Research on observation method of leader discharge thermal expansion based on quantitative schlieren technique

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Abstract. Lightning is one of the main causes of UHV DC transmission lines trip-outs. To measure the leader discharge thermal expansion of leader could help us to have an in-depth understanding of the lightning protection. In this paper, a temperature measurement system based on calibration schlieren principle is developed in the first place. Combined with a high speed camera, the spatial resolution of this temperature measurement system is 100 μm/pixel. Secondly, the image process is discussed in this paper. Thirdly, the temperature distribution of an alcohol lamp is obtained by using this system. It shows a good agreement with the measurement results of precision thermocouple which validates the effectiveness of the developed temperature measurement system. Finally, this system is used to acquire the thermal expansion of leader discharge voltage in a 1m rod-plane gap, and the measurement results are discussed.

1. Introduction
Lightning is one of the main causes of UHV DC transmission lines trip-outs. With the improvement of the insulation configuration of UHV DC lines, lightning wrap is the main cause of lightning strikes on UHV overhead transmission lines [1] [2]. The overvoltage caused by the upward leader generated by the conductor connects to the downward leader generated by the lightning is considered as the reason of the UHV DC lightning strike[3]. Therefore, the study of the positive lead produced by the conductor under the thundercloud has an important role in the research of lightning protection for UHV DC. The leader discharge is a high-conductivity thermal ionization channel formed by the electrons generated by the streamer, and the channel gas temperature can reach several thousand K is shown by the theoretical calculations. Gas temperature plays an important role in the initiation and development of leader discharge, its accurate measurement is of great significance for the study of lightning protection.

The temperature measurements of leader discharge require a combination of high spatial resolution and temporal resolution. A 16.7 m positive rod-plate leader channel was observed using the schlieren method, the transmitted optical density of the schlieren photo under the light was measured by the researchers, taking 1/4 of the photon density peak and valley as the threshold to get the thermal diameter of the leader [4]. However, the accurate thermal expansion characteristics of the discharge channel cannot be obtained by this method. The leader channel diameter was obtained by setting the threshold value for the grayscale curve and measuring the grayscale of the leader optical images [5],
but the grayscale of the optical images is affected by the optical observation distance and the optical imaging system, and the threshold value is also lack of scientific basis.

As above, because of the characteristics of hundreds of micro meter in diameter, thousands of K in temperature, and dozens of microseconds in discharge time during the leader development, the existing measurement methods for arc are not suitable for the measurement of the leader thermal diameter. However, calibration schlieren diagnosis provides a simple and nonintrusive way of measuring the temperature field of leader discharge with high spatial and temporal resolution [6] [7].

In this paper, a calibration schlieren system aimed at measuring the temperature of leader discharge is proposed. The design of the optical system was described. The next section presents the image processing method. Then the alcohol lamp and the precision thermocouple were used to evaluate the accuracy of the system. In order to measure the thermal expansion of leader, 1m rod-plane discharge experiment subjected to positive switching impulse was described, and the results were discussed. Finally, conclusions were given.

2. Design of measurement system

![Schematic diagram of the schlieren system.](image)

The measurement system is schematically illustrated in figure 1. It mainly consists of a light source, a coupling fiber, a diverging lens, a collimating lens, a converging lens, a knife edge and a high-speed camera (imaging system). The devices are arranged coaxially in order to ensure the accurate measurement. The Diverging lens is disposed at the focus of the collimating lens, and the collimating lens converts the divergent light emitted by the light source into a parallel beam. The parallel beam passes through the measurement area and is focused by a converging lens, then the source image is generated at the focus of the converging lens. A knife edge with a cutting step of 10 μm is placed at the focal plane and it is adjusted so that the detected intensity signal is reduced to approximately 50% of the signal without knife edge. The beam passes through the knife edge is imaged on the camera photosensitive element by the photographic objective lens adjustment to realize the recording of the schlieren image. It can be seen that the spatial resolution of the schlieren measurement system is mainly determined by the main lens and the imaging system. Therefore, the improvement of the spatial resolution is depend on the main lens and the imaging system optimized design.

2.1. Design of the light source

The laser source and LED source are used in the schlieren system. The laser light source has the advantages of high brightness and strong directivity. However, due to the strong coherence of the laser beam, the diffraction effect is easily caused by the optical system, and the diffraction ring appears on the image, which affects the imaging effect of the measurement system. Therefore, an LED light source with incoherence is used in the system as the illumination source.
A monochromatic light is used in the system, which can eliminate the influence of dispersion. A typical CCD/CMOS spectral response curve is shown in figure 2. The center of the spectral response curve is 550 nm, which is the green light region. The system uses a quasi-monochromatic LED light source with a center wavelength of about 532 nm. The maximum output illuminance is 230,000 Lx, and the output optical signal is coupled with a diameter of 3 mm. The coupling efficiency is 90%.

2.2. Design of the light path
Since the divergence angle of the coupling fiber is difficult to match with the divergence angle of the collimating lens, the uniformity of the plane light is not homogeneous when the diameter of the beam ejaculating from the optical fiber expand to 150 mm directly, which affects the imaging quality. Therefore, a diverging lens is arranged between the collimating lens and the coupling fiber. A flat concave divergent lens is obtained by two-stage expansion of a diverging lens and a collimating lens to obtain high-flat planar light, and the two-stage collimated beam expanding system is shown in figure 3.

After the virtual image of the coupling fiber passes through the collimating lens and the condenser lens, it is imaged at the focus of the condenser lens, that is, the spot diameter formed by the plane of the knife edge is about 9.9 mm. The development speed of the positive leader is about $1 \sim 1.5 \times 10^5 \text{m/s}$ [8], and the gap length is 1-3 m, the duration of the discharge is about 67-300μs, respectively. In order to achieve high time resolution of the leader discharge temperature field schlieren image, the FASTCOM SAX2 high-speed camera based on CMOS image sensor is used as the schlieren image recording device in the system. A telephoto lens with 400 mm focal length is used and the spatial resolution of system is 100μm/pixel. The imaging system consists of a concentrating lens, a high-speed camera, and an imaging objective (camera lens) of the high-speed camera. The light emitted from the temperature field to be measured is focused by a condenser lens, and the imaging objective is adjusted to image the emitted light on the image plane (CMOS sensor) of the high-speed camera. The converging lens first performs an imaging process, and the imaging objective lens is imaged by the converging lens as an observation object, and is subjected to secondary imaging on a high-speed camera CMOS sensor. Therefore, the imaging effect of the measurement system is determined by the lens system composed of the imaging objective lens and the condenser lens.
3. Image process
The spatial resolution of the schlieren system is 100μm/pixel, too few sample points will cause a large error in the calculation of the temperature. Therefore, the bicubic interpolation method is used in the schlieren image interpolation, different interpolation multiple results are shown in figure 4.

Due to the lower resolution of the original schlieren image, the edge position of the leader channel has a zigzag shape, and the internal grayscale of the leader channel has a mosaic phenomenon due to discontinuity. After bicubic image interpolation, the edge of the leading channel image is smoothly transitioned, and the internal grayscale of the channel is continuously distributed. In order to balance the sampling points and calculation efficiency, the interpolation multiple is selected to be 60 times.

4. Verification of Measurement System
For calibration reasons, the alcohol lamp and precision thermocouple with 0.5% accuracy is used to validate the uncertainty of the schlieren system. The temperature produced by the alcohol lamp is measured by the proposed schlieren system and thermocouple respectively. A typical comparison between thermocouple and schlieren measurements of temperature at the axial plane y=17 mm is shown in figure 5. The measurement results is shown in figure 6, the results show that an excellent agreement between the two measurement techniques. The uncertainty of system is estimated to be about 5%.
5. Measurement results
The typical measurement results of the quantitative schlieren system under 1 m positive rod-plane discharge are shown in figure 7. The schlieren observation shows that when the flow-lead system stops developing, the radial expansion rate of the leader channel decreases rapidly due to no energy injection, and then the leader channel gradually dissipates, and the dissipation process lasts for about 350 μs.

The image processing techniques, Abel transforms and thermodynamic equations were used to calculate the temperature distribution of the leader channel from the schlieren images, as shown in figure 8. After the birth of the leader, the radius of the central thermal ionization region of the leader...
channel gradually increases with the injection of continuous current. When the gas molecular temperature in the high temperature region of the leader channel increases with the current injection, the gas pressure increases with the temperature according to the gas state equation. Therefore, the leader channel has a pressure gradient from the center to keep the high temperature gas in the center of the leader channel. The outward migration causes the temperature in the surrounding area to rise. When the injection of high temperature gas molecules gradually increases the temperature of the gas around the high temperature region to above 1500 K, the electrons in this region increase significantly, and the migration of a large amount of electrons causes the temperature in the region to continue to rise.

6. Conclusions
The applicability of calibration schlieren method for temperature measurement of leader discharge for positive discharge in long air gap was studied in this paper. A basis of light propagation characteristic in non-uniform flow field was proposed. The method made use of a calibration procedure that convert grayscale of each pixel in a schlieren image into a corresponding deflected angle directly. The bicubic interpolation method is used to improve image quality. The uncertainty of the system was estimated to be about 5% according to verification test. The 1 m rod-plane positive leader discharge experiments were conducted, the spatial and temporal distributions of the leader temperature of the leader channel were obtained. Then, the thermal expansion characteristics of the pilot channel are discussed in combination with the observations.

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