Research on the calculation of deviation angle of icicle build-up on insulators and its influential factor

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***Abstract*: A physical model for the calculation of deviation angle of icicle build-up on insulator is presented in this paper. Based on the force analysis on unfrozen water droplet at icicle tip, a mathematical analysis equation is obtained, which reveals the influence of wind velocity, ambient temperature, air pressure, and radius of water droplets on icicle deviation angle, as well as its constraint conditions have been obtained. Whereby the influential factors of icicle deviation angle and critical wind velocity of icicle growth have been analysed in this paper. The results show that icicle deviation angle is influenced by wind velocity, air pressure, ambient temperature and radius of water droplet at icicle tip. Among these factors, the wind velocity is the most influential one. When wind velocity increases to a certain degree, icicle will stop growing. In addition, comparing to that of the plain areas, the transmission lines acrossing high altitude regions tend to be confronted with more serious ice-cover and ice flashover problems, which is consistent with the previous experiment results.**

1. INTRODUCTION

In the previous researches, most experiments and theoretical studies were concerned with the situations where there is little wind or gentle breeze, and under the circumstance of which, the icicles would grow vertically. In fact, because these icing events are usually accompanied by winds, icicles will grow at an deviation angle. As the wind velocity increased, the icicle deviation angle increased, leakage distance increased and the flashover voltage increased.

Therefore, more careful studies on the icicle deviation angle are required for the construction of a more precise model to predict flashover voltage of ice-covered insulators.

2. RESULTS AND DISCUSSION

The icicle deviation angle depends on air pressure, ambient temperature, wind velocity and radius of water droplet, among which, the influence of ambient temperature is so little that it can be neglected and wind velocity is the most influential one. Icicle deviation angle is correlated positively with the pressure (P) and wind velocity. While it is correlated negatively with radius of water droplet (r). As the icicle deviation angle decreased, leakage distance the flashover voltage of ice-covered insulators decreased. When wind velocity increases to a certain degree, icicle deviation angle will be saturated.

There is a critical wind velocity for the growth of icicles. When wind velocity is greater than the critical wind velocity, icicles will stop growing. The critical wind velocity mainly depends on the air pressure and the radius of water droplet. The critical wind velocity is correlated negatively with the pressure (P) and radius of water droplet (r).

The icicle deviation angle is correlated negatively with the altitude. Consequently, as the altitude increased, the icing flashover voltage decreased under the same conditions. This conclusion is obtained by theoretical analysis. The further tests are necessary to supports above conclusion. They will be conducted in the next work.

The critical wind velocity is correlated positively with the altitude. Consequently, as the altitude increased, the range of effect wind velocity increased under the same conditions. This is one reason why the overhand transmission lines through high altitude regions face more serious ice accretion.

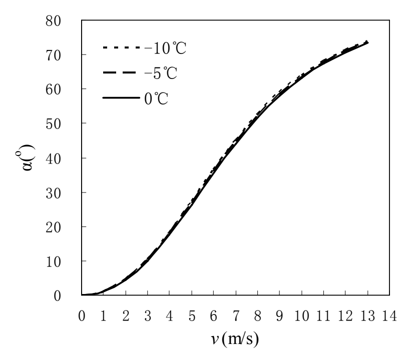

Figure 1. Relationship between icicle deviation angle and wind velocity for different ambient temperature
(P = 97.7 kPa , r = 2.5 mm, b = 1.5 mm, h = 0.4 mm)

3. CONCLUSION

A physical model for the calculation of deviation angle of icicle build-up on insulator is presented in this paper.

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***Abstract*: A physical model for the calculation of deviation angle of icicle build-up on insulator is presented in this paper. Based on the force analysis on unfrozen water droplet at icicle tip, a mathematical analysis equation is obtained, which reveals the influence of wind velocity, ambient temperature, air pressure, and radius of water droplets on icicle deviation angle, as well as its constraint conditions have been obtained. Whereby the influential factors of icicle deviation angle and critical wind velocity of icicle growth have been analysed in this paper. The results show that icicle deviation angle is influenced by wind velocity, air pressure, ambient temperature and radius of water droplet at icicle tip. Among these factors, the wind velocity is the most influential one. When wind velocity increases to a certain degree, icicle will stop growing. In addition, comparing to that of the plain areas, the transmission lines acrossing high altitude regions tend to be confronted with more serious ice-cover and ice flashover problems, which is consistent with the previous experiment results.**

Keywords — icicle, insulators, growth model, icicle deviation angle, critical wind velocity.

I. INTRODUCTION

AS power networks are expanded and the voltage level of transmission lines is being increased, more and more transmission lines will inevitably go cross the regions with the coexistent conditions of high altitude, pollution, and icing [1,2]. In alpine regions, overhand transmission lines and their substations are subjected to ice accumulations in cold periods. Power outages caused by insulator flashovers as a result of ice or wet snow accretions have been reported throughout China[3] as well as several other countries, particularly Canada[4], the United States [5], Japan[6], England [7], Yugoslavia [8], and Norway [9]. In 2008, when China was affected by ice, the 500kV power network was paralyzed in Guizhou and dozens of 500kV transmission lines were damaged in Central China. Ice disasters have posed a serious threat to the secure operation of power systems [10].

Insulator flashover under glaze ice accretion has received a great deal of attention. A large number of investigations and theoretical studies have been carried out in several laboratories. The distortion of the electric field and the decrease of the leakage distance are the major causes of the reduction in the electrical performance of the insulators. Depending on the weather conditions, different types of ice may accrete on an insulator surface, e.g. glaze, hard rime or soft rime. Among them, glaze accompanied with icicles, which is grown in wet regime, is known as the one most likely to induce flashover on insulators [2]. Therefore, glaze was often examined to research for the actual study.

In the previous researches, most experiments and theoretical studies were concerned with the situations where there is little wind or gentle breeze, and under the circumstance of which, the icicles would grow vertically [11~14]. In fact, because these icing events are usually accompanied by winds, icicles will grow at an deviation angle. As the wind velocity increased, the icicle deviation angle increased, leakage distance increased and the flashover voltage increased.

Therefore, more careful studies on the icicle deviation angle are required for the construction of a more precise model to predict flashover voltage of ice-covered insulators.

II. GROWTH OF ICICLE IN NATURE

A lot of observations of ice-coated insulator strings in Xuefeng Mountain nature ice-cover test site show that the icicles build-up on insulators are mainly in the form of glaze. After the icicles formation, featherlike soft rime will be formed on icicles due to supercooled water droplet as shown in Figure 1.

While supercooled raindrops exert impact upon the insulators surface under the wind force, a part of them will not freeze immediately, and they will flow toward the lee side of the insulator due to gravity, wind drag, and surface tension of water droplets. Then they converge and freeze under the edge of the insulator skirt, which deviates to some extent from the center of the windward side. If the water supply is sufficient, the unfreezed water drop will flow down along icicle surface and a pendant drop forms at the tip of the icicle. Only then can the icicle grow in length. The pendant drop grows until it reaches a certain size and then falls, whereafter another drop starts to grow. Because

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of the wind force, icicles will grow at a deviation angle, rather than vertical. All the icicles will basically grow in a straight line at an deviation angle, as shown in Figure 1.

Figure 1. Growth of icicle under nature condition

When there is a source of water at the root of the icicle, a liquid film forms on the icicle surface and flows towards the tip due to gravity or wind drag. Water spreads effectively on an icicle surface due to the high surface energy of ice. Therefore, the liquid water covers uniformly the entire icicle surface, unless the flux of water is extremely small.

III. MODEL FOR ICICLE GROWTH

The growth direction of icicle depends on the freezing direction of the liquid water drop. According to the model [14], the liquid water on icicles contains three parts: on icicle surface, inside icicle, at icicles tip. The liquid water trapped inside the icicle is not affected by the wind force. The liquid film on the icicle surface is very thin, about 40~l00 μm. The elongation rate of an icicle is typically 20-60 times the radial growth rate of the walls [14]. Therefore, the growth direction of icicle mainly depends upon the freezing direction of the liquid water drop at icicles tip, while the former two parts have little influence on it.

According to literature [14], the shape of the pendant drop changes during its growth and its mean shape can be approximated by a hemisphere, as shown in Figure 2.

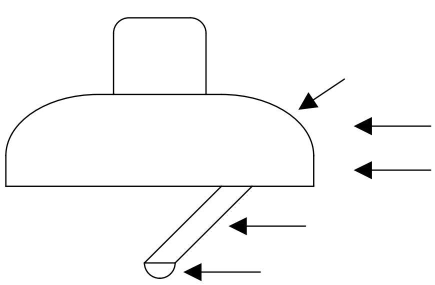

Figure 2. Sketch of icicle propagation
1—insulator；2—icicle；3—water droplet

There are three forces acting on the unfrozen water droplet at icicle tip: gravity force (G), wind force (F) and viscous force due to surface tension (f) [15,16]. The icicle deviation angle is a result of the joint function of above three forces as shown in Figure 3.

Gravity force (G) is in the vertical direction; the viscous force is upward along icicle. In nature, wind direction is horizontal at the height of insulators. Therefore, it is considered that wind is in the horizontal direction in this paper as shown in Figure 3. Consequently, the icicle deviation angle, α, be calculated as follows:

$$\tan\alpha = \frac{F}{G} \tag{1}$$

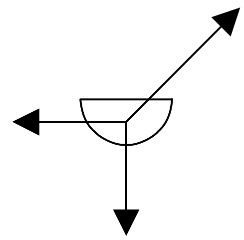

Figure 3. Diagram of force analysis of water droplet

The gravity of water droplet, G, is determined using the following equation:

$$G = V\rho_{water}g \tag{2}$$

Where V is the volume of the water droplet, m^3, r is the radius of water droplet, m; ρ_{water} is the density of water, ρ_{water} = 1000 kg/m^3; g is the acceleration of gravity, g = 9.78 m/s^2.

$$V = \frac{2}{3}\pi r^3 \tag{3}$$

Where r is the radius of the pendant drop, mm.

The wind force, F, is determined using the following equation:

$$F = P_{wind}S \tag{4}$$

Where P_{wind} is the wind pressure, Pa; S is the projection of the pendant drop into vertical, m^2.

$$S = \frac{1}{2}\pi r^2 \tag{5}$$

The wind pressure, P_{wind}, is given by

$$P_{wind} = 0.5 \times \rho_{air} \times v^2 \tag{6}$$

Where ρ_{air} is the air density, kg/m^3; v is the average wind velocity, m/s. According to the ideal gas state equation [17], ρ_{air} can be expressed as follows

$$\rho_{air} = \frac{P\mu_{air}}{RT} \tag{7}$$

Where P is the air pressure, Pa; T is the ambient temperature, K; μ_{air} is the mean molal mass of air, μ_{air} = 28.9×10^{-3} kg/mol; R is the universal gas constant, R = 8.31441 J·mol^{-1}·K^{-1}.

Substituting equation (2)~(7) into equation (1) yields:

$$\alpha = \arctan\left(\frac{3}{8} \times \frac{P\mu_{air}v^2}{Rr\rho_{water}g(t+273)}\right) \tag{8}$$

Where t is the ambient temperature, ℃.

IV. RESTRAINED CONDITIONS

A. Water droplet radius

When there is no wind, only gravity force (*G*) and the viscous force (*f*) act on the water droplet.

$$G = f \tag{9}$$

$$f = 2\pi r\sigma \tag{10}$$

Where, σ is the surface tension coefficient of water, $\sigma = 73 \times 10^{-3}$ *N*/m.

Substituting equation (10) into equation (9) yields,

$$r_{\max} = \sqrt{\frac{3\sigma}{\rho_{water} g}} \tag{11}$$

According to equation (11), the maximum of the radius of the water droplet is 4.73 mm. In fact, water droplet at icicle tip will break prematurely under gravity. Hence the radius of water droplet at icicle tip is smaller than the value calculated [18].

The typical shape and radius of icicles build-up insulators surface are determined based on previous studies [19~21], where the radius of icicle tip is 2.5 mm, which agrees well with laboratory observation. Therefore, *r* is chosen to be 2.5 mm in this paper. In order to conduct the investigations about the effect of radius of water droplet on icicle deviation angle, different radius of water droplet are concerned in this study.

B. Critical wind velocity

When the wind velocity exceeds a certain value, the droplet will be blown away by wind. As a result, the droplet fails to attach to the icicle and the icicle will stop growing. Therefore, there is a critical wind velocity. When the wind velocity is greater than the critical wind velocity, the icicles will stop growing, which is in accordance with the previous study [2].

The condition of water droplets falling is expressed as

$$\vec{F} + \vec{G} \geq \vec{f} \tag{12}$$

According to equation (12) yields:

$$F^2 + G^2 \geq f^2 \tag{13}$$

Subs tituting equation (2), (4) and (10) into equation (13) yields,

$$v \geq 2\sqrt{2} \times [(\frac{R(t+273.15)}{P\mu_{air}})^2 \times (\frac{\sigma^2}{r^2} - \frac{1}{9} \times r^2 \rho_{water}^2 g^2)]^{\frac{1}{4}} \tag{14}$$

The critical wind velocity is determined using the following equation:

$$v_{\max} = 2\sqrt{2} \times [(\frac{R(t+273.15)}{P\mu_{air}})^2 \times (\frac{\sigma^2}{r^2} - \frac{1}{9} \times r^2 \rho_{water}^2 g^2)]^{\frac{1}{4}} \tag{15}$$

The previous researches about ice accretion on overhand line demonstrate [1,2] that the raindrops are collected by windward of overhand lines and pendant droplets form under lines due to wind force and gravity, then freeze, which resembles the process of ice accretion on insulator. So the studies and analyses about critical wind velocity mentioned above are also appropriate for the ice accretion on overhand lines.

When p = 101.325 kPa, t = -5 ℃, and r = 2.5mm, the critical wind velocity is 13.19 m/s. When wind velocity is greater than this critical velocity, the icicles build-up on the insulators skirt will stop growing. This agrees with the result in [2].

Because R, μ_{air}, σ, ρ_{water} are nearly constant, the critical wind velocity mainly depends on air pressure (P), ambient temperature (t) and radius of water droplet (r, h, b). The ambient temperature (t) for formation of glaze is -5~2 ℃ [2]. As a result, the variation scope of (t+273) will be even smaller. Therefore, the influence factors for the critical wind velocity are mainly atmospheric pressure(P) and radius of water droplet (r, h, b).

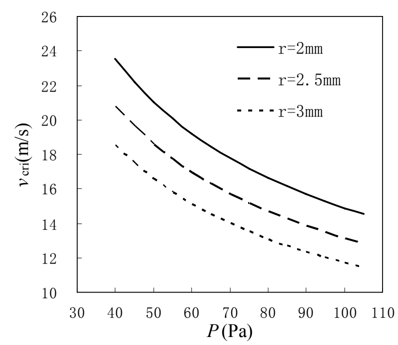

Figure 4. Relationship between air pressure and critical wind velocity for different radius of water droplet (t = -5 ℃)

Figure 4 demonstrates that the critical wind velocity is correlated negatively with air pressure (P) and radius of water droplet (r). The former is mainly because that the air density increases with increasing of air pressure. Same wind velocity can generate greater wind pressure according to equation (11). The later is mainly because the bigger radius of water droplet is, the greater gravity is. As a result, droplet will be blown away more easily.

C. Maximum icicle deviation angle

According to equation (8), it can be observed that the bigger the wind velocity is, the greater α is. Therefore, the critical wind velocity can be calculated by substituting $v_{\max}$ into equation (8). The critical wind velocity is expressed as

$$\alpha_{\max} = \arctan(\frac{3\sqrt{\sigma^2 - \frac{1}{9} \times r^4 \rho_{water}^2 g^2}}{r^2 \rho_{water} g}) \tag{16}$$

For the typical radius, r = 2.5 mm, $\alpha_{\max}$ is 73.8° .

The equation (11), (15) and (16) obtained by analysis is restrained conditions of equation (8).

V. INFLUENCE FACTOR

Because R, ρ_{water}, g are nearly constant, icicle deviation angle is mainly influenced by air pressure (P), ambient temperature (t), wind velocity (v) and radius of water droplet (r), which are shown in Figure 5 and Figure 6.

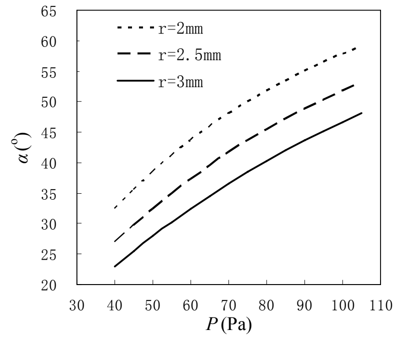

Figure 5. Relationship between air pressure and icicle deviation angle for different radius of water droplet (v = 8m/s, t = -5 ℃)

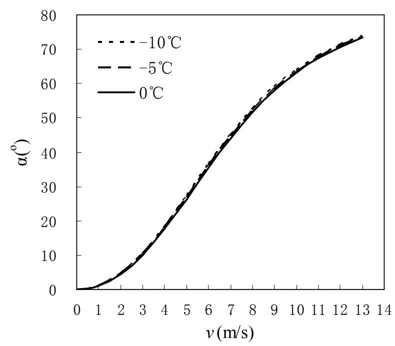

Figure 6. Relationship between icicle deviation angle and wind velocity for different ambient temperature
(P = 97.7 kPa , r = 2.5 mm, b = 1.5 mm, h = 0.4 mm)

Figure 5 shows the icicle deviation angle as a function of the air pressure and radius of water droplet. The icicle deviation angle is correlated positively with the air pressure (P) and is correlated negatively with radius of water droplet (r). The former is mainly because air density increases when the air pressure increases. So, same wind velocity could come into being greater wind pressure according to equation (11). The later is mainly because the bigger radius of water droplet is, the greater gravity is.

Figure 6 shows the icicle deviation angle is correlated positively the with wind velocity. When there is no wind, icicle will elongate vertically. When the wind velocity is over a certain value, the icicle deviation angle will be in saturation. As mentioned above, the range of ambient temperature that fit for the formation of glaze is small. As a result, the variation scope of (t+273) will be even smaller. Therefore, the influence of ambient temperature on the icicle deviation angle is very little.

Thus, the main influence factors on the icicle deviation angle are atmospheric pressure (P), wind velocity (v) and radius of water droplet (r).

VI. ICICLE GROWTH AT HIGH ALTITUDE REGIONS

In China, many overhand lines have to go across high altitude regions for geographical reasons. The overhand lines acrossing high altitude regions will be confronted with some problems that do not appear in low altitude regions.

According to literature [10], the relationship between altitude and atmospheric pressure is shown as follows,

$$P = P_0(1-\frac{H}{45.1})^{5.36} \tag{17}$$

Where P_0 is air pressure at standard reference, P_0 = 101.325 kPa; H is the altitude, km.

Substituting equation (17) into (8) and (15) yields;

$$\alpha = \arctan(\frac{3}{8}\times\frac{\mu_{air}v^2P_0(1-\frac{H}{45.1})^{5.36}}{Rr\rho_{water}g(t+273)}) \tag{18}$$

$$v_{\max} = 2\sqrt{2}\times[(\frac{R(t+273.15)}{\mu_{air}P_0(1-\frac{H}{45.1})^{5.36}})^2\times(\frac{\sigma^2}{r^2}-\frac{1}{9}\times r^2\rho_{water}^2g^2)]^{\frac{1}{4}} \tag{19}$$

According to equation (18) and (19), the relationship between icicle deviation angle and altitude is shown in Figure 7 and the relation between critical wind velocity and altitude is shown in Figure 8.

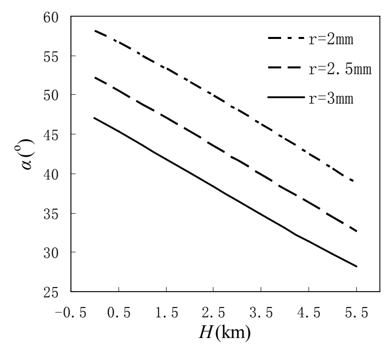

Figure 7. Relationship between altitude and icicle deviation angle for different radius of water droplet (v=8 m/s, t=-5 ℃)

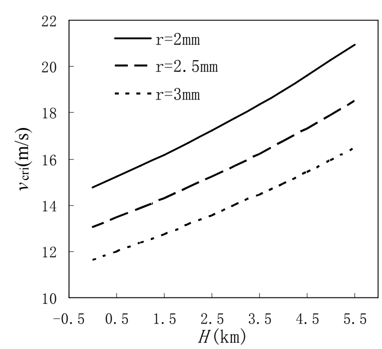

Figure 8. Relationship between altitude and critical wind velocity for different radius of water droplet (t=-5 ℃)

Figure 7 and Figure 8 show that the icicle deviation angle and the critical wind velocity are functions of the altitude. As the altitude increased, the icicle deviation angle decreased and the critical wind velocity increased. This means, comparing with that in low altitude regions, effective wind velocity has greater range and the leakage distance for insulator strings is even shorter in high altitude regions. (Effective wind velocity is the wind velocity that induce glaze accompanied with icicles. It is defined as v_{eff}, $0 \leqslant v_{eff} \leqslant v_{max}$).

Based on the mentioned above, two conclusions can be obtained as follows: (1) Ice accretion on insulators and overhand transmission lines are more serious with the increasing of altitude; (2) When there is wind during ice accretion, flashover voltage of ice-covered insulator string in high altitude regions will be lower than that in low altitude regions under the same conditions. The latter is obtained by theoretical analysis. The further tests are necessary to supports above conclusion. They will be conducted in the next work.

VII. CONCLUSION

(1) A model for calculating deviation angle of icicle build-up on insulators is presented in this paper;

(2) A physical mathematics model for the icicle growth is presented based on force analysis of unfrozen water droplet at icicle tip. According to this model, the mathematical analysis equation of icicle deviation angle and its constraint conditions have been obtained;

(3) The icicle deviation angle depends on air pressure, ambient temperature, wind velocity and radius of water droplet, among which, the influence of ambient temperature is so little that it can be neglected and wind velocity is the most influential one. Icicle deviation angle is correlated positively with the pressure (P) and wind velocity. While it is correlated negatively with radius of water droplet (r). As the icicle deviation angle decreased, leakage distance the flashover voltage of ice-covered insulators decreased. When wind velocity increases to a certain degree, icicle deviation angle will be saturated.

(4) There is a critical wind velocity for the growth of icicles. When wind velocity is greater than the critical wind velocity, icicles will stop growing. The critical wind velocity mainly depends on the air pressure and the radius of water droplet. The critical wind velocity is correlated negatively with the pressure (P) and radius of water droplet (r).

(5) The icicle deviation angle is correlated negatively with the altitude. Consequently, as the altitude increased, the icing flashover voltage decreased under the same conditions. This conclusion is obtained by theoretical analysis. The further tests are necessary to supports above conclusion. They will be conducted in the next work.

(6) The critical wind velocity is correlated positively with the altitude. Consequently, as the altitude increased, the range of effect wind velocity increased under the same conditions. This is one reason why the overhand transmission lines through high altitude regions face more serious ice accretion.

(7) This model can be considered as a part of a more complete ice flashover model.

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