Comparison on Lamp Characteristics of Highway Tunnel Lighting System

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Abstract. This paper introduces the expression form of the light field of the light source and the description method of the light intensity distribution characteristics, and details the different types of lamps in the tunnel lighting system from the principle of light emission, optical characteristics and application scope. A comprehensive comparison of performance. The results show that LED lights have high efficiency, long service life, and excellent color rendering, which are in line with the concepts of energy saving, emission reduction, and environmental protection. They have huge room for technological improvement and will gradually replace gas discharge lamps as the main light source for tunnel lighting.

1. Introduction

The luminaire is the core component of a tunnel lighting system. As a light source, it radiates electromagnetic waves in all or a certain direction in a three-dimensional space. The spatial distribution of light energy in the visible light range is the light field of the light source. Light intensity distribution characteristic data is the basis for lighting design and calculation. At present, the most widely used is to translate the coordinate system into a book. The International Lighting Commission [1] has adopted this scheme. As shown in Figure 1, the vertical line from the center of the light emitting surface to the illuminated plane is the first axis of the system. In road lighting, the \(0^{\circ}\sim180^{\circ}\) plane is parallel to the longitudinal centerline of the road, and the \(90^{\circ}\sim270^{\circ}\) plane is perpendicular to the longitudinal centerline of the road.

![Figure 1. Book-based coordinate system](image_url)
Figure 2 shows the light intensity distribution in the plane of C90°~270° and C0°~180° of an LED tunnel lamp, and Figure 3 shows the light intensity distribution in the plane of C90°~270° and C0°~180° of a high pressure sodium lamp.

As the electrical and optical properties of the luminaire are related to the safety, comfort, energy consumption, and early construction and later operating costs of the tunnel lighting, it is necessary to conduct in-depth analysis and comparison of the characteristics of the tunnel-related luminaires to fully utilize the tunnel lighting system efficiency [2].

2. Overview of Tunnel Lighting Types
To distinguish tunnel lighting from the principle of light emission, it can be divided into two categories: gas discharge lamps and solid state light lamps. The specific classification is shown in Figure 4. At present, the artificial lighting of highway tunnels mainly uses high-pressure sodium lamps and LED lamps, and a few of them use metal halide lamps, electrodeless lamps and other lamps. Fluorescent lights are generally used in urban tunnels, and are often used in emergency parking zones in highway tunnels. LED lamps are gradually replacing other types of lamps with the continuous improvement of their light efficiency and the continuous decline in cost.

3. Gas discharge lamp

3.1. High-voltage lamps
3.1.1. High-pressure mercury lamp. High-pressure mercury lamp is the first generation of high-pressure gas discharge lamp, put into practical use in the 1930s. The discharge tube is made of quartz glass, the interior is filled with mercury and inert gas, and the pressure during discharge is about 106Pa. Due to the existence of the auxiliary electrode beside the main electrode of the lamp, the high-pressure mercury lamp can be started without an external starter, and its structure is shown in Figure 5.

The discharge tube is contained in a glass shell, which is filled with an inert gas for insulation, and the inner surface of the glass shell is coated with fluorescent powder to make up for the lack of red spectral lines in the high-pressure mercury lamp and improve the light efficiency of the lamp.

The high-pressure mercury lamp has a maximum light efficiency of 65lm/W and a fast light decay rate. Its spectrum has a strong green light component. The color rendering index ranges from 40 to 60. The color temperature ranges from 3500K to 4500K. The life is about 15000h. Compared with other high-pressure discharge lamps, high-pressure mercury lamps have a lower market price and are more commonly used in courtyard and landscape lighting.

3.1.2. High-pressure sodium lamp. High-pressure sodium lamps are a type of high-pressure gas discharge lamps, which were applied in the 1960s and quickly replaced low-pressure high-pressure mercury lamps. The discharge tube has two kinds of polycrystalline alumina and ceramic, which are filled with mercury and metallic sodium, and filled with xenon gas as the starting gas. The structure of the high-pressure sodium lamp is shown in Figure 6.

The light-emitting principle of high-pressure sodium lamp is: after the lamp is powered on, an arc occurs between the electrodes at both ends of the discharge tube, and the high temperature of the arc acts on the sodium and mercury in the gasification tube, and the electrons emitted by the cathode impact the sodium atom during the movement toward the anode, so that it obtains Energy generates ionized excitation, which radiates light energy in the process of recovering from an excited state to a stable state.

The optical characteristics of the high-pressure sodium lamp are related to the pressure of sodium vapor in the discharge tube. The light source has the highest luminous efficiency when the pressure is 10kPa, the color temperature is about 2000K, and the color rendering index is about 20. Increasing the sodium vapor pressure in the discharge tube can increase the color temperature of the entire lamp and improve the color rendering, but at the same time significantly reduce the luminous efficiency.

The main part of the spectrum of the high-pressure sodium lamp is centered on the yellow wavelength region, and the light energy distribution is also more in the red wavelength region, but the light energy distribution in the shorter wavelength region is smaller, as shown in Figure 7.

High pressure sodium lamps are widely used in places with high brightness levels and insensitive to color rendering, such as roads, streets and parks. High-pressure sodium lamps commonly used in tunnel lighting have three power ratings: 100W, 250W and 400W. Compared with high-pressure mercury
lamps, fluorescent lamps and metal halide lamps, high-pressure sodium lamps have a higher light efficiency of up to 140lm/W, a lifetime of 20,000h, and low color temperature and poor color rendering are their disadvantages[3].

3.1.3. Metal halide lamps. The structure of the metal halide lamp is similar to that of the high-pressure mercury lamp. It differs from the high-pressure mercury lamp in that the discharge tube is filled with metal halides in addition to mercury. If the metal is directly filled, the metal in the discharge tube will be vaporized and charged after being energized. Attached to the inner wall of the discharge tube, this phenomenon does not occur with metal halides, which is also the origin of the name of the metal halide lamp. In addition, in order to improve the light efficiency and color rendering, argon is often filled. The power of a single metal halide lamp can reach 2000W, and the output luminous flux is large. It can be applied to stadiums, large shopping malls, industrial plants, stations and docks.

Metal halide lighting has a high efficiency of 65 ~ 120lm/W. The spectrum is widely distributed in the visible light range. The color temperature range is 2700 ~ 4500K. The color rendering index is 65 ~ 90. The light efficiency and color rendering are better than high-pressure mercury. Lamp, and can adjust the output of the luminous flux, but the cost of the dimming equipment is high. The life of low-power metal halide lamps is about 7500h, and the life of high-power lamps is about 20,000h. It takes 5min when fully started, and it needs to wait 5 ~ 10min if it restarts after power off.

3.2. Positioning

3.2.1. Low-pressure sodium lamp. The low-pressure sodium lamp was invented in 1930. It is an electric light source that generates visible light by using low-pressure sodium vapor discharge. In 1932, the Dutch company Philips commercialized the low-pressure sodium lamp for the first time. The low-pressure sodium lamp emits monochromatic light with a wavelength of 589.0nm and 589.6nm. The two yellow spectral lines are located close to the most sensitive green spectral line of the human eye at a wavelength of 555.0nm[4]. There is no chromatic aberration in the human eye. Seeing high resolution and good contrast, but because the spectral distribution is too narrow and the color rendering is extremely poor, it is not suitable for commercial lighting applications. It is mainly suitable for roads, viaducts, tunnels and intersections with high visibility and color rendering requirements. The low-pressure sodium lamp has a long life span of 10,000 ~ 20,000h and a luminous efficiency of 200lm/W. It is the light source with the highest light efficiency among all artificial light sources.

3.2.2. Fluorescent lamp. Fluorescent lamps are a type of low-pressure mercury lamp, which is filled with mercury and some inert gases, as shown in Figure 8. Due to the large length and size, it can provide better longitudinal uniformity in the tunnel, and the visual induction effect is better than short lamps. Fluorescent lamps have a light efficiency range of 70-90lm/W, a narrow spectral range, a color temperature of about 4000K, and a color rendering index of about 80.
3.2.3. Induction lamp. Induction lamps are called electromagnetic induction lamps. Because there are no electrodes and filaments in them, they are divided into low frequency electromagnetic induction lamps and high frequency electromagnetic induction lamps by electromagnetic frequency. Both are composed of high frequency generators, couplers and bulbs. As shown in Figure 9. the coupler of the low-frequency electromagnetic induction lamp is externally installed, which has a good heat dissipation effect, but the volume is large; the coupler of the high-frequency electromagnetic induction lamp has a built-in, which has a poor heat dissipation effect, but the volume is small. The light effect of low frequency electromagnetic induction lamp is generally about 85lm/W, the light effect of high frequency electromagnetic induction lamp is generally about 80lm/W, and the electromagnetic interference of low frequency electromagnetic induction lamp is relatively small.

Because of the use of reflectors, the electromagnetic induction lamp used in tunnel lighting has a low overall light efficiency and a wide spectral distribution range. The color rendering index is generally greater than 80, which has better color rendering. The color temperature range is 2700 ~ 6500K. Due to serious electromagnetic interference problems, the application place is strictly restricted, and the heat dissipation of the electromagnetic induction lamp is difficult to solve, and it is difficult to make high power.

Figure 9. Structure of electromagnetic induction lamp

4. Solid state light (LED lamp)
LED lamp is the only solid-state light source at present. Its essence is a semiconductor diode. The core part is an internal PN junction. The light-emitting principle is: When the LED is powered on, the electric field in the P region and the electrons in the N region are recombined at the PN junction. Optical radiation is generated during the process, as shown in Figure 10.

In the early days, gallium arsenide (GaAs) light emitting diodes could only emit infrared or red light. Later, blue LEDs based on wide bandgap semiconductor materials gallium nitride (GaN) and indium gallium nitride (InGaN) appeared. It emits approximately monochromatic light, and the lighting place needs white light. Therefore, based on the blue LED lamp, a phosphor is covered above the LED chip. The phosphor converts the LED monochromatic light into white light with three primary colors, as shown in Figure 11. This method is mostly used on the market because of its lower cost.

Figure 10. LED lighting principle

Figure 11. Phosphor conversion
The distribution of the LED spectrum\[5\]using this method has the following characteristics: a relatively narrow peak near the wavelength of 450nm, a relatively broad peak in the range of 550-600nm, and the other wavelength ranges are relatively radiant. The intensity is very low, as shown in Figure 12.

The light efficiency, color temperature, and color rendering index of LED lamps are greatly affected by the composition of the phosphor. By adjusting the composition and dosage of the phosphor, the color temperature can be adjusted between 2700K and 10000K. In general, the higher the color temperature is, the higher the light efficiency is, but the color rendering is poor, and the color rendering index is generally lower than 75. When the LED color temperature is lower, the light efficiency is lower and the color rendering performance is better. The color rendering index is generally greater than 80.

Early LEDs had lower power and lower luminous flux, and were mainly used to make indicator lights. High-power LEDs began to appear only at the end of the 20th century. In 2002, 5W LEDs appeared with a luminous efficiency of 18-22lm/W. In April, 2012, CREE's LED test specimens achieved 254lm/W. The company announced that its light efficiency has historically exceeded 300lm/W and reached 303lm/W.

5. **Comprehensive comparison of lamp characteristics**

In fact, there is no perfect luminaire for tunnel lighting. Each type of luminaire has its advantages and disadvantages. It needs to combine factors such as energy consumption, light decay, color temperature, color rendering, penetration, life span, and dimming. After comprehensive consideration, according to the previous analysis of each type of lamp, the characteristics of different lamps are arranged as shown in Table 1.

As can be seen from the table above, compared with gas discharge lamps, LED lamps have obvious advantages in many aspects:

1. Energy saving. At present, the commercialized LED light efficiency reaches 135lm/W. Since LED is a directional light source, the light utilization rate is high, and the difference between the light efficiency of the light source and the system light effect is small.

2. Long life. At present, the life of LED light sources can reach 50000h, which is significantly higher than other discharge lamps, and the failure rate is very small. The main cause of failure is the power driver.

3. LED has excellent color rendering, and the color rendering index is generally greater than 70.

4. The color temperature range of the LED is 3000K to 6500K, which can be configured according to the needs of the lighting scene.

5. LED supports stepless dimming, which is easy to achieve "on-demand lighting" and can achieve maximum energy saving through refined management\[6\].

In addition, since LEDs distribute light through a lens, the lens parameters are easy to control during processing. Therefore, the light intensity distribution of LED lamps can be accurately controlled through the lens.
Although fluorescent lamps, high-pressure sodium lamps, and metal halide lamps can adjust the output of luminous flux, the technology to achieve it is complicated. At the same time that the luminous flux is reduced, the indicators such as light efficiency, color temperature, and strobe will be significantly changed, and the overall efficiency of dimming is poor.

As shown in Figure 13, in terms of growth of light efficiency, the light efficiency of traditional gas discharge lamps has no room for improvement after decades of technological development, and the light efficiency of LEDs has been rapidly improved in the past 10 years. Experiments Room and commercial LED light efficiency maximum value is constantly being refreshed, and there is still a lot of room for growth.

![Figure 13. Luminous flux growth trend of various lamps](image)

| Lamp type               | Luminous efficiency / (lm/W) | Color rendering index | Color temperature /K | Life / h | Adjust the light |
|-------------------------|------------------------------|-----------------------|----------------------|----------|-----------------|
| Fluorescent lamp        | 70–90                        | 80                    | 4000                 | 20000    | √               |
| High-pressure mercury lamp | 35–65                        | 40–60                 | 4500                 | 15000    | ×               |
| HPS                     | 120–140                      | 25                    | <2500                | 20000    | √               |
| Metal halide lamp       | 80–120                       | 60–80                 | 4000                 | 20000    | √               |
| Electromagnetic induction lamp | 85                        | >80                   | 2700–6500            | 15000    | ×               |
| LED lamp                | 110–130                      | >70                   | 2700–6500            | 50000    | √               |

6. Conclusion
This article summarizes the light-emitting principle, optical characteristics, and application range of commonly used lamps in tunnel lighting systems, and compares the characteristics of different types of lamps on this basis. The results show that LED lamps are gradually replacing gas discharge lamps with the advantages of energy saving, long service life, good color rendering, wide adjustable color temperature, and support for stepless dimming. They will become the main light source for tunnel lighting and have broad application prospects.

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