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LED 光源在淡水雾和海雾中的穿透性能

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摘 要:交通、船舰、机场等应用领域的信号灯、探照灯容易受到天气因素的影响,本文通过实验比较了不同颜色 LED 光源在淡水雾和海雾中的穿透性能,并研究了淡水雾中 LED 光源的透光性与距离的关系.结果显示:各种颜色 LED 光源在雾中的透射率随距离呈指数关系下降;而且,淡水雾和海水雾中,黄光 LED 的透过率均为最大.本研究工作为信号灯、探照灯等功能照明提供了设计依据.

关键词:穿透性能;LED 光源;雾;信号灯

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Penetration Properties of LED Light Sources in Water Fog and Sea Fog

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Abstract: Signal lights, navigation lights and searchlights used in transportation, ships, airport and other applications are vulnerable to be influenced by weather factors. The penetration properties of different color LED light sources in water fog and sea fog were compared by a series of experiments, and the relationship between the transmittance T of LED light sources and distance in water fog was researched. Experimental results show that the transmittance T of all kinds of color LEDs declines exponentially with the increasing of transmission distance in fog; both in water fog and sea fog, the yellow LED has the maximum transmittance compared to other color LED sources. This research work will provide a basis for the design of signal lights, searchlights and other functional illuminating fields.

Key words: Penetration properties; LED light source; Fog; Signal light

0 Introduction

As LED has a series of advantages such as narrow wavelength bandwidth, large color gamut, adjustable voltage, energy-saving and long life, it has been widely used in navigation lights, transportation lights, airport signal lamps, ship searchlights and other traffic-functional illuminating fields[1-3]. One of the most important indexes to evaluate whether a light source used at traffic fields good or not is the visibility distance. Research indicates that weather is one of the most critical factors that influences the visibility distance, including atmospheric particles, aerosols, fog, snow and hail[4]. Fog is the most critical factor that restricts human′s traffic activities and it has a serious hazard to the traffic safety. So the improvement of penetration

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property of LED light source in fog will effectively improve the traffic safety in foggy weather.

At the present time, all the traffic navigation lights, airport lights and ships signal lights use yellow light to display the position and the outline in fog. Although it has international generality, so far there haven't any hard relative evidences. As for the research about the penetration properties of light in fog medium, B. R. Babaria *et al*. once made a series of research about this in a circumstance that was filled with synthetic fog. It was found that with the increasing of density of fog and the distance, it actually had a restrict effect on the transmission of different colors' light, but the most evident color LED's result was not shown. Lv Zheng *et al*. also studied the optimum wavelength of visible light with good penetration properties in fog by several experiments. They used air humidifiers to make artificial fog, chose the high power halogen lamps as the light source, and made a comparison of penetration properties of light in different densities of fog. But they only verified the penetration properties of halogen lamps in their experiments and ignored the LEDs'. Zhang Qian *et al*. measured the penetration properties of low power halogen lamps and LEDs of four colors in fog, and concluded the optimum range of wavelength of visible light with good penetration properties. But they only did a research about the relationship between penetration properties and fog density, ignored the distance. And most of them only tested the illuminance value at one point, due to the fog is instable, the experimental value will have a big measurement error[5-7].

In this paper, we chose different color LEDs as the light sources and used 25 illuminance meters to detect the illuminance value at different points to minimize the experiment error caused by the fog instability. A comparison of penetration properties of different colors LED light sources in water and sea fog were made, and the relationship between the transmittance T of LED light sources and distance in water fog were studied.

1 Weather changes influencing signal lights

The influences on signal lights by the weather changes are mainly reflected by the influences on the visibility distance by fog (water vapor), dust, smoke, rain, snow, hail and other weather factors. There is large amount of water vapor in the air. When the amount of water vapor increases, water vapor will condense into fog, then the absorption, refraction and scattering function of fog will greatly shorten the visibility distance. Dust and smoke also have strong absorption to the lights of short wavelengths. In quite a long distance, when we look at the light in the air of dust and smoke, the color of lights will turn to red, which belongs to long wavelength light. It is easy for snow to cover on the refraction glasses and colored glasses to create a phenomenon named snow cover, which will make snow have a serious effect on the visibility distance. In contrast, rain and hail will clear the dust and smoke for the air, so their impacts on the visibility of signal lamps are less than that of fog[8-9]. So the paper preferred to research the effect of fog on the visibility distance of traffic signal lights.

As is known that there's large amount of water vapor in fog, and it will absorb, refract and scatter the incident light. The refraction can be ignored in actual measurement for it has little influences on the signal lights. The other two effects will create a comprehensive attenuation. The intensity of water molecules' absorption and scattering ability on different wavelengths are slightly different. Table 1[9] shows how the scattering intensity, the absorption intensity and their comprehensive attenuation intensity change with the wavelengths both in distilled water and bay water, in which a is volume absorption coefficient, b is scattering coefficient, c is volume attenuation coefficient.

Table 1 Distilled water's and bay water's scattering, absorption and their comprehensive attenuation intensity with the changes of wavelengths

Wavelength/	Distilled water			Bay water		
nm	a	b	c	a	b	c
400	0.042	0.038	0.080	—	—	—
420	0.031	0.030	0.061	0.625	0.175	0.800
440	0.021	0.025	0.046	0.448	0.180	0.628
480	0.020	0.017	0.037	0.267	0.180	0.447
520	0.028	0.013	0.040	0.171	0.180	0.351
560	0.044	0.009	0.053	0.143	0.180	0.323
600	0.190	0.007	0.197	0.249	0.180	0.429
640	0.287	0.005	0.292	0.320	0.180	0.500
680	0.402	0.004	0.406	0.409	0.180	0.589
700	0.572	0.004	0.576	0.560	0.180	0.740

As shown in Table 1, the transmittance windows of fresh water and sea water are different from each other because of the absorption and scattering of the suspended substances in bay water and the water itself. So in order to make it clear how the foggy weather influences the penetration properties of signal light sources, it requires us to research on the penetration properties of LED in water vapor and sea water vapor respectively.

2 Experimental apparatus and method

2.1 Choose LED light source for testing

Because of the relation between man and nature, eyes are more sensitive to red, yellow, green and blue. As for the signal light source, they must use some colors that are quite different from each other. So we usually choose white, red, yellow, green, blue, and purple as the color of signal lamps. In the meantime, signal lamps still need necessary intensity, due to the signal intensity of blue and purple is somewhat weaker, we firstly choose white, red, yellow and green as the signal light source colors[10]. Because LED′s spectral wavelength has a narrow bandwidth, and it has a good monochromaticity, it has been the best choice for signal lights at present. So in this paper, we did a research about the penetration properties of LED light sources of five colors, which were yellow, red, blue, green and white, in fresh water fog and sea fog respectively. The spectral distribution of LED light sources of five colors was shown is Fig. 1, and the peak wavelength of each color LED was given in Table 2. In the experiment, we used 25 illuminance meters of which the smallest range was 0.1 lx and in the actual measurement, the density of fog was a little bigger than that of nature fog, in order to minimize the experiment error, we had to make sure every illuminance meter was working at ×10 and ×100 grades. So LEDs with the power of 2 W were chosen in this experiment based on the above limits. We chose the white LED of which the color temperature was 4 386 K. Because blue light excites the YAG-phosphor to generate white light, the peak wavelength of the white LED is as same as that of blue LED, just as shown in Table 2.

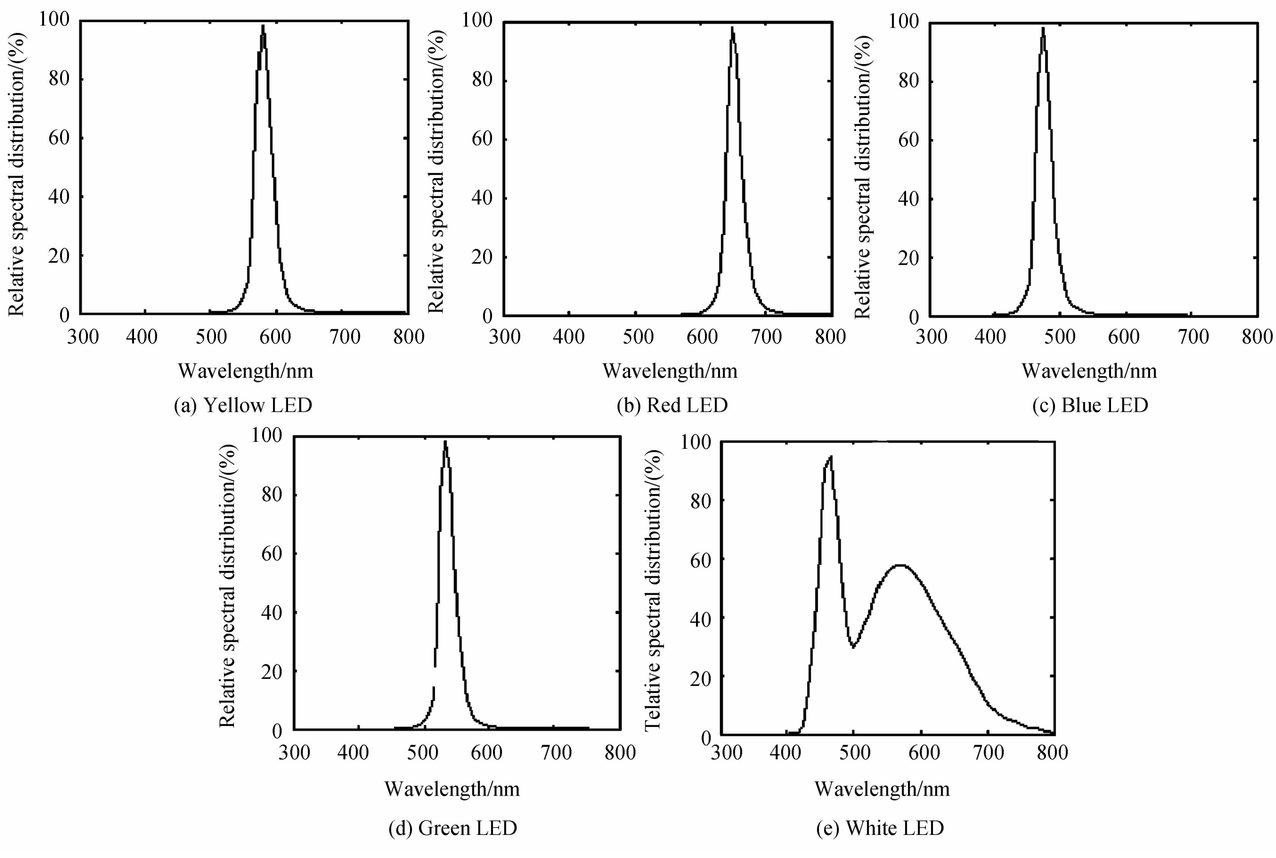


Fig. 1 The spectral distribution of yellow, red, blue, green and white LED

Table 2 The peak wavelength of five colors′ LED

LED	Yellow	Red	Blue	Green	White
Peak wavelength/nm	589	638	460	519	444

2.2 The generation of fog

2.2.1 *The requirements for fog*

Due to the penetration properties of LEDs were quite easily to be affected by the fog concentration, it required that the experimental fog have a good uniformity and stability. In the meantime, in order to make sure the adaptive range of the penetration properties, it required that we can adjust the density of fog during the experiment. In the experiment, we adopted the principle of vision testing table as the reference to measure of the fog concentration. We put several papers of different sizes of words at different distances away from the fog box and then let people read them. By testing the size of words people could see clearly, we defined the density of the experimental fog. All the above requires determined that the experiment fog should be artificial fog which was produced in a closed space in the laboratory.

2.2.2 *The instructions for artificial fog*

This experiment used air humidifiers to make artificial fog. The advantage of the artificial fog made by air humidifiers is that the composition of fog is large amounts of water drop, which is similar with the component of natural fog. Four air humidifiers were used. The density of artificial fog can be adjusted by controlling the numbers of humidifiers and their working time. This method simulated the process of thin radiation fog changing into thick advection fog[11].

2.3 Experimental apparatus

With the propagation of light in the medium, the light intensity will follow the following rule

$$I=I_0 e^{-cr}=I_0 e^{-(a+b)r} \tag{1}$$

where I_0 and I are the intensity of the input and output light, respectively. c is the attenuation coefficient of the medium and composed by two parts: $c=a+b$, where a is the attenuation coefficient of the medium, b is the scattering coefficient; r is the transmission distance of the light in the medium. Then the transmittance T can be expressed as[12-13]

$$T=I/I_0=e^{-cr}=e^{-(a+b)r} \tag{2}$$

According to the Formula (2), as long as the light intensity of the incident light and the outgoing light are measured, we can get the penetration properties of the LED light source in fog. Because the light source is paralleled with the receiving surface, the illuminance E and the light intensity I have such relation:

$$E=I/r^2 \tag{3}$$

we can use the illuminance E, which is measured by an illuminance meter, to substitute the light intensity I in the measurement.

In the experiment, we firstly adopted the experiment apparatus proposed by Zhang Qian *et al*. to test, but found that changing another LED could not assure that it was placed on the exactly same place. And because of the instability of fog, when we changed another LED to do the same test, even it was stilled placed on the same place, the tested data would be quite easily influenced. Although we tried to repeat the process for several times to eliminate experiment error, the floating of illuminance value was still quiet evident and could not avoid. So the single tube and single place testing method was not accurate.

So we built a measurement apparatus shown in Fig. 2. It included an organic glass box, the volume of which was $500\times500\times1000$ mm^3, and five groups of LEDs ($n=25$) of yellow, red, blue, green and white five colors respectively, 25 silicon photocell detectors, illuminance meters($n=5$) and humidifiers ($n=4$). Each LED light source included a heat dissipation device, which could avoid the influences caused by the heat of light source, a reflector cup, a drive circuit board and a fixed mount.

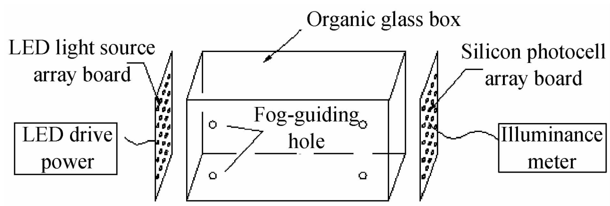


Fig. 2　Schematic drawing of the measurement apparatus

The LED light source of each color was arranged into a 5×5 array, with spacing of 80mm. Silicon photocell detectors ($n=25$) were also arranged into a 5×5 array in the same interval. During the whole process of the experiment, we must make sure that the location of each detector was in a line with the LED light source on the same position. The LED light source array, the organic glass box, and the silicon photocell array were both fixed on a optical platform, just as Fig. 3. showed. In front of each LED light source, there was a small black baffle, which would block the light from the other LEDs to affect the testing effects.

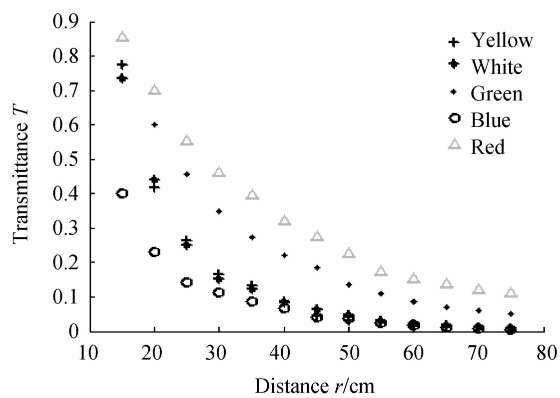


Fig. 3　The relationship of five color LEDs' transmittance T and distance (tested)

2.4 The measure process

1) Make sure the experiment is proceeding in a dark room, and correct the illuminance meters' value to zero;

2) Turn on the LED drive power supply to turn on the LED light sources;

3) When the output of the LED light source is stable, open the black baffles in front of each LED light respectively and write down the value of each illuminance meter. The values will constitute a incident energy matrix $\boldsymbol{M}_0$;

4) Atomize the fresh water with four air humidifiers and transmit the artificial fog into the organic box from the bottom and the upside;

5) When the artificial fog is stable and uniform, check if we can see the biggest words (size 72) clearly which has been placed on a distance of 1 000 mm away from the box. Act as step 3), write down the value matrix $\boldsymbol{M}_{\text{fresh}}$ of each LED light source illuminating in fresh water fog;

6) After testing the penetration properties of fresh water fog, use the sea water to do the same experiment again. Write down the value matrix $\boldsymbol{M}_{\text{sea}}$ of each LED light source illuminating in the sea water fog. The sea water used in the experiment is taken from Dong Men island seas at Xiangshan in Zhejiang province.

3 Results and discussion

3.1 Results

During the process of the measurement, the detector of each illuminance meter was always contacting with the organic glass box. Due to the uniformity of the fog in organic glass box was hard to control and the density of fog in different area had a obvious difference, it required that the experiment should be acted only when the fog was relatively uniform and the measuring time should be as short as possible. Measure the transmittance T of LED light sources of the same color($n=25$) in fog, average the T value and make it as the final transmittance T of the LED light source, then repeat measuring for ten times.

From formula (2), we got the transmittance value of fresh water T_{fresh} and that of sea water T_{sea}. Then we could get the volume attenuation coefficient of the fog according to

$$c=-\frac{\ln(T)}{r} \tag{4}$$

Finally we obtained the average transmittance T and average volume attenuation coefficient c of each color LED light sources. Table 3 showed the average transmittance T of five color LED light sources through fog, and the average volume attenuation coefficient c of five color LED light sources through fog was given in Table 4.

Table 3 The average transmittance T of five color LED sources

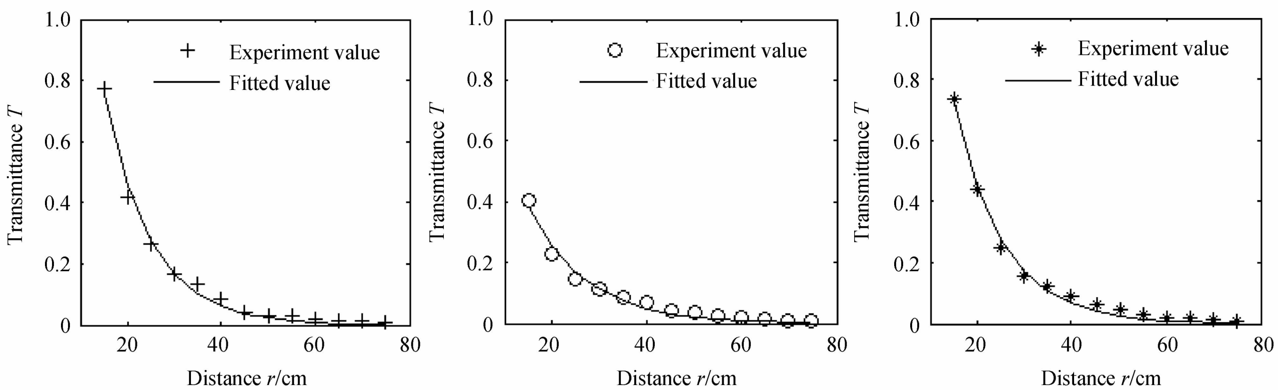
	Yellow	Red	Blue	Green	White
Fresh water fog	0.479	0.164	0.335	0.242	0.372
Sea fog	0.407	0.184	0.288	0.199	0.299

Table 4 The average volume attenuation coefficient c of five color LED sources

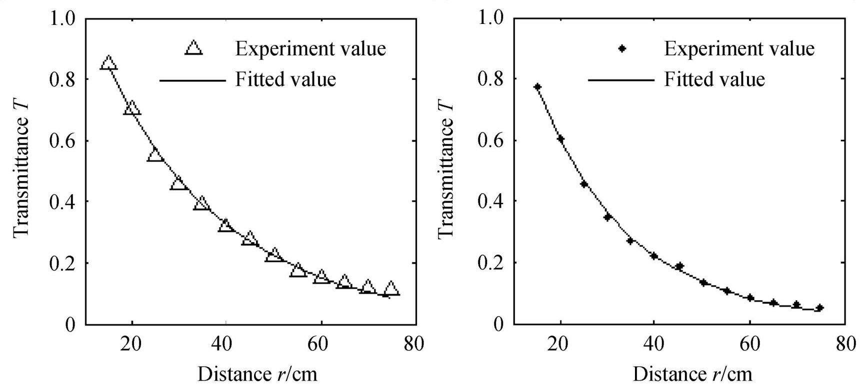
	Yellow	Red	Blue	Green	White
Fresh water fog	0.736	1.808	1.094	1.419	0.989
Sea fog	0.899	1.693	1.245	1.614	1.207

Table 3 and Table 4 showed that no matter it was in fresh water fog or sea fog, the transmittance T of yellow LED light sources was the biggest, and the transmittance T of white LEDs in fresh water fog was bigger than that in sea fog.

We also did a research about the relationship between the transmittance T and distance in fresh water fog. We chose to act this experiment when the fog was at the density that we could see clearly the size 48, black bold words placed on the other side of the box(the distance was 1 000 mm). Fig. 3 and Fig . 4 showed the relationship between the



(a) Green LED (b) Red LED (c) Blue LED



(d) Yellow LED　　(e) White LED

Fig. 4　The relationship between transmittance T and distance of five color LEDs (fitted)

transmittance T and distance in fresh water fog. From Fig. 3 and Fig. 4, we could see the decline of yellow LEDs′ transmittance was the gentlest with increasing of distance, followed by the white LED. By curve fitting, the relationship between transmittance T and distance was obtained, which was $T=\alpha \cdot e^{-\beta r}$, the value of α and β were given in Table 5.

Table 5　The value of α and β when curve fitting

	Yellow	Red	Blue	Green	White
α	1.48	1.305	3.033	3.43	1.617
β	0.037 95	0.081 87	0.095 64	0.101	0.049 73

3.2　Experimental analysis

Table 3 ~ Table 5 showed that the transmittance T in fresh water fog and sea fog in turn was as follows: yellow light, white light, blue light, green light and red light. From Table 3 and Table 4, we also could see that the transmittance T of blue light in sea fog was obviously bigger than that in fresh water fog, and this explained why sea water always looked blue. And at the approximately same density of fog (when we could see the size 72 words at the distance 1 000 mm), the transmittance T in sea fog was less than that in fresh water fog, this was because the sea water used in this experiment was taken from Dongmen Island seas of Xiangshan in Zhejiang Province and it had settled for one week in the laboratory before the experiment. It contained some big particle material and this led to the complexity of the absorption and the scattering of sea fog and the declination of transmittance T.

When we studied the transmittance T of LED light sources of the same color($n=25$) in water fog and sea fog, the error source mainly included the instrumental error and the measurement error. Instrumental errors were as below: the detector noise and the unstability of light sources, while the uncertainty caused by this part was below 1%. Measurement errors mainly included the error caused by tiny voltage change and the density of fog. Although the density of fog was relatively stable, it was still changing during each measurement process. This would have some effect on the experiment result. We tried to eliminate the error by shortening the measurement time and repeating the experiment to gain an average data. Table 6 showed the tested transmittance T in water fog of a yellow light source by repeating the experiment for 10 times, and the illuminance value was detected by photocell detectors (D1 ~ D25) placed as the experimental apparatus showed in Fig. 2. Results showed that the standard deviation of the transmittance T detected by the same one

Table 6　Tested transmittance T of a yellow LED light source in water fog

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12
1	0.862	0.752	0.635	0.381	0.198	0.614	0.703	0.849	0.657	0.316	0.459	0.538
2	0.859	0.774	0.622	0.412	0.179	0.575	0.707	0.856	0.664	0.311	0.497	0.521
3	0.803	0.761	0.603	0.370	0.200	0.579	0.712	0.877	0.68	0.261	0.500	0.514
4	0.825	0.750	0.628	0.409	0.207	0.592	0.686	0.824	0.697	0.262	0.464	0.505
5	0.819	0.762	0.644	0.401	0.212	0.617	0.670	0.831	0.698	0.263	0.459	0.517
6	0.807	0.755	0.615	0.391	0.204	0.589	0.677	0.864	0.650	0.306	0.521	0.528
7	0.827	0.722	0.640	0.397	0.212	0.619	0.700	0.825	0.637	0.273	0.492	0.523
8	0.818	0.745	0.635	0.396	0.223	0.607	0.720	0.865	0.695	0.267	0.501	0.499
9	0.859	0.716	0.631	0.394	0.196	0.624	0.679	0.875	0.663	0.254	0.468	0.528
10	0.837	0.761	0.636	0.394	0.208	0.616	0.703	0.865	0.695	0.265	0.503	0.496

1	D13	D14	D15	D16	D17	D18	D19	D20	D21	D22	D23	D24	D25
2	0.693	0.518	0.306	0.362	0.495	0.432	0.350	0.263	0.26	0.485	0.373	0.461	0.253
3	0.689	0.519	0.337	0.356	0.488	0.445	0.343	0.248	0.264	0.506	0.388	0.443	0.237
4	0.696	0.508	0.352	0.374	0.501	0.441	0.346	0.225	0.265	0.468	0.395	0.463	0.210
5	0.645	0.498	0.321	0.407	0.533	0.390	0.389	0.233	0.281	0.478	0.403	0.438	0.270
6	0.690	0.510	0.312	0.369	0.503	0.451	0.351	0.272	0.296	0.467	0.353	0.438	0.237
7	0.655	0.504	0.306	0.404	0.530	0.441	0.358	0.255	0.255	0.470	0.361	0.421	0.218
8	0.659	0.52	0.346	0.408	0.507	0.408	0.348	0.256	0.304	0.470	0.347	0.428	0.216
8	0.677	0.512	0.304	0.361	0.487	0.431	0.396	0.238	0.305	0.486	0.341	0.450	0.231
9	0.664	0.476	0.322	0.384	0.485	0.435	0.357	0.276	0.271	0.492	0.353	0.429	0.212
10	0.640	0.506	0.329	0.375	0.516	0.438	0.364	0.259	0.281	0.497	0.396	0.427	0.246

illuminance meter at the same position was 0.011 2～0.022 3, while the standard deviation range of the average transmittance T was 0.113～0.223.

When we studied the relationship between the transmittance T of different color LEDs with distance, the experiment was performed on the same rolling optical guide. There were two main error sources, one was the fluctuation of the tested data caused by the small disturbance of light intensity value, and the other was the disturbance of fog which was caused inevitably by moving the rolling guide to adjust the distance between a light source and a detector. We eliminated the first error by repeating the experiment and averaging the tested data. While the disturbance of fog was the main error source of the experimental error, we used an electric rolling guide and controlled the move velocity. By curve fitting, the final fitted curve′s sum variance (SSE) was 0.002 1～0.004, and its certain coefficient was no less than 0.981 1.

4 Conclusion

An analysis of the obtained results by the above experiments shows that the transmittance T of five color LED light sources will decline exponentially with the increasing of distance in fog, but the declining rate of the transmittance of each color LED light sources is different from each other: yellow LEDs′ is the slowest, followed by white, blue, green, and the fastest is red. This means that yellow LEDs′ penetration property in fog is the best, followed by white. And the penetration properties of yellow, red, green and blue LEDs in sea fog are approximately similar to that in fresh water fog, but for white LEDs, the penetration property in sea fog is better than that in fresh water. So if signal lights, street lights and searchlights often work in a foggy weather, we′d better choose yellow LEDs or those LEDs′ spectral distribution that contains much yellow light as their light sources. Further experiments will include the comparison between a daytime and night time fog measurement. These will contribute to the future advancement of traffic signals and airport lighting technology and will improve the traffic safety in foggy weather.

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