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Investigation of LED Light Attenuation in Fog

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Introduction

Solid-state lighting technology based on light-emitting diodes (LEDs) allows for the development of intelligent street lighting systems with the dynamic changing of the photometric characteristics of luminaires and the luminance of the road surface, depending on traffic and weather conditions [1]. One of the climatic phenomena is fog. In fog, the illuminance of street surface alters and the visibility is reduced. Also, fog results in that the luminance of the surface of an object that is in the observer's field of view changes.

Natural fogs occur at various conditions; they are inhomogeneous and the size of their droplets is different. The droplet radii and concentration range from 2 to 50 μm and from 20 to 200 cm^{-3}, respectively, and these parameters vary during the fog life cycle [2, 3].

When light propagates through fog, the electromagnetic waves interact with water droplets suspended in the air. Because of this interaction, the light is attenuated. The transmittance of a light beam in fog can be described by the classical expression known as Beer-Lambert-Bouguer law

$$I/I_0 = \tau = \mathrm{e}^{-ax}, \tag{1}$$

where I_0 is the initial light intensity, I is the light intensity after passing through a layer of fog of thickness x, τ is the transmittance, and a is the extinction coefficient (fog density).

Light attenuation in a medium occurs due to absorption and scattering. Since the fog particles are droplets of water, light absorption is negligible; therefore, light attenuation is almost due to scattering only, i.e. $a = k$. The light scattering coefficient k depends on the wavelength of light and on the optical properties of the medium. It is to be noted that in real conditions, the optical properties of fog vary due to the variation of droplet size and concentration.

If an illuminated object under observation is in fog, its luminance also depends on the density of fog. In addition when light passes through fog, the fog glows itself due to scattering. A similar situation can occur when the visibility of an object illuminated by car headlights decreases because of fog glowing due to the diffused light of street luminaires. Therefore, the luminance in the field of view depends on the luminance of the object and fog luminance.

Intelligent street lighting systems can be based on various solid-state sources of light, such as phosphor conversion LEDs, as well as clusters of coloured LEDs. In order to develop intelligent street lighting systems that adapt to fog conditions, the propagation of light of different spectral composition and the peculiarities of the formation of luminance patterns of objects in fog of different density are to be known. Some models described in the literature [3,4] can be used for this purpose. However, these models lack experimental data on light propagation and object luminance for different LEDs under fog conditions.

In this paper, we present an experimental investigation of the characteristics of the propagation of light emitted by solid-state sources of various colours in artificial fog with varying density.

Materials and methods

The light transmission and luminance attenuation in fog for coloured and white LEDs was investigated at different fog densities. For this purpose, a fog chamber that allowed for varying the parameters of fog was developed (Fig. 1).

The interior of the chamber was black matte and the dimensions were 1010×680×660 mm. A LED was installed within a slot on a wall of the chamber. The transmittance was measured using the measuring head of a photometer (KONICA MINOLTA CL200A Chroma) that was mounted on the opposite wall of the chamber centred at the optical axis of the LED. The head was surrounded by a ring of white matte paper that served as an object for the investigation of luminance. The luminance was measured by a luminance meter (KONICA MINOLTA LS110) with the objective directed towards the ring. The fog was injected through the hole in the bottom wall of the chamber.

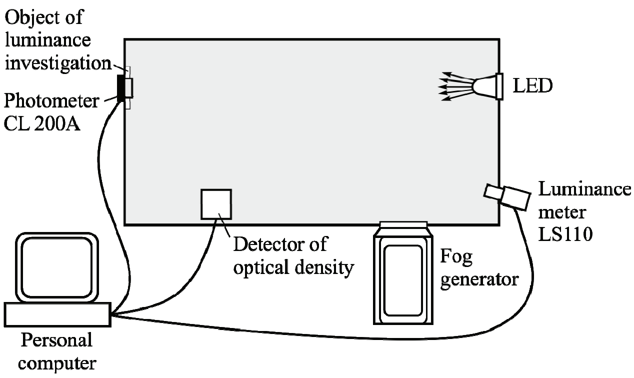


Fig. 1. Fog chamber and experimental setup

Two types of fog were used in this research: one from a fog generator (ANTARI Z300) and another from dry ice. The fog generator used fluid that was supplied by the manufacturer. Its main components were water (about 80 %) and glycol (about 20 %). To maintain the uniformity of fog in chamber, an electric fan was used. Dry-ice fog was produced by the evaporation of solid carbon dioxide (CO_2) in hot water.

The density of fog inside the chamber was being estimated by a custom-made detector. The principle of operation of the detector was based on measuring the intensity of scattered light in the direction perpendicular to a sampling laser beam. Such an approach allowed for the direct estimating of fog density rather than of transmitted light intensity as reported in [5]. The detector comprised a laser diode (655 nm), a research radiometer (INTERNATIONAL LIGHTING TECHNOLOGIES IL1700), and an appropriate set of filters and lenses. The laser diode was driven by a 17.3 ± 0.1 mA current provided by a DC power source. The detector was placed inside the chamber and screened from gauges and light sources. The output of the detector was set to zero, when the chamber was free of fog. When the chamber was filled with fog, the output of the detector was proportional to the intensity of scattered light. This quantity was designated as the relative fog density d^*, which is proportional to the extinction coefficient. Such an approach is reasonable provided that the distances the light passes within the detector are much smaller than the inverse extinction coefficient (this condition was held in our experiment).

The data on narrow viewing angle LEDs that were selected for the investigation are presented in Table 1. The LEDs were powered by a 30 mA regulated current provided by a DC power source. The current was monitored by an ammeter. The ambient temperature (20 ± 1 °C) was monitored by a digital thermometer (MASTECH MS8264).

Table 1. Data on the investigated LEDs

Type	Colour	Dominant wavelength λ (nm)	Current (mA)	Light intensity (cd)	Viewing angle	Quantity (pcs)
SKU-9077	Blue	463	30	2	20°	1
SKU-9076	Green	514	30	8	20°	1
HB10b-433BG	Yellow-green	572	30	4	7°	3
HB10b-434FY	Amber	590	30	11.2	7°	3
HB10b-436ARA	Red	645	30	8.5	10°	3
HB10b-439AWCA	White		30	16	6°	3

A computer program was developed for the registration of the measured data. The results of measurement were recorded by a personal computer every 5 seconds, starting from the highest concentration of fog until total dissipation.

The evaluation of light scattering in fog was based on measuring transmittance τ. Since the illuminance is proportional to light intensity, Eq. (1) shows that the transmittance can be estimated as $\tau = E/E_0$, where E_0 is the illuminance measured in the absence of fog and E is the illuminance measured in the presence fog. The dependence of transmittance on relative fog density was obtained for each kind of LED by monitoring the recovering of τ with time during the dissipation of fog.

Also, the dependences of the relative luminance of the object L^* on the relative density of fog were obtained for different colour (dominant wavelength) of the LEDs. The relative luminance was estimated as $L^* = L/L_0$, where L_0 is the luminance of the object measured in the absence of fog and L is the luminance measured in the presence fog.

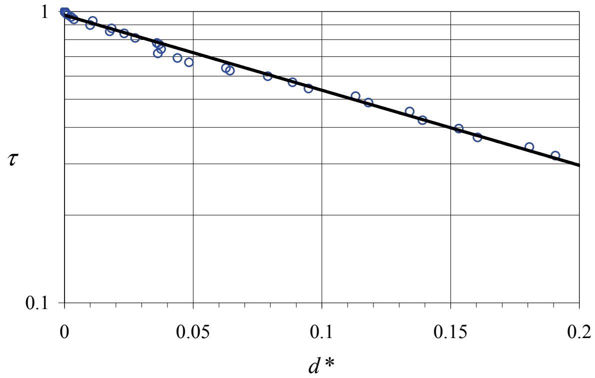
In total, over 50 tests were carried out using different combinations of LEDs and fog types.

Illuminance attenuation

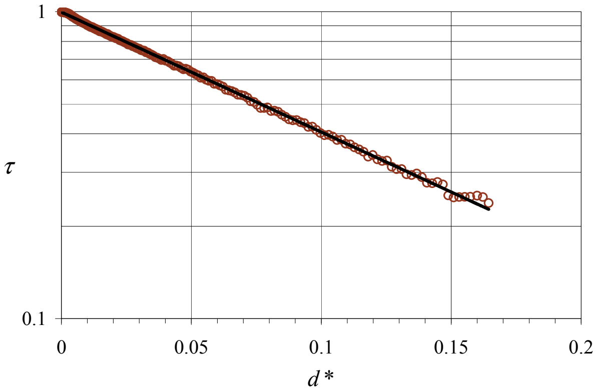
The obtained dependence of fog transmittance on the relative density was exponential (Fig. 2). The regression functions were straight lines on the logarithmic scale and were described by an equation $\tau = \exp(-k_E d^* x_E)$ with the confidence coefficient of at least 0.95. Here k_E is the illuminance attenuation coefficient, which generally depends on LED colour (dominant wavelength) and fog type, and x_E is the fog layer thickness (equalled 1 m in this case).

The obtained dependences correspond to the Beer-Lambert-Bouguer law (Eq. (1)) under conditions of variable fog density. The actual light scattering coefficient equals $k = k_E d^*$.

The fog opacity can be characterized by the meteorological optical range (V_{met}), defined as the length of the path in the atmosphere, which is required for attenuating the luminous flux from a collimated light source by 95 % [3]: $\tau = e^{-aV_{met}} = 0.05$. This converts to $V_{met} \approx 3/k_E d^*$.



a)



b)

Fig. 2. Experimental dependence of transmittance on relative fog density and regression functions for the blue (a) and yellow (b) LEDs

Table 2. Illuminance attenuation coefficient for different LEDs

Colour	λ (nm)	k_E (m^{-1})	Standard deviation
Red	645	9.01	1.51
Amber	590	9.09	1.19
Yellow green	572	9.28	0.10
Green	514	5.90	1.12
Blue	463	5.95	0.50
White		8.56	0.66

The dependence of the measured illuminance attenuation coefficient on LED colour (dominant wavelength) is presented in Table 2 and Fig. 3. (The results were very similar for both types of fog within the experimental uncertainties; therefore the average values are presented). The light of shorter wavelengths (blue and green) is seen to be less attenuated by scattering than that of longer wavelengths (amber with the dominant wavelength close to that of high pressure sodium lamps that presently are widely used in street lighting, yellow-green, and red). The shorter-wavelength and longer-wavelength illuminance attenuation coefficients differ by more than 1.5 times in average. It can be seen that light of white LEDs might be advantageous over sodium lamps due to a somewhat lower scattering.

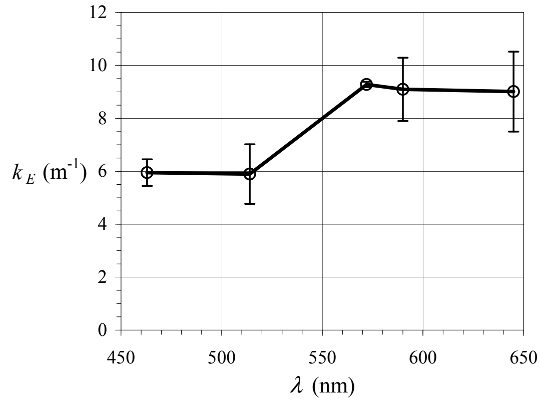


Fig. 3. Dependence of the illuminance attenuation coefficient on the dominant wavelength of LEDs

Luminance attenuation

The luminance in the field of view depends on the luminance of an object, L_{ob}, and on fog luminance, L_{f}, as $L = L_{\text{ob}} + L_{\text{f}}$. In the absence of fog, the luminance of the object is largest and equals $L_{\text{ob}} = L_0$. The relative luminance used in this work is defined as

$$L^* = L/L_0 = (L_{\text{ob}} + L_{\text{f}})/L_0 . \qquad (2)$$

The fog luminance is mostly influenced by lateral diffused lighting. In the absence of the latter, L_{f} is negligible and $L^* = L_{\text{ob}}/L_0$.

In this work, the luminance of a white object illuminated by LEDs of different colour was measured. The luminance of the object depends on illuminance. In the fog chamber, light passes the layer of fog, is reflected from the object and after repetitive passing the layer of fog falls onto the objective lens of the luminance meter. In this case, the fog layer thickness increases by a factor of 2 in comparison with the scattering experiment. The results of the investigation (not shown) were similar to those obtained for transmittance measurements and indicated that the relative luminance L^* exponentially depends on the density of fog. The form of regression function of this dependence is $L^* = \exp(-k_L d^* x_L)$, where k_L is the luminance attenuation coefficient, which generally depends on LED colour (dominant wavelength) and fog type, and x_L is the fog layer thickness (2 m in this case).

Again, the obtained dependences correspond to the Beer-Lambert-Bouguer law (Eq. (1)) under conditions of variable fog density. The actual light scattering coefficient equals $k = k_L d^*$.

The dependences of the measured luminance attenuation coefficient on LED colour are presented in Table 3 and Fig. 4. The values for each fog type as well as the average values are presented.

Again, the luminance is seen to be less attenuated for shorter wavelengths (blue and green light). Meanwhile for longer wavelengths (amber, yellow-green, and red) the attenuation is higher. The corresponding luminance attenuation coefficients differ by a factor of 1.5 in average. The dependence of the attenuation coefficient on fog type can be also resolved. For fog generator, they were from 1.24 to 1.57 times lower than those for dry-ice fog. This indicates that the size of water droplets in fog and the presence of impurities (as in the case of fog in polluted urban atmosphere) might have a significant influence on light scattering.

Table 3. Luminance attenuation coefficient for different LEDs

Colour	λ (nm)	k_L (m^{-1})	Standard deviation
Fog generator			
Red	645	7.48	0.10
Amber	590	7.61	0.80
Yellow-green	572	8.22	-
Green	514	5.10	0.47
Blue	463	5.65	0.88
White		7.98	0.20
Dry-ice fog			
Red	645	10.14	0.78
Amber	590	10.70	-
Yellow-green	572	10.94	0.44
Green	514	7.99	0.02
Blue	463	7.00	0.53
White		9.01	0.83
Average			
Red	645	8.81	
Amber	590	9.15	
Yellow-green	572	9.58	
Green	514	6.54	
Blue	463	6.32	
White		8.50	

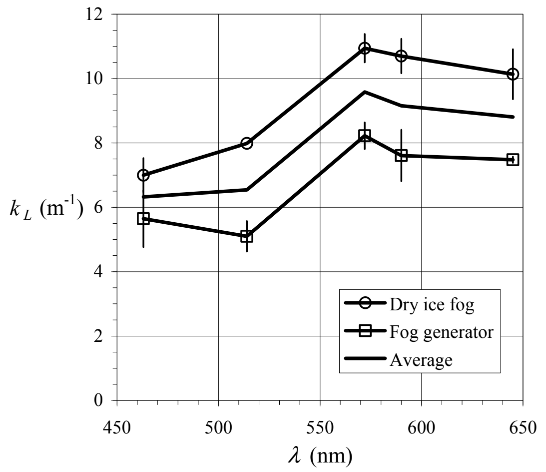


Fig. 4. Dependence of the luminance attenuation coefficient on the dominant wavelength of LEDs

For the white LED, illuminance attenuation was investigated for two values of distance. The results for the measured light scattering coefficient are presented in Table 4.

Table 4. Luminance attenuation coefficient for the white LED

Distance (cm)	k_L (m^{-1})	Standard deviation
54	10.28	0.65
108	11.05	0.09

As one can see from Table 4, the doubling of the distance from the object to the luminance meter results in almost no variation of the light scattering coefficient. This is in line with the Beer-Lambert-Bouguer law.

The comparison of the results for the transmittance and luminance attenuation shows that the obtained values of the attenuation coefficient for the two measurements are very similar in the absence of scattered foreground light.

The luminance of the object in fog illuminated by LEDs of different colour was also investigated under conditions of additionally illuminated foreground. The additional LEDs were installed on top of the fog chamber between the object and luminance meter and emitted vertically downward. The dependences of relative luminance measured in the field of view of the luminance meter on the relative fog density are shown in Fig. 5 for two types of LEDs used for foreground illumination.

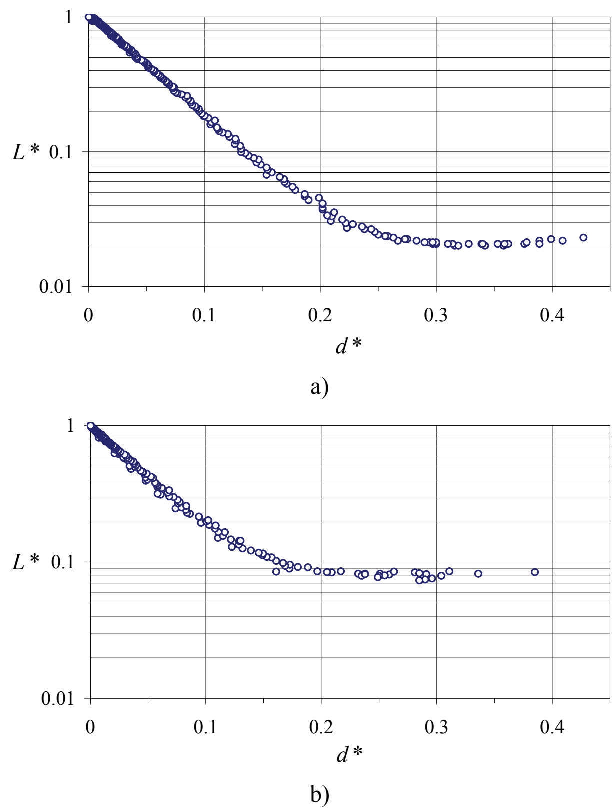


Fig 5. Experimental dependence of relative luminance on fog density for the object illuminated by the white LED with additional yellow (a) and white (b) foreground light

The obtained dependences of luminance on fog density with additional foreground light can be divided into 3 regions. In the region of low fog density (for $d*$

from 0 to about 0.1), the main contribution to relative luminance is due to the luminance of the object. Here, the dependences are exponential as described above ($L^* = \tau$). In the intermediate region (for d^* from 0.1 to 0.25), the relative luminance still decreases with fog density, although it is considerably contributed by foreground light. Here, the total luminance is to be determined with both components taken into account ($L^* = \tau + L_f / L_0$). In the high relative fog density region ($d^* > 0.25$), the relative luminance is almost constant and is determined by foreground light scattered in fog rather than by the luminance of the object ($L^* = L_f / L_0$). This means that the object "vanishes" in fog and its visibility is very poor. This effect is illustrated in Fig. 6, where the images obtained from the camera of the luminance meter are presented for three densities of fog.

a) b) c)

Fig. 6. Images of the object in the fog chamber under illumination by the white light LED with additional white light falling from top for different densities of fog. (a), (b), and (c), low, average, and high fog density, respectively

Our experiments also showed that the correlated colour temperature, T_{CC}, of the white LED varied with the density of fog. This can be attributed to the dependence of the scattering index on the wavelength of light. The stronger scattering of light for longer wavelengths resulted in that the light intensity in the yellow, amber and red regions of the spectrum is decreased in comparison with shorter wavelengths. Eventually, the correlated colour temperature increased (Fig. 7). The increase of T_{CC} by a factor of 1.3 was observed in dense dry-ice fog at a distance of 1 m. One can imply that this effect should be even more prominent with increasing the distance of observation.

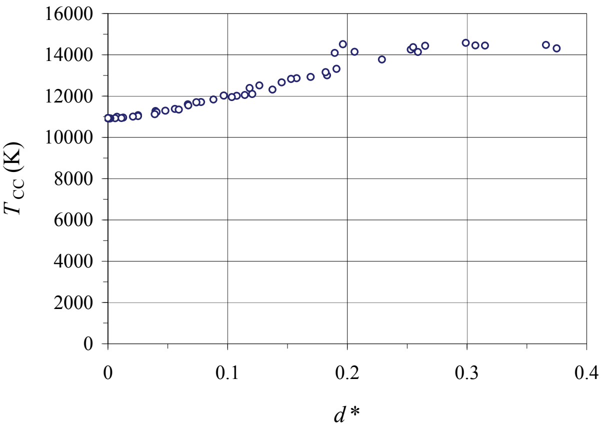


Fig. 7. Correlated colour temperature vs. relative fog density in dry-ice fog measured at a distance of 1 m

Conclusions

An experimental setup for the measurement of illuminance and luminance attenuation under conditions of varying density of fog was developed. The setup was equipped with a fog density detector operating in the light-scattering mode. After an appropriate calibration, the output of such a detector can be used in intelligent street lighting systems.

The experimental dependences of transmittance on the relative density of fog for LEDs of different colour were found to be exponential and corresponded to the Beer-Lambert-Bouguer law. Light of shorter wavelengths (blue and green) was found to be scattered weaker by 1.5 times than that of longer wavelengths (yellow-green, amber, and red).

In the absence of scattered foreground light, the dependences of the relative luminance of the object illuminated by light of different wavelengths on the fog density were found to be also exponential with almost the same light scattering coefficient as for illuminance attenuation. When an object was illuminated by LEDs of different colour in fog with a higher density with additional foreground light applied, the main contribution to luminance in the field of view was due to the luminance of the foreground light scattered in fog rather than due to the luminance of the object itself.

It was also found that the correlated colour temperature of white LEDs increases with the increase of the fog density due to the dependence of light scattering on wavelength.

Acknowledgement

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K. Otas, V. J. Pakenas, A. Vaskys, P. Vaskys. Investigation of LED Light Attenuation in Fog // Electronics and Electrical Engineering. – Kaunas: Technologija, 2012. – No. 5(121). – P. 47–52.

In fog, visibility reduces and the illuminance levels of street surface and objects that are in the observer's field of view alter. In order to establish the technical characteristics of intelligent street lighting with the effect of fog taken into account, the peculiarities of light propagation and luminance of objects in fog are to be known. In this work, a fog chamber that allowed for the experimental investigation of the transmittance and luminance attenuation for white and coloured LEDs in fog with variable density was developed. The obtained dependences of transmittance and relative luminance on relative fog density were described by exponential regression functions. The dependence of the illuminance and luminance attenuation coefficients on light colour (dominant wavelength) was investigated. Light of shorter wavelengths (blue and green) was found to be scattered by about 1.5 times weaker than that of longer wavelengths (yellow and red). When additional foreground light was applied, a high fog density resulted in that the main contribution to luminance in the field view was due to the luminance of the foreground light scattered in fog rather than due to the luminance of the object itself. An increase of the correlated colour temperature of the white LED was observed due to the dependence of light scattering on wavelength. Ill. 7, bibl. 5, tabl. 4 (in English; abstracts in English and Lithuanian).

K. Otas, V. J. Pakėnas, A. Vaškys, P. Vaškys. Šviesos diodų šviesos silpimo rūke tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 5(121). – P. 47–52.

Rūke sumažėja matomumas, pakinta gatvių paviršiaus apšvieta ir stebėtojo matymo lauke esančių objektų skaistis. Norint nustatyti išmaniojo gatvių apšvietimo technines charakteristikas, atsižvelgiant į rūko įtaką, reikia žinoti šviesos sklidimo ir objektų skaisčio rūke ypatybes. Šiame darbe sukonstruota rūko kamera, leidžianti atlikti šviesos praleisties ir skaisčio silpimo kintamo tankio rūke eksperimentinius tyrimus, naudojant vienspalvius ir baltus šviesos diodus. Nustatytos šviesos praleisties ir santykinio skaisčio priklausomybės nuo rūko santykinio tankio, išreikštos regresinėmis eksponentinėmis funkcijomis. Ištirta apšvietos ir skaisčio silpimo koeficientų priklausomybė nuo spinduliuotės spalvos (vyraujančiojo bangos ilgio). Nustatyta, kad rūke trumpesnių bangų šviesa (mėlyna ir žalia) sklaidoma 1,5 karto silpniau nei ilgesnių bangų šviesa (geltona ir raudona). Kai objektas apšviestas papildomai sudarant šviesinį foną rūke, didesnio tankio rūke skaistį regėjimo lauke lemia ne tiek paties objekto skaistis, kiek rūko išsklaidyta foninė šviesa. Stebėtas balto šviesos diodo susietosios spalvinės temperatūros didėjimas keičiantis rūko tankiui dėl šviesos sklaidos priklausomybės nuo bangos ilgio. Il. 7, bibl. 5, lent. 4 (anglų kalba; santraukos anglų ir lietuvių k.).