the dry ice particles against the fouling layer. When the cleaning distance is short, the dry ice particles have small kinetic energy loss and large impact force, but the scattering surface is small and the impact surface is small; when the
cleaning distance is large, the dry ice particles have large kinetic energy loss, and the impact force is small, but the scattering surface is large and the impact surface is large. The dry ice cleaning angle and cleaning distance are shown in figure 1.

![Figure 1](image_url)

(α: Cleaning angle, D: Cleaning distance).

**Figure 1.** Schematic diagram of cleaning angle and cleaning distance.

Considering the influence of the insulator shed, the diameter of the connecting portion between the sheds is smaller than the diameter of the shed, so the cleaning angle cannot be too large, otherwise some parts of the insulator cannot be cleaned. At the same time, combined with the characteristics of dry ice cleaning, when the cleaning distance is too small, the scattering surface will be small and the cleaning efficiency will be low. When the cleaning distance is too large, the dry ice cleaning effect is poor. Taking into account various factors, the cleaning angle range should be 10°–60°, the cleaning distance range should be 10 cm–40 cm.

3. **Dry ice cleaning process parameter optimization experiments**

In order to obtain the optimal process parameters of the cleaning distance and cleaning angle, the dry ice cleaning experiments of the nozzle at different spray angles and different spray distances were designed and carried out [15], and the experiments results were compared and analyzed.

3.1. **Experiment device**

The dry ice cleaning experiment platform consists of a small dry ice washing machine, an air compression system, an electric turntable and lifting system, and a nozzle holder. The small dry ice cleaner can mix compressed air and dry ice and spray it onto the surface of the object to be cleaned; the air compression system provides dry compressed air for the small dry ice cleaner; the electric turntable and lifting system is used to place the insulator to be cleaned so that the insulator can rotate at a constant speed and rise and fall. The rotation speed of the turntable can also be adjusted; the nozzle bracket can adjust the distance and angle of the nozzle with the insulator. In the experiments, the cleaning angle and the cleaning distance are changed mainly by adjusting the nozzle holder.

3.2. **Experiment methods**

In the experiments, the quantitative coating method was used to artificially smear the insulator to simulate natural contamination, and the appropriate dextrin was added to enhance the adhesion of artificial contamination [16]. The effect of dry ice cleaning was evaluated by using the changing rate of ESDD and NSDD before and after washing as a standard. The ESDD changing rate η_E and the NSDD changing rate η_N are defined as follows:

\[
\eta_E = \frac{\rho_{EB} - \rho_{EA}}{\rho_{EB}} \times 100\%
\]

(1)

\[
\eta_N = \frac{\rho_{NB} - \rho_{NA}}{\rho_{NB}} \times 100\%
\]

(2)
In the formula, $\rho_{\text{EB}}$, $\rho_{\text{EA}}$ represent ESDD before and after washing [17], $\rho_{\text{NB}}$, $\rho_{\text{NA}}$ represent NSDD before and after washing [18].

3.3. Experiment results
According to GB/T16434-1996 for the classification of domestic sewage areas, the most serious grade IV pollution grade, its reference ESDD is greater than 0.25~0.35 mg/cm$^2$. In order to characterize the more serious contamination, the test selected the reference ESDD value of 0.4 mg/cm$^2$ to simulate the ESDD in the heavily polluted area. In order to better characterize the cohesiveness of natural contamination, the NSDD is set to 4.0 mg/cm$^2$, and the NSDD is composed of diatomaceous earth and dextrin, and the content is 2.0 mg/cm$^2$. The required sodium chloride, diatomaceous earth and dextrin are calculated for the artificially painted single-layer on insulator surface based on the insulator surface area and the selected ESDD and NSDD values. The weight of sodium chloride, diatomaceous earth and dextrin required for single layer coating of the insulator surface was calculated and weighed.

3.3.1. Influence of single parameter on cleaning effect
- The influence of cleaning angle on cleaning effect

When the cleaning angle experiments carried out, the cleaning angle of the dry ice nozzle is controlled to be 10°~60°, and the cleaning angles are 10°, 20°, 30°, 40°, 50°, 60°, with fixed cleaning distance of 24 cm, cleaning single-layer insulator dry ice dosage of 0.3kg, turntable speed of 15 r/min, air supply pressure of 0.6 MPa, dry ice flow rate of 2.5 kg/min. The cleaning rate of ESDD and NSDD under different cleaning angles is shown in figure 2.

![Figure 2. Cleaning rate curve of $\rho_{\text{ESDD}}$ & $\rho_{\text{NSDD}}$ at different cleaning angle.](image)

- The influence of cleaning distance on cleaning effect

When the cleaning distance experiments carried out, the cleaning distance of the dry ice nozzle is controlled to be 10 cm~35 cm, and the cleaning distances are 10 cm, 15 cm, 20 cm, 25 cm, 30 cm, with the fixed cleaning angle of 20°. The other parameters are the same as the cleaning angle experiments. The cleaning rate of ESDD and NSDD under different cleaning distances is shown in figure 3.

![Figure 3. Cleaning rate curve of $\rho_{\text{ESDD}}$ & $\rho_{\text{NSDD}}$ at different cleaning distance.](image)

3.3.2. Influence of combined parameters on cleaning effect. In the single-parameter experiments, only the cleaning angle and the cleaning distance were considered as the influence factors, and the conclusion that the dry ice cleaning effect decreased with the dry ice cleaning angle or the cleaning distance was obtained. However, in fact, the two process parameters of cleaning angle and cleaning distance affect each other. When the cleaning angle increases and the cleaning distance increases, the vertical impact component of dry ice increases due to the increase of cleaning angle, but the kinetic
energy of dry ice particle decreases due to the increase of cleaning distance so that the impact force reduced. Therefore, in the later experiments, the two parameters of cleaning angle and cleaning distance are cross-combined to obtain more accurate experiment results.

When the cleaning angle and cleaning distance cleaning effect experiments carried out, the cleaning angle of the dry ice nozzle is controlled to be 5°~60°, and the cleaning angles are 5°, 10°, 15°, 20°, 25°, 30°, 40°, 50°, 60°; control cleaning distance varies from 10 cm to 30 cm, and the cleaning distances are 10 cm, 15 cm, 18 cm, 21 cm, 24 cm, 27 cm, 30 cm. The amount of dry ice cleaning each layer is set to 0.3 kg, with turntable rotation speed of 15 r/min, the supply pressure of 0.6 MPa and the dry ice flow of 2.5 kg/min. The influence of different cleaning distances on the cleaning effect under different cleaning angles is tested to get the optimal cleaning angle range and cleaning distance range.

![Figure 4](image1.png)  ![Figure 5](image2.png)

Figure 4. Cleaning rate curve of $\rho_{ESDD}$ at different cleaning angle.

Figure 5. Cleaning rate curve of $\rho_{NSDD}$ at different cleaning angle in combination experiment.

It can be seen from figures 4 to 5 that in the cleaning distance and cleaning angle experiments, the ESDD cleaning rate and the NSDD cleaning rate are positively correlated. When the cleaning distance is between 18 cm and 24 cm and the cleaning angle is between 15° and 25°, the ESDD cleaning rate and the NSDD cleaning rate can reach 80% or more, and the cleaning effect is excellent. When the cleaning distance is 21 cm and the cleaning angle is 20°, the ESDD cleaning rate reaches 93.2%, and the ESDD cleaning rate reaches 89.9%, achieving the best cleaning effect. The comparison of the cleaning effect before and after washing at different cleaning angles is shown in figure 6, with the cleaning distance of 21 cm.
4. Simulation analysis of the force distribution on the surface of insulator

According to the experiment results, three sets of combined parameters are taken, within and beyond the optimal parameter range respectively. The dry ice cleaning insulator simulation model is established under three sets of combined parameters, and then the three groups of models are simulated and analyzed by Comsol software. The force distribution of the insulator surface under three sets of combined parameters was obtained. It is expected to study the cleaning effect under the optimal parameter combination condition and the stress condition of large area and uniform distribution on the insulator surface.

4.1. Simulation process

The simulation process generally includes: building a three-dimensional model and dividing the mesh, selecting a physical field and a calculation model, setting operating conditions and boundary conditions, solving calculations, and analyzing the results.

A three-dimensional model of the jet flow field and insulator was built using Comsol software and meshed. In this paper, three sets of models with combined parameters of injection distance and injection angle (10 cm, 10 degrees), (21 cm, 20 degrees), (30 cm, 30 degrees) are established respectively. Figure 7 below shows the grid model of nozzle and insulator at the injection distance of 10 cm and the injection angle of 0°.

Run Comsol software and set as follows: (1) Model selection: the turbulent flow model is coupled with the particle tracking model. (2) Substance: air and dry ice particles. (3) Operating conditions: the pressure is 0.6 MPa, the dry ice dosage is 2.5 kg/min, the diameter of dry ice particles is 3 mm and the density of dry ice is 1565 kg/m³. (4) Boundary conditions: the nozzle pressure is set to 0.6 MPa; the nozzle, the outer wall of the insulator, and the outer region of the solution are defined as walls. (5) Simulating solution.

4.2. Simulation results

When the injection distance is set to 10 cm and the injection angle is set to 10°, the force distribution on the outer wall of the insulator is as shown in figure 8. It can be seen from the force distribution diagram that the force of the insulator outer wall is large, but the scattering area is small.
Figure 8. Force distribution of insulator outer wall (when the distance is 10 cm, the angle is 10°).

When the injection distance is set to 21 cm and the injection angle is 20°, the force distribution on the outer wall of the insulator is as shown in figure 9. It can be seen from the force distribution diagram that the outer wall force of the insulator is large and the scattering area is relatively large.

Figure 9. Force distribution of insulator outer wall (when the distance is 21 cm, the angle is 20°).

When the injection distance is set to 30 cm and the injection angle is 30°, the force distribution on the outer wall of the insulator is shown in figure 10. It can be seen from the force distribution diagram that the force on the outer wall of the insulator is significantly reduced.

Figure 10. Force distribution of insulator outer wall (when the distance is 30 cm, the angle is 30°).

When the injection distance is set to 30 cm and the injection angle is 30°, the force distribution on the outer wall of the insulator is shown in figure 10. It can be seen from the force distribution diagram that the force on the outer wall of the insulator is significantly reduced.

4.3. Comparison of experiments results with simulation results
Under the conditions of compressed air pressure of 0.6 MPa and dry ice flow rate of 2.5 kg/min, it can be seen from the experiment results that the ESDD cleaning rate and the NSDD cleaning rate can reach 80% or more, and the cleaning effect is excellent, when the cleaning distance is between 18 cm and 24 cm and the cleaning angle is between 15° and 25°.

According to the simulation results of Comsol, when the cleaning distance is less than 18 cm and the cleaning angle is less than 15°, the force of the insulator outer wall is large, but the scattering area is small, which affects the cleaning rate; when the cleaning distance and the cleaning angle are within the optimal range, the force of the insulator outer wall is large, and the scattering area is large too, where the cleaning efficiency is high. When the cleaning distance is greater than 24 cm and the cleaning angle is greater than 25°, the force on the outer wall of the insulator is significantly reduced, affecting the cleaning effect.
5. Conclusions
Dry ice cleaning is a new cleaning method applied to the insulator cleaning. It has the advantages of high cleaning efficiency and no pollution. When the system parameters are fixed, the dry ice cleaning effect is closely related to the cleaning angle and the cleaning distance.

- The cleaning distance experiments are carried out under the conditions of compressed air pressure of 0.6 MPa, dry ice flow rate of 2.5 kg/min, and cleaning angle of 20°. When the cleaning distance is less than 20 cm, the kinetic energy of the dry ice particles reaching the pollution is large, and the impact force on the dirty surface is large. As the distance increases, the cleaning area becomes larger and the cleaning rate increases. After the distance exceeds 20 cm, the cleaning distance is too large, resulting in a large loss of kinetic energy when the dry ice particles reach the contamination, and the impact force on the dirty surface is reduced, and the cleaning rate is lower.

- The cleaning distance experiments are carried out under the conditions of compressed air pressure of 0.6 MPa, dry ice flow rate of 2.5 kg/min, and cleaning distance of 24 cm. When the cleaning angle of the nozzle is less than 20°, the vertical impact component of the dry ice particles acting on the dirty surface is small, and the cleaning rate is low. As the angle increases, the vertical strike component gradually increases, and the cleaning rate gradually increases. However, after the cleaning angle exceeds 20°, the cleaning range is reduced due to the shielding effect of the edge of the insulator shed, and the cleaning rate is remarkably lower.

- Under the conditions of compressed air pressure of 0.6 MPa and dry ice flow rate of 2.5 kg/min, by comparing the experiments results of the combined parameters with the simulation results, it can be concluded that the ESDD cleaning rate and the NSDD cleaning rate can reach 80%, when the cleaning angle ranges from 15° to 25° and the cleaning distance ranges from 18 cm to 24 cm. Above, dry ice cleaning can achieve good cleaning effect. When the cleaning distance is 21 cm and the cleaning angle is 20°, the ESDD cleaning rate reaches 93.2%, and the NSDD cleaning rate reaches 89.9%, achieving the best cleaning effect.

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References
[1] Guan Z C 2006 Insulator and external insulation of power transmission equipment (Beijing, China: Qinghua University Press)
[2] Yu H Y and Xu W C 2005 Analysis of filthy flashover technology and prevention Electric Safety Technology 7 28-30
[3] Yan Z and Zhu D H 2002 High voltage and insulation technology (Beijing, China: China Electric Power Press) 130
[4] Wei Z F 2012 On-line cleaning technology applied to Guangdong power system The World of Cleaning 26 13-6
[5] Lu T C 2009 Hyper-voltage of power systems (Beijing, China: China Water Power Press)
[6] Spur G and Uhlmann E 1999 Dry-ice blasting for cleaning: process, optimization and application International Conference on Erosive and Abrasive Wear ICEAW) 402-11
[7] Nakashima M, Yakabe H and Maruyama Y 1995 Application of semi-automatic robot technology on hot-line maintenance work Proceedings of IEEE International Conference on Robotics and Automation 843-50
[8] Yano K, Maruyama Y and Morita K 1995 Development of the semi-automatic hot-line work robot system “phase-II” ESMO-95Proceedings of IEEE Seventh International Conference on Transmission and Distribution Construction, Operation and Live-line Maintenance 212-8
[9] Guan G Z 2005 High voltage engineering foundation (Beijing, China: China Electric Power
Press)

[10] Fang J, Mo W X, Liang G K et al 2018 Analysis of stress process of dry ice cleaning external insulation surface pollution Guangdong Electric Power 31 113-9

[11] Gao C, Dong W, Xu X Q et al 2016 Characteristics analysis of dry-ice snow cleaning insulators Insulators and Surge Arresters 19 273-5

[12] Chen J W, Mu H, Hu Q and Jiang Z 2018 Investigation on the process of dry ice cleaning insulators Materials Science and Engineering (ACMME) 394 1-8

[13] Liu M, Wang J and Ma X 2011 Cleaning experiment of substation insulators by dry ice High Voltage Technology 1649-55

[14] Zhou W J, Liu M and Liu S N 2012 On the mechanism of insulator cleaning using dry ice IEEE Transactions on Dielectrics and Electrical Insulation 9 1715-22

[15] Yang S C, Lin Y C and Huang K S 2007 Optimization of a pulsed carbon dioxide snow jet for cleaning CMOS image sensors by using the Taguchimethod Sensors and Actuators 139 265-71

[16] Salam M A and Ahmad H 2000 Derivation of creepage distance in terms of ESDD and diameter of the contaminated insulator IEEE Power Engineering Review 44 9-20

[17] Sun C X 2002 Atmospheric environment and electrical insulation outside (Beijing, China: China Electric Press)

[18] Zhang Y J 2006 Study on flashover impact of insulator chain characteristics of SDD and NSDD (Chongqing, China: Chongqing University)