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Effects of geometrical parameters of two height-unequal adjacent objects on corona discharges from their tips during a thunderstorm

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ABSTRACT

A two-dimensional time-dependent numerical model in Cartesian coordinate system has been developed to evaluate the mutual effect of two height-unequal adjacent objects on corona discharge occurring on their tips during a negative charging process of thundercloud. The results show that the higher object has a significant effect on the corona discharge of the shorter one. The relationships between the three geometric parameters (the height of the shorter object (h), the height difference (Δh) and the horizontal distance (d) between them) and the two corona properties of the shorter object (the background electric field for corona onset (E_{onset}) and the peak value of the corona current (I_{p})) are investigated. When d is fixed ($d = 30$ m), the variation of E_{onset} of the shorter object varies with h orΔh is linear and the rate of the variation no matter with or without the presence of the taller object is the same. The only difference is that E_{onset} with the presence of the taller object is about 10% greater than without. I_{p} of the shorter object also has a linear variation with h or Δh no matter with or without the presence of the taller object, but the rate of the variation when the taller object is present is smaller than absent. When the heights of the two objects are fixed as 70 m and 100 m respectively, E_{onset} of the shorter object with the presence of the taller object decreases exponentially and I_{p} increases exponentially with increasing d. When d is more than 70 m, the effect of the taller object on E_{onset} and I_{p} of the shorter object is so weak that can be neglected. Furthermore, it is interesting to find out in the study that E_{onset} of the shorter object in the presence of a taller object is affected strongly by the geometric parameters of the two objects and weakly by the corona space charges generated from the taller object, while I_{p} is affected not only by the geometric parameters of the two objects but also by the corona generated from the two objects.

1. Introduction

Corona discharge, initiated by thundercloud electric fields at the tips of trees, bushes, grass, buildings and tall towers below a thunderstorm (Macgorman et al., 2008), is often referred to as a point discharge. If corona space charge accumulates sufficiently around lightning rods, forming a thick space charge layer, it can affect the initiation and further propagation of an upward connecting leader, and the attachment of downward lightning to objects. Thus, corona discharges that occurs near the tips of lightning rods or the objects have attracted more and more attentions in recent years due to its influence on the efficiency of lightning rods to attract lightning to protect objects (Chalmers, 1976; Standler and Winn, 1979; Chauzy and Soula, 1987; Chauzy et al., 1991; Soula and Chauzy, 1991; Qie et al., 1994; Soula and Serge, 1994; Aleksandrov et al., 2001, 2002, 2005a; Becerra et al., 2007; Becerra, 2013, 2014; Bazelyan et al., 2008, 2015).

However, in most of the above researches, the object or the lightning rod considered was just a single one. Actually, whether in cities or towns, the grounded objects or the lightning rods on building's roof (Golde, 1974; Bazelyan and Drabkin, 2003; Rizk, 2010) are rarely isolated and mostly are placed in multiples. Under this circumstance, the corona discharge on each object's tip would interfere with the rest. And this should not be ignored when considering corona discharges.

According to the experimental studies of corona discharges on multi objects, ambient electric field required for corona onset is founded to be increased with decreasing distance between objects (Chalmers, 1976; Aubrecht et al., 2001a, 2001b). For further investigation, corona ions developing form numerous corona-producing points were analyzed by Bazelyan et al. (2014a,b). It is shown that all the ions can unite into a flat space charge layer. But for the sake of simplicity, they assumed that all coronating points are identical and the diffusion of the corona charges is not considered. And their studies are based on analytical analysis or one-dimensional numerical simulation. However, it should be noted that the effect of the corona charges' diffusion on the distribution of the corona space charges generated from a multi-point system cannot

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be ignored especially when the coronating points are adjacent with each other during a thunderstorm. Obviously, the object or the lightning rod is usually surrounded by other objects with different heights (trees, buildings, etc.) which may affect the characteristic of the corona discharge on the object and even affect other further discharge process (corona-stream-leader, and the propagation of the leader and so on) on the object. Thus, it is meaningful to study the corona discharge on a system with several different height objects rather than considering all the objects as a same height or even simplifying each object as an isolated rod. But, it's rarely found in the current literatures, let alone revealing the relationships between geometrical parameters of the objects and corona parameters.

What's more, corona discharge models in the presented researches mostly are 1D model (Aleksandrov et al., 2001, 2002, 2005a; Bazelyan et al., 2014a, 2014b) or 2D axisymmetric model (Becerra, 2013), both of them are inapplicability in simulating the objects with asymmetric structure. Thus, for investigating the corona discharge in a system with two height-unequal adjacent objects numerically, it is an essential condition that all the calculation must be in a two-dimensional time-dependent numerical model in Cartesian coordinate system.

The purpose of this study is to investigate the above-mentioned outstanding issues through numerical modeling of the drift of the corona space charge generated from a system with two different height adjacent objects under thunderstorm condition using a two-dimensional model in Cartesian coordinate system. Then the time variation of corona currents on each objects, the spatial-temporal evolution of the distribution of corona space charge density and the electric field are all investigated. The interference of the corona discharges within a system with two different height adjacent objects is considered. And we mostly focus on revealing the relationships between geometrical parameters of the objects and corona parameters.

2. Formulation of the two-dimensional time-dependent numerical model

2.1. Introduction of our numerical model method

Under the negatively charged thundercloud (seen as Fig. 1), the background electric field at ground level is upward and the corona discharge is positive, and the positive corona ions are produced from the

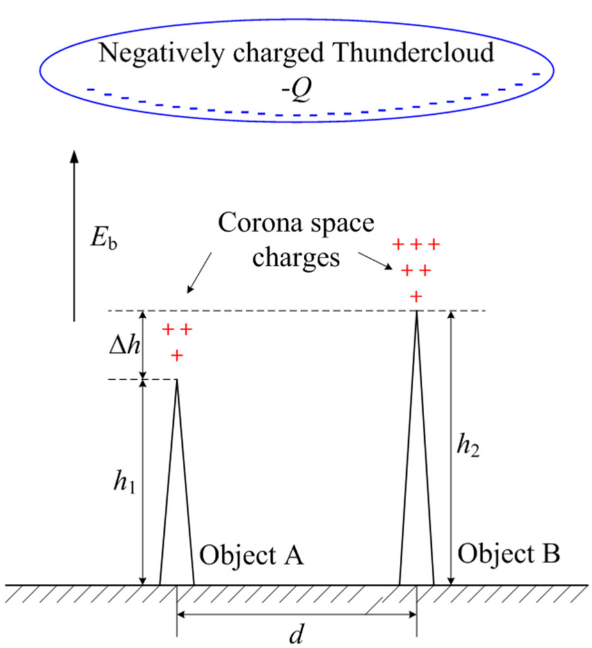

Fig. 1. Configuration of the two-dimensional (2D) time-dependent numerical model.

natural tip. From Aleksandrov et al. (2002) and Becerra (2013), two assumptions were used to simplify the corona discharge process. First, because we are interested in the time-dependent production and evolution of corona ions in larger space domain of several of meters, the thickness of the ionization layer within several of mm near the corona discharge surface is ignored. According to Kaptzov's assumption, the local electric field near a corona-producing surface is equal to onset corona field (E_{cor}) (Aleksandrov et al., 2002), which assumption is valid for a non-stationary corona when the background electric field changes slowly (Waters and Stark, 2001; Aleksandrov et al., 2005b; Liu and Becerra, 2016). Second, it is assumed that only the positive corona ions are considered and move away from the corona-producing surface, while all the negative ions in the ionization layer are instantly absorbed by the anode.

According to the above assumptions, the set of continuity equations for small positive ions n_+, large positive aerosol ions N_+, and aerosol neutrals N_a in 2D Cartesian coordinates are given by

$$\frac{\partial n_+}{\partial t} = D \cdot \nabla^2 n_+ - \nabla \cdot \left[n_+ \cdot \left(\mu_{n_+} \cdot \mathbf{E}\right)\right] - k_{nN} \cdot n_+ \cdot N_a \quad (1)$$

$$\frac{\partial N_+}{\partial t} = D \cdot \nabla^2 N_+ - \nabla \cdot \left[N_+ \cdot \left(\mu_{N_+} \cdot \mathbf{E}\right)\right] + k_{nN} \cdot n_+ \cdot N_a \quad (2)$$

$$\frac{\partial N_a}{\partial t} = D \cdot \nabla^2 N_a - k_{nN} \cdot n_+ \cdot N_a \quad (3)$$

where t is the time, μ_{n_+} and μ_{N_+} are the mobility for small ions and large aerosol ions, respectively, k_{nN} is the attachment coefficient of small ions to aerosol particles, D is the diffusion coefficient, E is the electric field. The values of μ_{n_+}, μ_{N_+}, k_{nN} and D are 1.5×10^{-4} m^2 s^{-1} v^{-1}, 1.5×10^{-6} m^2 s^{-1} v^{-1}, 2.9×10^{-12} m^3 s^{-1} and 1 m^2 s^{-1}, respectively (Qie et al., 1994; Becerra, 2013). Eqs. (1)–(3) are coupled with Poisson's equation given by

$$\nabla^2 \varphi = -\frac{e}{\varepsilon_0}(n_+ + N_+) \quad (4)$$

where ε_0 is the permittivity of air, e is the electron charge and φ is the electric potential.

In the computed method, the second-order upwind difference scheme (Courant et al., 1952; Davis and Davis, 1984) is used to discretize the convection terms from Eqs. (1) to (3) in order to eliminate numerical oscillation, and the central difference scheme is used to discretize the diffusion terms. Poisson's equation is solved by finite different method (FDM), and once the potential distribution is obtained, the electric field is calculated as below

$$\mathbf{E} = -\nabla \varphi \quad (5)$$

For analyzing the interaction between the production and drift of positive corona ions generated from the two adjacent grounded objects' tip, the object height (shown as h, the heights of object A and B are shown as h_1 and h_2 respectively in Fig. 1) and their height difference (shown as Δh in Fig. 1, which equal to $h_2 - h_1$) and the distance between them (shown as d in Fig. 1) have been considered. An analysis space domain is defined from the ground level to the upper boundary with the height of 500 m while the width in the horizontal direction is 200 m. The two objects are simplified as cylindrical lightning rods placed on the ground and both radii are 0.5 m. The spatial resolution of the computational grids in the domain is uniform and was set to be 1 m × 1 m. The temporal resolution matches the spatial resolution, and was set to be 0.01 s.

The boundary conditions for the electrostatic calculation are defined as follows. During the formation of a negatively charged thundercloud, the background electric field (E_b)close to the ground level slowly increases from the fair weather field (about 100 V m^{-1}) up to a few