Droplet Distributions and Electric Fields on the Angled Railway Composite Insulator

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ABSTRACT

Composite insulators in railway systems are often installed at inclined angles, supported by cantilevers positioned relative to the railway masts and overhead line configurations. These inclinations significantly influence droplet deposition patterns, self-cleaning performance, and the distortion of electric field distribution. Such distortions can alter the mechanical and electrical properties of the insulators, potentially impacting electrical resistance, discharge activity, and the risk of flashover. This study investigates the electric field distribution of 25 kV composite railway insulators under clean and wet conditions. Experiments included artificial rain sprayed onto insulators at various orientations, captured via imaging, alongside simulations using Finite Element Analysis software. Results revealed that insulator orientation affects water droplet distribution and self-cleaning performance. Horizontal insulators exhibited superior self-cleaning efficiency, with droplets moving downward due to gravity and angle. Inclined insulators displayed acute and obtuse contact angles, with skewed ellipsoid droplets creating non-uniform electric fields and intensities concentrated at droplet edges. In contrast, horizontal insulators maintained more symmetric field distributions. Despite these differences, the maximum electric field intensities occurred near end fittings and remained below the critical value for corona initiation. These findings highlight the importance of insulator orientation in optimizing performance and mitigating risks associated with wet conditions.

Keywords-inclined insulator; water droplets; electric field; self-cleaning performance; railway systems

I. INTRODUCTION

Outdoor insulators are among the important protective components of the overhead line centenary system, performing two main functions. One is a dielectric isolation between high voltage conductors and their supporting structures. Another function is to provide support for any mechanical loads that act on them, especially when the train is passing through [1]. Glass, porcelain, and composite insulators are commonly used in railway applications. As technology has advanced over the past few decades, composite insulators are rapidly increasing in overhead line traction system due to their numerous advantages [2]. These include lightweight characteristics, ease of installation and maintenance, lower cost, hydrophobic characteristics, anti-contamination properties, and good flashover performance [3-5]. The high performance of the insulators, when properly designed, is essential for ensuring the reliability of electrical railway transportation.

In the railway industry, insulators are typically combined with railway masts or gantries for the purpose of insulating cross-arms and enhancing the aesthetic view. The insulators are, therefore, positioned at an inclined angle [6]. These non-standard angles of insulators, neither vertical nor horizontal, can influence the deposition or movement of water droplets, and this may impact the insulator's electrical characteristics. The role of installation angle thus represents a research gap and raises concerns regarding the high-voltage performance of insulators during rainfall events. Considering the design of an insulator that combines the end fitting, core, and shed, it has been demonstrated that the steeper surface of the insulator shed encourages rapid water drainage. This can provide a comparatively high operational resistance to aging issues [7]. It is therefore reasonable that the inclined orientation of the insulator could also increase the possibility of water drainage and enhance self-cleaning performance. In addition, it has been reported that the stresses from the operational voltage levels and polluted, wet environmental conditions are key causes of high electric field strengths, which eventually affect the short- and long-term performance of insulators [8-9].

In the short term, the non-uniform accumulation of droplets on certain parts of the angled insulator, as well as droplet deformation, can distort the electric field distribution [10-11]. This may increase the likelihood of a partial discharge. Several investigations have been conducted to reveal the effect of water droplets on composite insulator performance. Water droplets on the surface of a sheath insulator cause electric field enhancements at the triple point, which is the interfacial point of three dielectric mediums (insulator, liquid, and air) [12-13]. In addition, water droplet deformation or droplet oscillation can influence the local electric field and partial discharge inception [14-15]. In the long term, partial discharges on the surface of an insulator accelerate its transition from hydrophobic to hydrophilic. This results in a change in properties, long-term aging, and compromises the reliability of the electrical system [16-18]. According to [19-21], experimental results show that the breakdown inception voltage of insulators can be reduced in wet and contaminated environments. The effect of insulator orientation on a flashover test in rain conditions is reported in [22], which claims that vertical orientation has the lowest flashover voltage.

Although prior studies have improved our understanding of the electrical behavior of insulators under the influence of water droplets, much of the focus has been on polymeric suspension or long-rod insulators. However, there has been limited attention paid to the behavior of droplets on the inclined surfaces of composite railway insulators. Consequently, there is a critical need to investigate and optimize the inclined configurations of these insulators to ensure enhanced performance, durability, and longevity of high-voltage insulators for railway applications.

This study integrates experimental analysis of droplet distribution on inclined insulators with numerical simulations to assess electric field characteristics, distortions, and intensifications induced by water droplets, including the prediction of corona discharge initiation.

II. RESEARCH METHODOLOGY

A. *Spraying Test*

The test was conducted in a laboratory area of Rajamangala University of Technology Thanyaburi (RMUTT) in a wet condition with no energisation and no power applied. An artificial rain was produced by tank of tap water. Water was pumped and subsequently sprayed onto the insulator samples via the nozzles. The spraying rate was generated in accordance with the IEC 60060-1 standard, ensuring a precipitation rate of 2 to 3 mm/min [23]. A preliminary spraying process was conducted for a minimum of 15 min to ensure uniform coverage of droplets on the insulator. The spray nozzles should be positioned at a higher elevation than the samples, with their direction set at a specific angle, typically around 45°, to effectively simulate rainfall. Two insulator samples have been deployed on the railway mast. One is arranged in a horizontal direction, whereas another is positioned at a 35° angle from the railway cantilever available in the laboratory. During the spraying test, a camera was used to capture images of rain droplets that were deposited on the railway insulator. The experimental test setup is illustrated in Figure 1.

B. *Simulation Work*

1) *Insulator Model*

In this simulation, a 3D model of a railway composite insulator was created using a Finite Element Analysis (FEA) tool. The configuration of the model is outlined in Table I. Two cases were considered: the clean and dry insulator and the wet insulator covered by multiple droplets of varying shapes. The characteristics of the water droplets, specifically their relative permittivity values used in this study, are defined in Table II [24, 25]. Figure 2 illustrates the 3D model of the railway composite insulator and the location where high voltage is applied. The simulation setup is based on a connection of the high voltage to the insulator in the railway electrification system. Therefore, a 25kV phase-to-ground voltage is applied to the high voltage end, whereas the other end is grounded.

TABLE I. CONFIGURATION OF THE RAILWAY INSULATOR

Specification	Value
Rated voltage (kV)	25
Arcing distance (mm)	550
Insulator length (mm)	500
Creepage distance (mm)	1400
Number of sheds	13

TABLE II. THE RELATIVE PERMITTIVITY OF MATERIALS

Material	Relative permittivity
Silicone	4.3
Glass fiber	7.2
Steel/ cast iron	1.0
Water droplets	81.0
Air	1.0

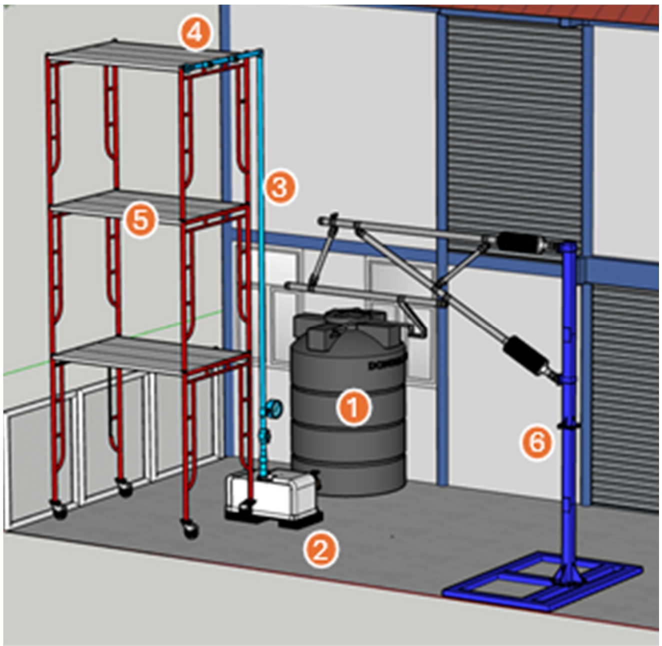


Fig. 1. Wet-condition experimental test setup: (1) water tank, (2) pump, (3) water tube, (4) nozzle ,(5) support structure, and (6) railway insulator and its mast.

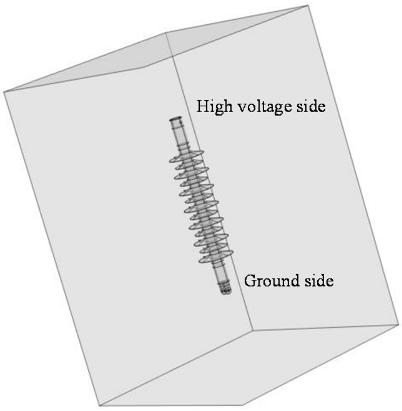


Fig. 2. 3D model of the railway composite insulator.

2) *Equations for Electric Field and Potential*

This study utilizes a FEA to investigate whether the distribution of the electrical field along the inclined insulator is subject to change in the presence of water drops. According to the electrostatic field theory, the electric field distribution can be expressed as:

$$E = -\nabla V \tag{1}$$

where E is the electric field and V is the electric potential.

Using Maxwell's equation, the relationship between charge density and the electric field can be expressed as follows:

$$\nabla \cdot E = \frac{\rho}{\varepsilon} = \frac{\rho}{\varepsilon_0 \varepsilon_r} \tag{2}$$

where ρ is the space charge density, ε is the permittivity of the dielectric material, ε_0 is the free space permittivity, and ε_r is the relative permittivity.

By substituting (1) into (2), the equation can be rewritten as the Poisson's equation:

$$\nabla \cdot (-\nabla V) = \frac{\rho}{\varepsilon} \tag{3}$$

From these equations, the electric potential distribution is calculated using (3). Then, the electric field distribution is obtained by (1).

III. RESULTS AND DISCUSSION

A. *Characteristics of Droplets on Inclined Insulator*

An artificial rain was sprayed onto the 25kV cantilever insulators, as shown in Figure 3. It was observed that the insulator samples are covered with rain droplets after 15 min of spraying.

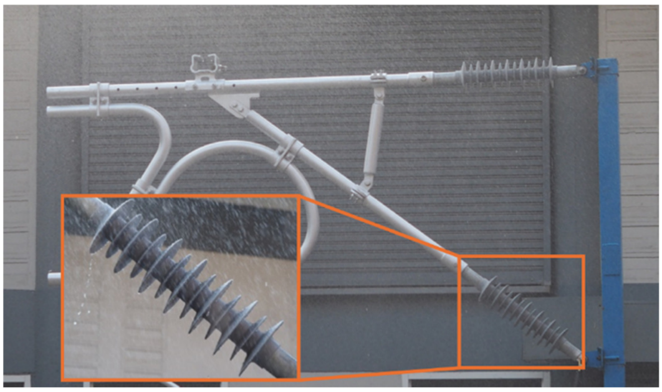


Fig. 3. Insulators under rainfall environment.

Nevertheless, due to the orientations of the insulators, the wet areas may vary significantly based on the arrangement of the insulators on their cantilever. Figure 4 illustrates the presence of wet parts and droplets on horizontal and inclined insulators. A summary of the wet areas is provided in Table III, which aims to demonstrate the impact of rainfall on the deposition of water droplets on the insulators operated at varying angles. As can be seen from this table, the horizontal arrangement is likely to provide the most efficient cleaning, as it applies equivalent rain rates to the insulator surfaces, which allows for uniform rainfall across all components. It was also found that there are numbers of droplets packed in the below area and they are hanged at the rim of shed before falling.

TABLE III. SUMMARY OF WET AREA ON THE DIFFERENT ORIENTATIONS OF INSULATOR

Arrangement	Wet area			
	Upper shed	**Lower shed**	**Core**	**End fitting**
Horizontal	Wet	Wet	Wet	Wet
Inclined	Wet	Partial wet	Partial wet	Wet

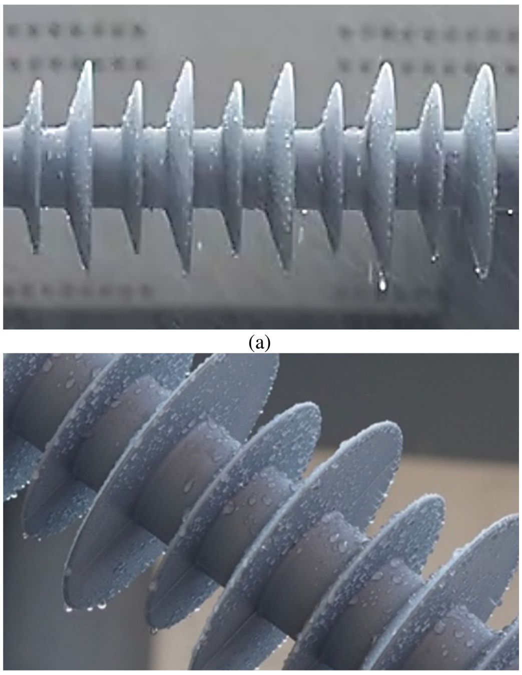


Fig. 4. Rain droplets on railway insulators: (a) horizontal insulator, and (b) inclined insulator.

On the other hand, some areas of the inclined insulator could be obstructed from direct rainfall, such as the lower shed and core area. Rain droplets directly hit the upper shed area of the inclined insulator while the underside of the shed and core are indirectly hit by rain. The deposition and motion of a water droplet on insulator surfaces are determined by both the angle of inclination and the force of gravity. As a result, cleaning performance is non-uniform. Furthermore, it has been observed that the relationship between inclination and the hydrophobic surface of the insulator is crucial. The hydrophobicity of the surface ensures that water rolls off quickly on well-inclined surfaces, thereby preserving the insulating properties of the surface.

Therefore, the distribution of wet areas on the insulator surface is highly influenced by its orientation, as the angle at which it is mounted on the cantilever determines the extent and pattern of raindrop impact. Insulators positioned at different inclinations experience varying levels of exposure to rainfall, leading to non-uniform wetting across their surfaces. This variation in moisture distribution can potentially affect the insulator's self-cleaning performance and overall operational reliability in wet conditions.

A comparative analysis between the present study and previous research reported in [26] reveals a strong alignment in findings. The orientation of composite insulators significantly influences water droplet behavior, affecting both self-cleaning performances.

Considering the hydrophobicity class of the tested insulator, the railway insulator appears to provide class 2 of hydrophobicity (HC2) [27]. As illustrated in Figure 5(a), the criteria used to identify HC2 are consistent with the experimental observation of water droplets shown in Figure 5(b).Water does not follow a path of layers, but rather discrete droplets. The configuration of the railway insulator itself provides a small-angled shed, thereby causing the droplets to adopt a sliding shape with two different contact angles, acute and obtuse.

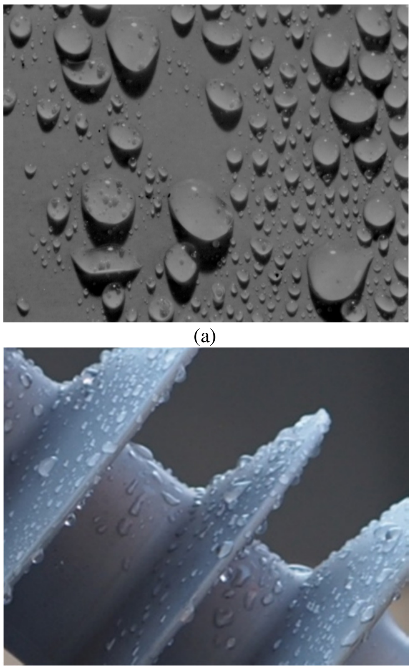
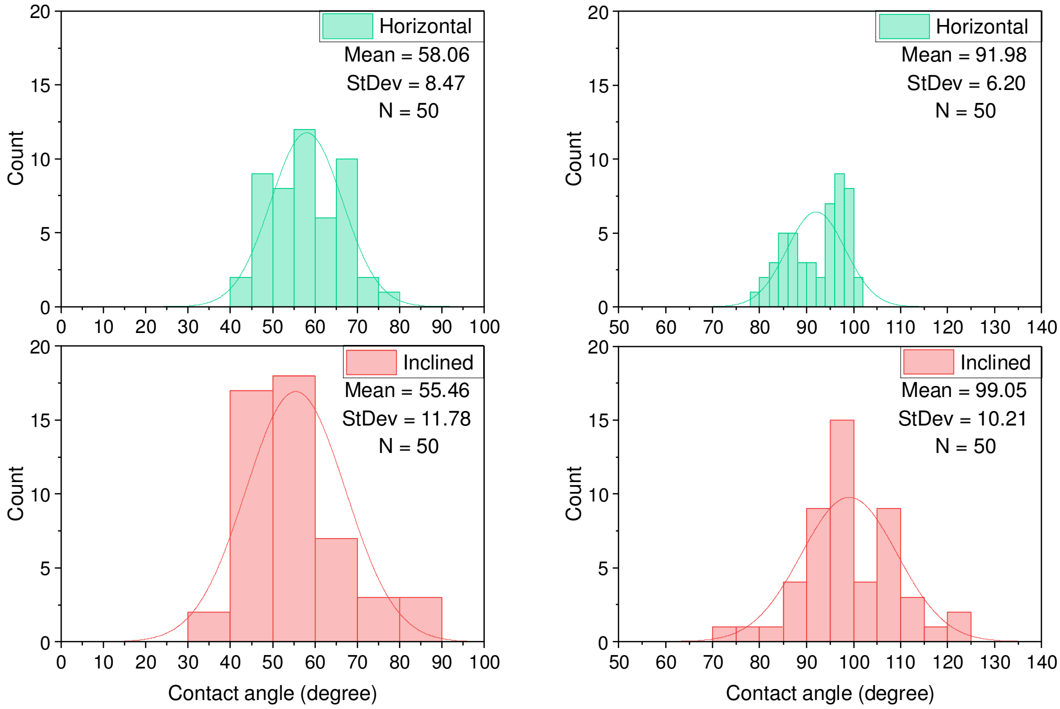


Fig. 5. Hydrophobic class of the railway insulator: (a) HC2 according to the STRI hydrophobicity classification guide, and (b) HC2 surface of railway insulator from the wet experimental test.

When the insulator is inclined at an angle of 35°, the presence of sliding droplets on its surface is evident. This inclination results in smaller acute and greater obtuse contact angles of 55.46° and 99.05°, respectively, compared to the 58.06° and 91.98° angles of a horizontal insulator. Figure 6 clearly illustrates the distribution of contact angles on the railway insulator for different angles.

The results indicate that the orientation of the insulator plays a significant role in determining the contact angles of water droplets, which in turn influence their shape deformation. This deformation directly impacts the local electric field distribution, potentially altering the electrical strength of the insulator and increasing the likelihood of dielectric breakdown. Research acknowledges that the inclination of the insulating surface can influence the contact angle of water droplets, as reported in [28].

The experimentally observed droplet contact angles, relevant to their geometries, were subsequently replicated in the simulation work. Droplets of varying shapes, including static and sliding droplets, which presumably sit on the horizontal and inclined insulators, were modeled to observe the effect of droplets on the distribution of electric field. The droplet modeling is detailed in the next section.



(a) (b)

Fig. 6. Distribution of contact angles on the railway insulator: (a) distribution curve of acute contact angles, and (b) distribution curve of obtuse contact angles.

B. Electric Potential and Electric Field of Railway Insulators

1) Clean and Dry Insulator

Figure 7 illustrates the equipotential and electric field lines of a railway insulator in a clean and dry environment. According to Figure 7(a), it is evident that the potential lines are likely evenly spaced and parallel to each other at the shed region. However, they tend to curve around insulator end fittings due to the distortion of the electric field. This denser concentration near the end fittings corresponds to areas of higher electric field intensity.

Conversely, the electric field lines will be highly denser near the conductor end fitting, indicating a higher field strength. Therefore, the maximum electric-field strengths are typically observed at the ends of the insulators. In this case, the maximum value of 14.80 kV/cm electric field occurs at the high voltage side of the end fitting, as illustrated in Figure 7(b). While most of the stressed area is represented by the end fittings, with a maximum value of about 15 kV/cm, the occurrence of corona is more likely to be observed at the metallic end fittings in the event of overvoltage.

The subsequent topic is mandatory to model how the railway insulator will perform in wet conditions, where the inclined insulator can experience greater electric and environmental stresses.

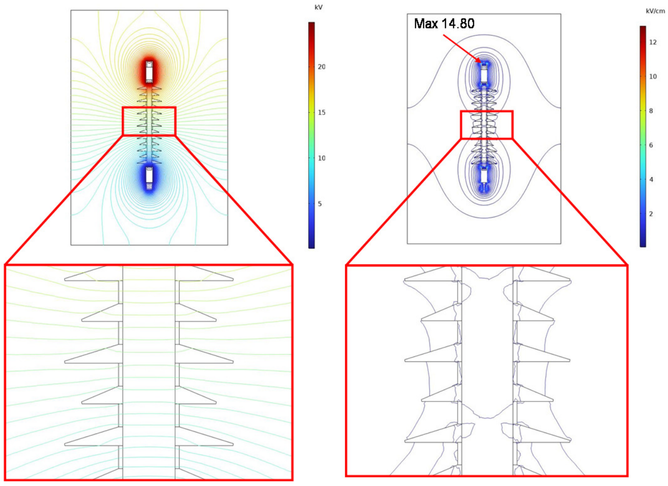
2) Wet Insulator

Numerous studies have demonstrated that the deposition of water droplets on an insulator surface enhances the electrical field intensity in the area of such droplets, which can then allow an initiation of corona discharge [29-33]. In this section, the multiple rain droplets are modeled to verify their effect.

According to the experimental results, the surface of the railway insulator is classified as HC2. Thus, the simulated droplets are discrete droplets with varying shapes that match the insulator's orientations. On a horizontal insulator, static droplets (ellipsoid shape) are laid, whereas sliding droplets (skewed ellipsoid shape) sit on an inclined insulator. The wet area where the droplets are placed is dispersed on the shed surfaces for inclination. In contrast, on the horizontal insulator, the droplets are additionally modeled at the rim of the sheds due to the accumulation water at this area before dropping down.

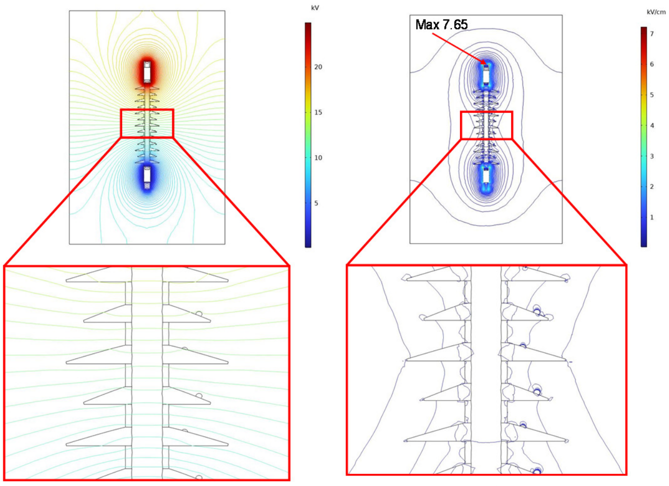
a) Inclined Insulator

Figure 8 shows the potential and electric field lines at the cross section of an inclined railway insulator. As illustrated in Figure 8(a), the potential lines exhibit a similar trend to the case of a clean insulator. Therefore, the equipotential lines of railway insulator are not significantly affected by the presence of droplets. In contrast, water droplets, being conductive or having a high dielectric constant compared to air, cause significant distortion of the electric field lines near their presence. Electric field lines become concentrated at the edges of the droplets, leading to higher local electric field strengths. This can then enhance the electric fields at the tips or edges of the droplets. Unlike the case with a clean insulator, the high voltage side of the end fitting now experiences the maximum electric field of 7.65 kV/cm. The result is demonstrated in Figure 8(b).



(a) (b)

Fig. 7. Simulated equipotential and electric field lines of a dry railway insulator: (a) electric potential, and (b) electric field.



(a) (b)

Fig. 8. Simulated equipotential and electric field lines of an inclined railway insulator: (a) electric potential, and (b) electric field.

Figure 9 shows the electrical field lines on the first top shed of the insulator, where triple points—defined as the area where the insulator surface, the droplet, and the surrounding air connect—generate higher field intensities than dry shed. The high electric field intensity at this triple point can induce leakage current and can eventually initiate the electrical discharges.

b) Horizontal Insulator

Figure 10 illustrates the potential and electric field lines along the horizontal insulator. The presence of water droplets on the shed, particularly at the tip of the horizontal insulator, indicates a specific location where water is accumulated before falling. The electric field lines become concentrated at this area, whereas the potential lines are likely evenly spaced and parallel to each other at the shed region, as shown in Figures 10(a) and 10(b). The maximum electric-field strength is observed at the high voltage side of the end fitting, with a value of 6.29 kV/cm. In this case, the maximum electric-field strength is lower than in the two previously mentioned cases.

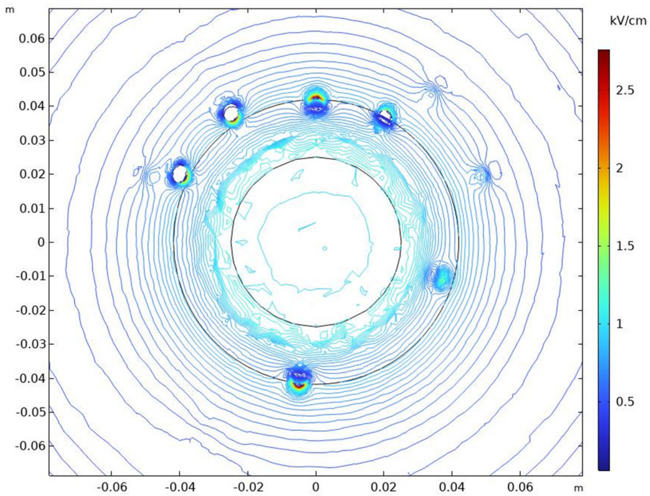
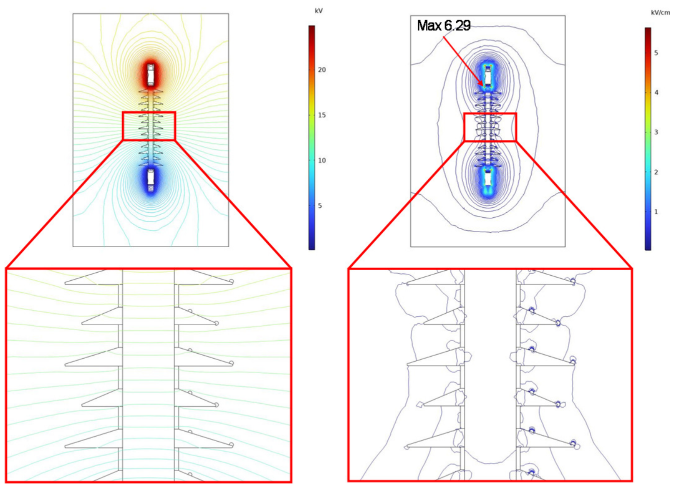


Fig. 9. Electrical field lines on the first top shed of an inclined insulator.



(a) (b)

Fig. 10. Simulated equipotential and electric field lines of a horizontal railway insulator: (a) electric potential, and (b) electric field.

The presence of droplets may contribute to a reduction in the maximum electric field intensity. The electric field is known to intensify in areas where water droplets accumulate. This phenomenon results in a redistribution of the field across the surface of the insulator. Consequently, the maximum electric field intensity is reduced for both wet inclined and horizontal insulators.

When droplets are present on the insulator surface, they provide higher field intensities than dry and clean sheds. Figure 11 shows the electrical field lines on the top shed of the horizontal insulator, where the contour plot confirms that the higher electric field can be found at the triple point. Furthermore, a comparison of Figures 9 and 11 reveals that the droplets on inclination and on horizontal insulators give different values of maximum electric-field strengths around those droplets.

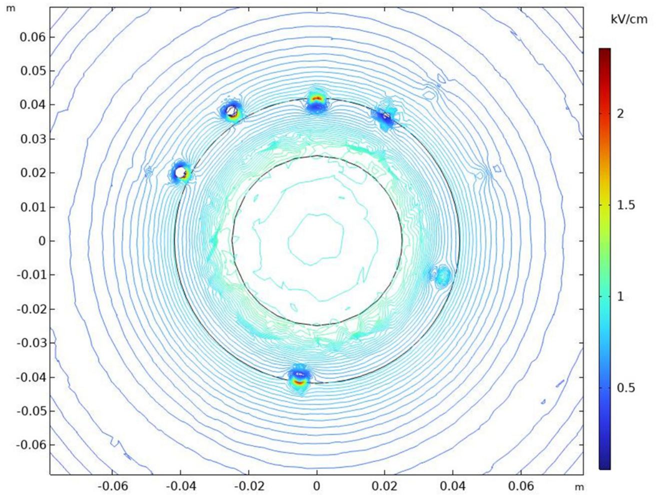


Fig. 11. Electrical field lines on the first top shed of a horizontal insulator.

The presence of water droplets on the insulator surface plays a crucial role in influencing its electrical performance, particularly through the distortion of the surrounding electric field. The findings of this section confirm that droplets induce localized field intensifications, with the highest distortions occurring at the triple point where the droplet, insulator, and surrounding air connect. This observation aligns with previous research, reinforcing the understanding that water droplets on polymer insulators contribute to electric field enhancement, which may increase the risk of partial discharge or dielectric breakdown under high-voltage conditions [34]. A key strength of this study lies in its combined experimental and simulation approach. However, certain limitations exist, particularly in replicating the model with complex wet conditions that insulators face in real-world applications. Despite these constraints, the study significantly advances knowledge on the influence of insulator orientation on droplet behavior and field distortion, which is critical for improving insulation design and reliability in railway and high-voltage applications.

C. Comparison of Electric Field Distribution on Different Orientations

In this section, the simulation of the distribution of electric fields along the polymeric-based surface of insulators (blue line) is performed, as shown in Figure 12. The objective is to examine the influence of droplets on their electric field profiles along the leakage path. The metallic end fitting area is currently excluded from consideration. A comparison of the electric field distribution on different orientations under clean and wet conditions is illustrated in Figure 13. For the dry and clean insulator, the electric field distribution along the leakage path is typically high at the area of sharp edges, which are located at the shed boundaries and the connection area of the end fittings, as shown in Figure 13(a). However, in the presence of water droplets, the electric field distribution along the leakage path becomes more distorted, showing a spike at the droplet locations, as shown in Figures 13(b) and 13(c). Figures 13(b) and 13(c) also show that an increased number of water droplets on the insulator surface leads to greater distortion in the electric field distribution curve. As the droplet concentration increases, localized field intensifications become more pronounced, resulting in heightened non-uniformity in the field profile.

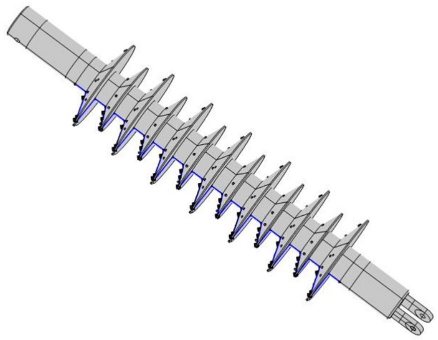
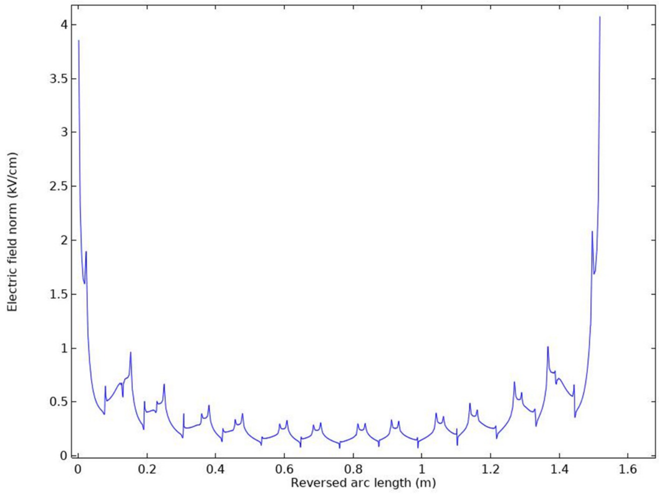
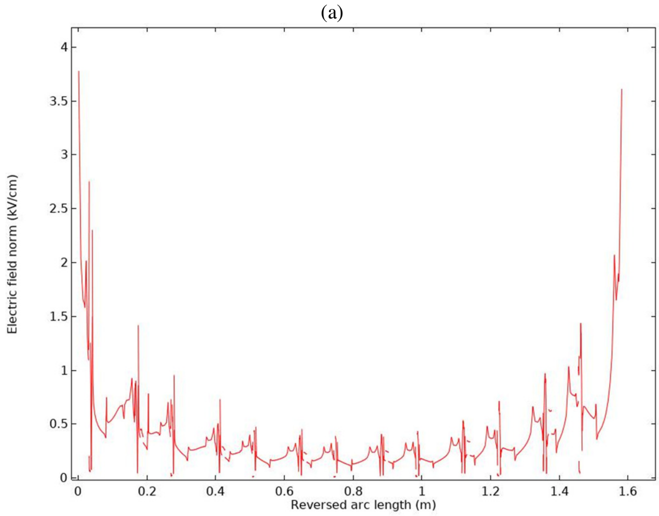


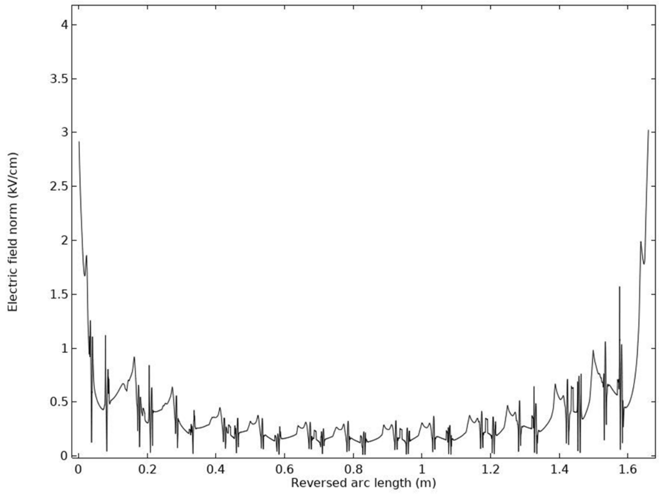
Fig. 12. Simulation of the distribution line along the insulator surface.



(a)



(b)

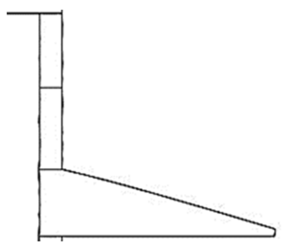
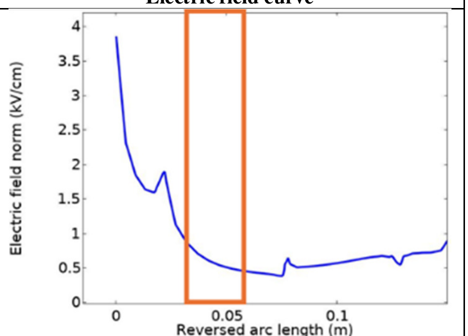
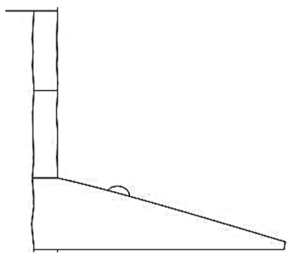
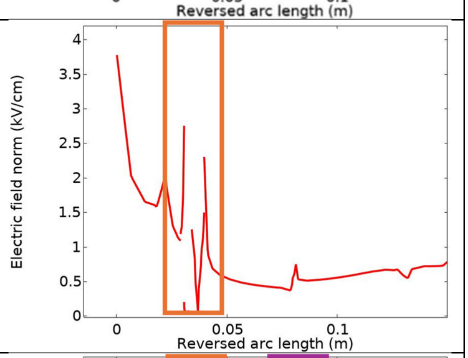
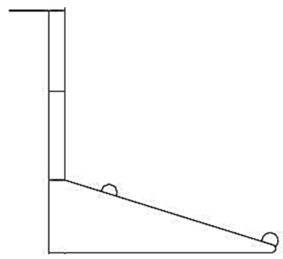
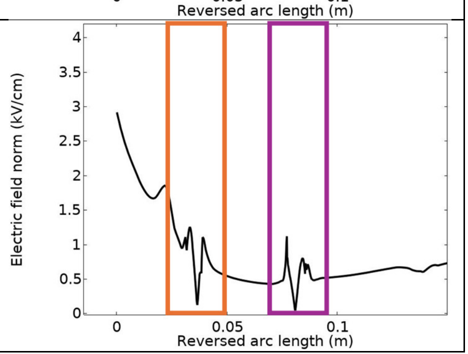


(c)

Fig. 13. Distribution of electric field along the leakage path of a railway insulator: (a) clean insulator, (b) inclined insulator, and (c) horizontal insulator.

Focusing on the electrical field at the first top shed, over a leakage distance of 0.15 m, the results indicate that when there are no droplets, the electric field is only about 0.5-1 kV/cm, suggesting a uniform distribution with minimal localized enhancements. However, the electric field spikes to 2.4-2.8 kV/cm when a skewed ellipsoid shape of droplets are placed on the inclination. This represents an approximate 2.5- to 5.6-fold increase compared to the dry condition, highlighting the significant role of droplet shape and orientation in field distortion. The horizontal insulator exhibits only a slight change in the electric field, with electric field values around 1.25 kV/cm at the area of the ellipsoid droplets. The results are presented in Table IV. The presence of skewed ellipsoidal droplets on inclined insulator surfaces contributes to the generation of a highly non-uniform electric field, with the highest field intensities occurring at the endpoints of the droplets.

TABLE IV. ELECTRIC FIELD DISTRIBUTION ON THE FIRST TOP SHED OF THE INSULATOR

Case	Model	Electric field curve
Clean		
Inclined		
Horizontal		

In contrast, symmetrically shaped ellipsoidal droplets generate a more evenly distributed electric field, though localized increases in electric potential still occur. The intensified electric field around elongated droplets is particularly critical, as it increases the likelihood of partial discharge and corona formation, especially in high-voltage environments.

Prior experimental studies [35, 36] have established that water droplets on insulator surfaces require a critical electric field strength of approximately 5–7 kV/cm to initiate corona discharge activity. In this study, the maximum observed field values remained below this threshold, reaching only up to 2.8 kV/cm, which is still significantly lower than the required initiation level. Therefore, corona discharge from water droplets on the insulator surface is unlikely under the present conditions.

The findings reported in this study suggest that the electric field intensity is enhanced by the presence of droplets on the insulator surface. The skewed ellipsoid droplets on the inclined surface result in a high degree of distortion of the electric field distribution relative to the ellipsoid droplets. However, the area of end fittings continues to indicate the highest electric field, and the electric field spiking around water droplets is far lower than the critical value. Consequently, the metallic end fitting is where corona could occur in the event of an overvoltage.

IV. CONCLUSION

This study examines the behavior of rain droplets on both inclined and horizontal railway insulators and evaluates how their presence influences electric field distribution. A comprehensive understanding of these characteristics is essential for optimizing insulator design to mitigate electric field distortions, discharge activities, and potential reliability concerns.

The findings indicate that droplet distribution is significantly affected by the orientation of the insulator on its cantilever. The interplay between gravitational forces and surface inclination determines the movement of droplets, leading to variations in self-cleaning performance. Horizontally positioned insulators tend to exhibit more effective self-cleaning, as all surfaces receive uniform rainfall exposure. Conversely, inclined insulators develop shaded regions where water accumulation is obstructed, reducing their capacity for self-cleaning.

Furthermore, the presence of water droplets has been shown to distort the electric field distribution, with field intensities increasing by at least twofold compared to dry conditions, particularly at the triple point region where the insulator, droplet, and air interface converge. The shape of the droplets is of particular significance in this intensification, influencing the overall electric stress along the surface. Compared to previous studies on wettability and electric field behavior on insulators, this work provides a more detailed analysis of how droplet orientation and shape specifically influence local electric field intensification. The observed doubling of field intensity, especially around the triple point, constitutes a notable deviation from typical assumptions in standard models.

However, despite the presence of droplets, the highest field intensities remain concentrated around the end fittings. Notably, the electric field strength surrounding water droplets remains well below the threshold required for corona discharge initiation.

Future research should explore the long-term impact of water droplet accumulation under dynamic weather conditions, as well as potential mitigation strategies such as hydrophobic coatings or modified shed designs to further improve insulator performance in railway applications. Additionally, the examination of the impact of Ultraviolet (UV) radiation and environmental pollution on inclined composite insulators would be a significant topic of research.

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