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The heat transfer characteristics of lightning return stroke channel

Caixia Dong [a], Ping Yuan [a,*], Jianyong Cen [b], Xuejuan Wang [a], Yali Mu [a]

[a] Key Laboratory of Atomic and Molecular Physics and Functional Materials of Gansu Province, College of Physics and Electronic Engineering, Northwest Normal University, Lanzhou 730070, China
[b] School of Physics and Information Engineering, Shanxi Normal University, Linfen 041004, China

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ABSTRACT

Based on the time-resolved spectra of lightning return stroke processes, the evolutional characteristics of thermal conductivity and thermal diffusivity of the discharge channels are discussed. The distribution of temperature along the radial direction of channels at the peak current stage of return stroke is also investigated, and then the heat transferring characteristics along radial direction of the channels are analyzed. The results show that a temperature gradient along radial direction of lightning channel is formed due to the outward heat transfer. The closer the distance is to the current core channel, the greater the temperature gradient is and the more heat is transferred along the radial direction of the channel. The heat transferring in per unit length of the channel and per unit time is in the order of 10^4 J/m · s at the initial moment of lightning return stroke. After the peak current, the channel temperature decreases slowly and the heat transport coefficients vary as a monotonically decreasing function.

1. Introduction

The strong current during lightning discharge process resulted in a plasma channel with a temperature of 30,000 K or so in the atmosphere. Such a high temperature channel is the main source of forest fire and other lightning disasters related to the heating effect. Therefore, the issue about the heat and energy transmission of discharge channel is a subject of concern in lightning protection and research field. Based on the time integral spectra of the lightning return stroke processes, the thermal conductivity and the thermal diffusivity along the axial direction of the discharge channels have been analyzed by Chang et al. (2010). The internal energy and the total energy for per unit length of return stroke channel have been estimated according to the gas-dynamics model by Borovsky (1998). Heat and energy transmission are closely related to the temperature and its distribution in lightning discharge channel. The heat transferring along the radial direction of the return stroke channel is the main factor that affects the temperature decline of the core channel. Researches in this area will provide theoretical basis for improvement and perfection of the lightning protection systems. Presently, there are few reports about the heat transferring and its evolutional characteristics along radial direction of lightning channel.

Using time-resolved spectra of cloud-to-ground lightning return stroke processes recorded by a slitless high-speed spectrograph, and combing with the transport theory of air plasma, the variations of thermal conductivity and thermal diffusivity with time are analyzed in this work. And then the heat transfer characteristics of the return stroke channel are also investigated. This will provide reference data for further study on the thermodynamic properties, energy transmission characteristics of lightning discharge channel and the microcosmic physical mechanism of the discharge process.

2. Theoretical methods

2.1. Channel temperature

The core current channel is in typical plasma state and nearly fully-ionized during the lightning discharge process. In order to study the characteristics of lightning discharge channel by spectral diagnostics and plasma theory, the following basic assumptions (Orville, 1967, 1968; Spitzer, 1962) are needed: (1) Lightning discharge channel is optically thin; (2) The discharge channel is in local thermodynamic equilibrium (LTE). Uman and Orville (1965) have investigated the time integrated lightning spectra and verified the discharge channel to be optically thin for singly ionized nitrogen (NII). Moreover, Uman (1969) indicated that the quasi equilibration time for NII ions and that for electron and ion kinetic energies in the lightning return stroke channel is on the order of 0.01 μs. So the local thermodynamic equilibrium is achieved within the lightning channel in a short time compared with that in which the parameters of the channel change.

Under the local thermodynamic equilibrium (LTE) model, the temperature of lightning discharge channel (Cen et al., 2011; Wang et al., 2014) is calculated by.

$$\ln\left(\frac{I\lambda}{gA}\right) = -\frac{1}{kT}E + c \qquad (1)$$

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[*] Corresponding author.
E-mail address: yuanp@nwnu.edu.cn (P. Yuan).

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Where λ is wavelength; *c* is a constant; *I* is relative intensity of spectral lines (Barasch, 1970; Qiu, 2001; Campos et al., 2014); *E* is excitation energy; *k* and *A* are Boltzmann constant and transition probability, respectively; and *g* is statistical weight. Selecting multiple spectral lines of the same particle, and fitting line with $\ln(I\lambda/gA)$ as vertical coordinates, *E* as the horizontal coordinates and then the temperature can be calculated by the slope of the fitted line.

2.2. Electron density

Under the action of electromagnetic field, the atoms and ions can generate an additional energy, that is, their energy levels will be split, which result in the broadening of the spectral lines. The Stark broadening of spectral lines caused by the strong electric field plays a leading role in the lightning discharge plasma. Griem (1964) gave the following relationship between the electron density and the full width at half maximum (FWHM) of the line profile:

$$\Delta\lambda_{1/2}^{s} = 2\omega\left(\frac{N_e}{10^{16}}\right) + 3.5\mathrm{A}\left(\frac{N_e}{10^{16}}\right)^{1/4} \cdot \left[1\text{-}1.2{N_\mathrm{D}}^{\text{-}1/3}\right] \cdot \omega\left(\frac{N_e}{10^{16}}\right) \tag{2}$$

Here ω is the impact broadening coefficient of electron; A is the ion broadening parameter; and N_D is the number of particles within the Debye sphere (Xu et al., 2014). Since the widening of ion-induced perturbation is very small, and the contribution of quasi-static particles broadening is less than about 4% (Griem, 1964; Xu et al., 2014). In addition, the intensity of circular magnetic field around the core channel is usually in the order of 10^{-1} T, whose effect on spectral line broadening is much smaller than that of the strong electric field (Borovsky, 1995; Kong et al., 2015; Qie et al., 2005). Therefore, only the Stark broadening is considered in the calculation. Then the expression of electron density can be simplified to:

$$N_e = \frac{\Delta\lambda_{1/2}^{s}}{2\omega} \times 10^{16} \tag{3}$$

According to FWHM and broadening parameter of the corresponding spectral line, then the electron density can be determined by Eq. (3).

2.3. Transport coefficients of lightning return stroke channel

Thermal conductivity and diffusion coefficient are the basic parameters reflecting the characteristics of energy transmission of the discharge channel, which depend on the particle concentration, pressure, temperature and electron density in the discharge channel, and they also depend on the collision effects between particles. The main components in the lightning channel are NI, NII, NIII, OI, OII, OIII, ArI, ArII, ArIII and electrons. Here, the NI, NII, NIII represent the neutral nitrogen atom, the single ionized nitrogen ion and the second ionized nitrogen ion, respectively. The relative concentrations of ions with higher ionization degree in the channel are so low that their contribution can be neglected. And then the collisions between electron and electron, electron and neutral atoms, electron and the singly or the secondary ionized ions are mainly considered in the calculation. The collision integral between *i* and *j* particles is followed as (Capitelli et al., 1996, 2000a, 2000b; Devoto, 1967):

$$Q_{ij}^{(l,s)}(T) = \frac{4(l+1)}{(s+1)!\left[2l+1-(-1)^{l}\right]} \cdot \int_0^\infty \exp(-\gamma^2)\gamma^{2s+3}Q_{ij}^{(l)}(\nu)d\gamma \tag{4}$$

Where $Q_{ij}^{(l)}(\nu)$ is the differential transmission cross section (Liboff, 1959); ν is the relative speed of particles; and the reduced relative speed is defined by $\gamma = \sqrt{\frac{\mu_{ij}}{2kT}}\nu$ in which μ_{ij} is the reduced mass of the colliding particles.

According to the formula (4), the collision integral for $l = 1$ and 2 is estimated (Capitelli et al., 2000b), and then under the LTE condition, the transport coefficients of discharge channel are obtained according to the transport theory of the air plasma.

a. Thermal conductivity (Capitelli et al., 1996, 2000a; Devoto, 1967):

$$\lambda_e = \frac{75{n_e}^2k}{8}\left(\frac{2\pi\mathrm{kT}}{m_e}\right)^{1/2} q^{22}\left(\begin{vmatrix} q^{11} & q^{12} \\ q^{21} & q^{22} \end{vmatrix}\right)^{-1} \tag{5}$$

b. Thermal diffusivity (Capitelli et al., 1996, 2000a; Devoto, 1967):

$$D_e^T = \frac{15{n_e}^2\sqrt{2\pi m_e kT}}{4}\begin{vmatrix} q^{01} & q^{02} \\ q^{21} & q^{22} \end{vmatrix} \cdot \left(\begin{vmatrix} q^{00} & q^{01} & q^{02} \\ q^{10} & q^{11} & q^{12} \\ q^{20} & q^{21} & q^{22} \end{vmatrix}\right)^{-1} \tag{6}$$

The q^{mp} elements (Devoto, 1967) depend on the electron density, the particle number density and the collision integral $Q_{ij}^{(l,s)}(T)$.

2.4. Heat transfer along the radial direction of the discharge channel

Heat conduction and diffusion are the main ways of energy transmission along the radial direction of lightning channel. Since the temperature difference along the axial direction of the lightning channel is very small, the lightning channel could be regarded as an axial uniform cylinder. If the convection between the plasma gas in channel and the surrounding air is neglected, the radial heat conduction is only considered. On the basis of Fourier heat conduction law, the heat passing through a given area in per unit time can be expressed as:

$$dQ = -\lambda\left(\frac{dT}{dr}\right)_{r_0} dA \tag{7}$$

Where λ is the thermal conductivity; *dT*/*dr* represents the temperature gradient along the radial direction; and *A* is the area of transmission. Besides, negative sign means that heat transport along the direction of temperature decrease.

Under the condition of one-dimensional steady heat conduction, according to energy conservation and their transfer rate equation, the differential equation of heat conduction along radial direction under the cylindrical coordinate system can be expressed as:

$$\frac{1}{r}\frac{d}{dr}\left(\lambda\mathrm{r}\frac{dT}{dr}\right) = 0 \tag{8}$$

Within the range of the radius of our concern, the thermal conductivity almost remains unchanged along the radial direction. Solving differential Eq. (8) with boundary conditions, the distribution of temperature along the radial direction of the channel can be analyzed.

3. Results and analysis

The spectra of two cloud-to-ground (CG) lightning discharge processes were captured by a slitless high-speed spectrograph in the wavelength range of 400–1000 nm; the recording system of the spectrograph was a high-speed video camera with recording speed of 9110 fps. And a transmission grating of 600 lines mm^{-1} was put in front of the object lens of the camera. The original spectra are the pictures of the whole discharge channel. According to the shape of the channel, the positions with good spectral resolution along the channel are selected, and the pictures are transformed into the spectral graphs represented by the relative intensity distributions of spectral lines. Fig. 1 shows the time-