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On the Energy Estimation of Lightning Discharge

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Abstract

In this paper, we calculated thermal power, dissipated heat energy and radiated energy due to the current flowing in the body of lightning channel. The peak value of thermal power and total dissipated heat/thermal energy come out to be of the order of 10^{10} W and 10^6 J respectively. The calculated radiated energy comes out to be around 3.23 kJ. It is found that the energy lost in the form of radiation is much low as compared to the dissipated heat energy in the lightning channel.

Keywords: Lightning, return stroke, lateral corona, thunderclouds.

Introduction

Lightning is one of the most dangerous natural disasters in earth's atmosphere. It is a transient, high-current electric discharge in air. The most common source of lightning is the thundercloud or cumulonimbus cloud in which electric charge regions of opposite polarity are separated due to several mechanisms. The upper and lower parts of the thundercloud have positive and negative charges respectively. The mechanisms of thundercloud electrification include drop-breakup, ion charging, convective and induction[1]. The positive and negative charged regions in thunderclouds can develop a high voltage between them, and between one charged region and ground. When this voltage reaches beyond the dielectric strength of air (3×10^6 V/m) lightning takes place. There are commonly four types of lightning discharges known as intracloud, cloud-to-cloud, cloud-to-air and cloud-to-ground. Intracloud lightning occurs more than half times of all lightning discharges. However, cloud-to-ground lightning has been studied more extensively than other lightning forms because of its practical interest (e.g., as the cause of injuries, deaths and forest fires)[2]. Cloud-to-ground lightning has been categorized according to the sign of charge carried out by the stepped leader from cloud to the Earth. Discharge initiated by a downward-moving negative stepped leader is called negative cloud-to-ground lightning. Similarly, positive leader initiates the positive cloud-to-ground lightning. In about 90% of world wide cloud-to-ground lightning, negative charge is transported from cloud to ground. The electric and magnetic fields both in time and frequency domains have been calculated due to the cloud-to-ground lightning[3]. It has been found that the electromagnetic fields peak at a frequency of 5 kHz. Recently, it has been observed experimentally that the small tiny particles suspended in air called "aerosols" enhance the lightning activity significantly[4], i.e. highly polluted places attract the lightning more. Apart from the tropospheric lightning as discussed above, some upper atmospheric discharges also have been documented during last two decades. Red sprites, elves, blue jets and blue starters are some of the discharges which constitute the family of upper atmospheric lightning. Several researchers presented the principal observational characteristics of these discharges[5]. Now, it is widely accepted that the upper atmospheric discharges especially sprites and elves are related to the strong tropospheric cloud-to-ground lightning[6, 7]. We will not discuss in detail about upper atmospheric discharges in this paper.

In this paper we calculated the thermal power, dissipated heat energy and radiated energy due to the current flowing in the tropospheric lightning channel.

Methodology

Thermal Power and Dissipated Heat Energy in the Lightning Channel: Cloud-to-ground lightning contain two different types of current. The first one and most intense is the return stroke current. It can ranges from 10-100 kA with duration of 100-200 μs[8]. The estimated peak current of first return stroke has been reported about 300 kA in temperate region and about 450-500 kA in tropics[9]. The other one is called lateral corona current. Lateral corona current will be discussed in next section. The heat energy dissipated in the lightning channel is mainly due to the return stroke current. The maximum temperature in the lightning channel can reach up to 30,000 K[10, 11]. The highly ionized core of return stroke forms the plasma. The velocity and current expressions for return stroke are given by[3, 12]

$$V_{rs}(t) = V_0\left(e^{-at} - e^{-bt}\right) \tag{1}$$

$$I_{rs}(t) = I_0\left(e^{-\alpha t} - e^{-\beta t}\right) \tag{2}$$

where, $V_0=9\times10^7$ m/s; $a=3\times10^4$ s^{-1}; $b= 7\times10^5$ s^{-1}; $I_0=22$ kA; $\alpha=1.6\times10^4$ s^{-1}; $\beta=5\times10^5$ s^{-1}.

The thermal power in the lightning channel can be written by

$$P_{th} = I^2{}_{rs}(t)\times R(t) \tag{3}$$

where, R(t) is the resistance of the conducting channel. R(t) is given by

$$R(t) = \frac{L(t)}{\sigma \pi r^2} \quad (4)$$

where, σ=10^4 mho/m[13], the conductivity of lightning channel; r=2 cm, the average radius of cross section of the lightning channel[14]; and L(t) is the distance travelled by the lightning. L(t) is given by

$$L(t) = \int_0^t V_{rs}(t)\, dt \quad (5)$$

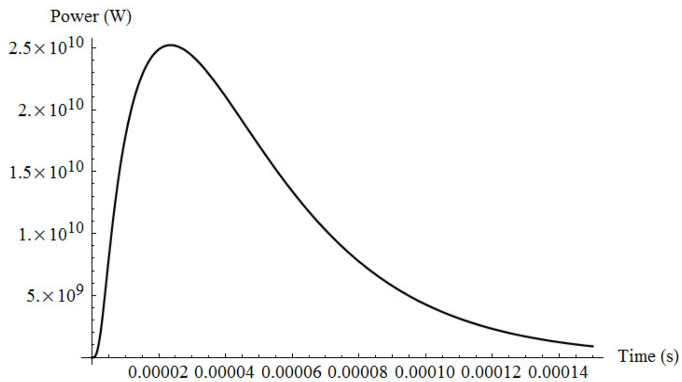

Figure-1
Thermal power in a lightning channel with time

The dissipated thermal power has been shown in figure 1. It has a peak value of about 2.6×10^{10} W. The total dissipated heat energy in the lightning channel is given by

$$W_{th} = \int_0^\infty P_{th}\, dt \quad (6)$$

The total dissipated heat energy in the conducting channel comes out to be around 1.58×10^6 J.

Radiated Energy: In this section, we calculated the total radiated energy due to the return stroke and lateral corona currents flowing in the lightning channel. Return stroke current has been described in the previous section. Below the tip of the return stroke, the whole channel up to ground surface is at higher potential than the surrounding medium left by the stepped leader. The negative ions and electrons along the entire channel from tip to the ground move towards the highly conducting return stroke core and constitute a current which immediately flows to the ground through this channel. Since this current is developed due to the radial movement of negative ions and electrons, it is known as "lateral corona current". The mathematical expression is given by[15]

$$I_{lc}(t) = \frac{KV^2V_0}{ab}\left[(b-a)\exp\left(\frac{-2t}{CR}\right) - b\exp\left[-\left(a+\frac{2}{CR}\right)t\right] + a\exp\left[-\left(b+\frac{2}{CR}\right)t\right]\right] \quad (7)$$

where, K=corona constant (10^{-16} AV^{-2} $m^{-1}s^{-1}$); V=potential difference between the return stroke and the leader sheath in volts and can be taken as 10^8 volts; C=distributed capacity of the leader sheath-return stroke core in farads/m; R=Distributed resistance of the above configuration (CR=5.3865 ms for I_0=22 kA).

Both currents flow simultaneously in the cloud-to-ground lightning channel and they are not separable, we call it return stroke-lateral corona (RS-LC) system. So, the total current is written by

$$I_{tot}(t) = I_{rs}(t) + I_{lc}(t) \quad (8)$$

Electric and magnetic fields have been calculated due to an arbitrary oriented lightning discharge channel using a vector potential "**A"** associated with the return stroke current[16]. Figure 2 shows the orientation of an arbitrary lightning channel in spherical-polar coordinates.

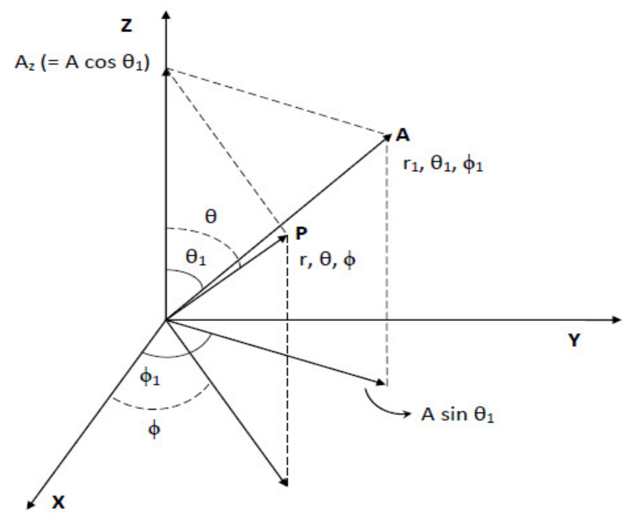

Figure-2
Schematic diagram shows the orientation of lightning channel. A(r_1,θ_1,ϕ_1) and P(r,θ,ϕ) are the lightning position and point of observation respectively

The general expression for "A" is given by

$$\boldsymbol{A} = \frac{\mu_0}{4\pi}\int \frac{I(t')}{r}\boldsymbol{dz}' \quad \textbf{(9)}$$

where, μ_0 is the permeability of the medium; r is the distance between the observation point and the source; dz' is the retarded elemental length of the channel; t' (= t-r/c) is the retarded time; and I(t') is the total current flowing through it. They did not consider the lateral corona current in their calculation. On the other hand we added this term to the return stroke current for better outcomes. The vector potential "A" can be written by

$$\boldsymbol{A} = \frac{\mu_0}{4\pi r} A_0 F(t') \quad (10)$$

"A_0" and F(t') can be found with the help of current distribution and velocity of the lightning discharge. The magnetic field components are given by[16]

$$H_r = 0 \quad (11)$$

$$H_\theta = \frac{A_0}{4\pi}\sin\theta_1 \sin(\phi_1 - \phi)\left[\frac{1}{r^2}F(t') + \frac{1}{cr}\frac{\partial}{\partial t}F(t')\right] \quad (12)$$

$$H_\phi = -\frac{A_0}{4\pi}\left[-\sin\theta\cos\theta_1 + \sin\theta_1\cos\theta\cos(\phi_1 - \phi)\right]\left[\frac{1}{r^2}F(t') + \frac{1}{rc}\frac{\partial}{\partial t}F(t')\right] \quad (13)$$

Similarly, the electric field components are given by[16]

$$E_r = \frac{2A_0}{4\pi\varepsilon_0}\left[\cos\theta\cos\theta_1 + \sin\theta\sin\theta_1\cos(\phi_1 - \phi)\right]\left[\frac{1}{r^3}\int F(t')dt + \frac{1}{r^2c}F(t')\right] \quad (14)$$

$$E_\theta = -\frac{A_0}{4\pi\varepsilon_0}\left[-\sin\theta\cos\theta_1 + \cos\theta\sin\theta_1\cos(\phi_1 - \phi)\right]\left[\frac{1}{r^3}\int F(t')dt + \frac{1}{r^2c}F(t') + \frac{1}{rc^2}\frac{\partial}{\partial t}F(t')\right] \quad (15)$$

$$E_\phi = -\frac{A_0}{4\pi\varepsilon_0}\sin\theta_1\sin(\phi_1 - \phi)\left[\frac{1}{r^3}\int F(t')dt + \frac{1}{r^2c}F(t') + \frac{1}{rc^2}\frac{\partial}{\partial t}F(t')\right] \quad (16)$$

Since, the RS-LC system is vertical (θ_1=0). So, the above expressions of magnetic and electric fields become

$$H_r = 0 \quad (17)$$

$$H_\theta = 0 \quad (18)$$

$$H_\phi = \frac{A_0}{4\pi}\sin\theta\left[\frac{1}{r^2}F(t') + \frac{1}{rc}\frac{\partial}{\partial t}F(t')\right] \quad (19)$$

$$E_r = \frac{2A_0}{4\pi\varepsilon_0}\cos\theta\left[\frac{1}{r^3}\int F(t')dt + \frac{1}{r^2c}F(t')\right] \quad (20)$$

$$E_\theta = \frac{A_0}{4\pi\varepsilon_0}\sin\theta\left[\frac{1}{r^3}\int F(t')dt + \frac{1}{r^2c}F(t') + \frac{1}{rc^2}\frac{\partial}{\partial t}F(t')\right] \quad (21)$$

$$E_\phi = 0 \quad (22)$$

The radiated energy by a source is determined by the Poynting vector "S", which describes the direction and magnitude of electromagnetic energy flow. The Poynting vector "S" is given by

$$\mathbf{S} = \mathbf{E}\times\mathbf{H} \quad (23)$$

where, E and H are the calculated electric and magnetic fields at point (r,θ,ϕ). All the terms in equation (23) which decrease much faster than ($1/r^2$) will have zero contribution to radiation energy at large distances. The survival components of electric and magnetic fields at large distances are given by

$$E_{rad} = \frac{A_0\sin\theta}{4\pi\varepsilon_0 rc^2}\frac{\partial}{\partial t}F(t')\ \hat{\theta} \quad (24)$$

$$H_{rad} = \frac{A_0\sin\theta}{4\pi rc}\frac{\partial}{\partial t}F(t')\ \hat{\phi} \quad (25)$$

E_{rad} and H_{rad} are the radiated electric and magnetic fields respectively. Imagine the source is at ground surface, the total radiated power passing through the upper hemispherical shell having radius "r" is given by

$$P_{rad}(t) = \int_{\theta=0}^{\pi/2}\int_{\phi=0}^{2\pi}|S|\, r^2\sin\theta\, d\theta\, d\phi \quad (26)$$

The total radiated energy is given by

$$W_{rad} = \int_{t=0}^{\infty} P_{rad}(t)\, dt \quad (27)$$

Using equations (23), (24), (25) and (26), "W_{rad}" becomes

$$W_{rad} = \frac{A_0^2}{12\pi\varepsilon_0 c^3}\int_{t=0}^{\infty}\left(\frac{\partial F}{\partial t}\right)^2 dt \quad (28)$$

The values of "A_0" and "F(t')" for the RS-LC system have been given by[3].

$$A_0 = \frac{V_0}{ab} \quad (29)$$

$$F(t') = F_1(t')\times F_2(t') \quad (30)$$

where,

$$F_1(t') = I_0\left[\exp(-\alpha t') - \exp(-\beta t')\right] + i_0\left[(b-a)\exp\left(\frac{-2t'}{CR}\right) - b\exp\left[-\left(a+\frac{2}{CR}\right)t'\right] + a\exp\left[-\left(b+\frac{2}{CR}\right)t'\right]\right];$$

$$F_2(t') = \left[a\exp(-bt') - b\exp(-at') + (b-a)\right];\ \text{and}\ i_0 = \frac{KV^2V_0}{ab};$$

where, I_0, V_0, a, b, α, β, V, K and CR are constants given in previous sections. The total radiated energy due to RS-LC system comes out to be around 3.23×10^3 J.

Results and Discussion

Lightning discharge contains huge amount of energy. Forest fires, making of holes in metal sheets, countless deaths and injuries to livestock, damage to buildings, communication systems, power lines and electrical systems are some of the observed facts which show the high energy dissipation in lightning. Aircrafts and space shuttles are also not safe to lightning strikes. Most of the energy is dissipated in resistive part of the air column, which appears as the heat or thermal energy to raise the temperature of the channel. The temperature of the column is so high and produces acoustic disturbances known as "thunder". Apart from thunder the electromagnetic radiation also carries energy. In this paper, we calculated the total thermal power, dissipated heat energy and total radiated energy due to the high current flowing in the lightning channel. The thermal power gets peak value of the order of 10^{10} W. The total dissipated thermal energy comes out to be of the order of 10^6 J. Most lightning return stroke contains heat energy approximately 3 kJ/m based on a peak current of 20 kA[17]. Experimental studies have shown that the return stroke channel length is ≤ 1.3 km[18], so the maximum heat energy for 20 kA current becomes of the order of 10^6 J, as we calculated. It has been observed that lightning generated shock waves and heat energy contribute to the production of atmospheric nitric oxide (NO) [19]. It is believed that the geomagnetic storms may also affect the lightning activity[20]. The calculated radiated energy comes out to be around 3.23 kJ or 1.2 J/m. The energy lost from the lightning channel by means of radiation has been estimated to be 10 J/m[21]. Some workers estimated the radiated energy about 24 kJ from lightning channel having peak current of 143 kA[22]. Our calculated radiated energy comes out to be one order less than the previous reported values. It is due to the moderate value of return stroke current used in our calculation. We have taken the peak value of return stroke current of 22 kA, but sometime it may reach up to 300 kA[9]. The total dissipated energy from lightning discharge in different forms may affect the ionospheric parameters like electron density, electron temperature, ion temperature, and ion composition etc. Strong seismic activity may also perturb the ionosphere[23].

It is found that the energy dissipated in the form of heat is much more than the radiated energy. With the potential dangers that lightning poses, scientists have tried to devise the lightning diversion techniques ranging from rocket-triggered lightning to laser-induced discharge[24,25]. In these techniques, electrified clouds get discharged prior to the lightning strikes and possible dangers can be avoided at a particular place. Rocket-triggered lightning experiments have been reported to successfully discharge the electrified clouds up to 60%[24]. It has been described that the laser induced techniques are the best source to trigger outdoor lightning[26]. In this technique, a collimated laser beam is used to ionize the air to create a conductive path for free charges in the sky to flow down to earth. This enormous amount of heat generating from lightning discharge may be used for mankind as an alternative source of energy, for example one can use this atmospheric electricity to heat the water, consequently hydrogen and oxygen gases will be produced. Hydrogen gas can be used as a fuel and oxygen will be beneficial in the hospitals. Further, we can avoid the lightning strikes on sensitive airborne operations and ground based experimental set-ups by using these techniques.

Conclusion

We calculated the energy dissipation by means of heat and radiation from the lightning discharge. It is found that the dissipated heat energy comes out to be much larger than the radiated energy. Further, the different modes have been described to avoid lightning strikes at the sensitive places. A technique of energy harnessing from lightning discharge also has been described. We hope that this study will yield a better understanding of the nature of lightning discharges, which could be important for future aeronautics problems.

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