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Influence of the reflector properties on the photometric characteristics of a luminaire with variable luminous intensity distribution

***Abstract**. The article presents the results of research on a reflector used in a luminaire with a variable luminous intensity distribution, which is a key element shaping the distribution of the luminous flux in space. The aim of the research is to analyze the impact of the reflective properties of the materials used for the production of reflectors on the possibility of obtaining appropriate luminous flux distribution characteristics and to assess the possibility of using specific materials in a system with variable luminous flux distribution.*

***Streszczenie.** W artykule przedstawiono wyniki badań odbłyśnika zastosowanego w oprawie oświetleniowej o zmiennej bryle fotometrycznej, który jest kluczowym elementem formującym rozsył strumienia świetlnego w przestrzeni. Celem badań jest analiza wpływu właściwości odbiciowych materiałów stosowanych do wytwarzania odbłyśników na możliwość uzyskania odpowiednich cech rozsyłu strumienia świetlnego oraz ocena możliwości zastosowania konkretnych materiałów w układzie o zmiennym rozsyle strumienia świetlnego. (**Wpływ właściwości odbłyśnika na charakterystykę fotometryczną oprawy oświetleniowej o zmiennym rozsyle światłości**)*

Keywords: variable luminous intensity distribution, luminaire, reflector, reflective properties, luminous flux.
Słowa kluczowe: zmienny rozsył światłości, oprawa oświetleniowa, odbłyśnik, właściwości odbiciowe, strumień świetlny.

Introduction

Luminaires fulfill many functions in lighting technology. One of the basic ones is shaping the distribution of the luminous flux, which is carried out mainly by the light-optical system. There are many lighting situations in the illuminated objects, for which the luminaires should have different design solutions of the light and optical system. Thanks to this, it is possible to use the appropriate luminaire for specific requirements, such as the mounting location, dimensions of the working plane and the distance between the working plane and the luminaire.

The development of lighting equipment takes place in areas such as improving the luminous efficacy or thermal conditions of luminaires [1-3]. Another development area is the possibility of forming a variable luminous intensity distribution [4-5]. This solution of the light-optical system allows to change the orientation of the photometric body in many directions without having to change the position of the luminaire and replace its elements. A luminaire with such features can be used in adaptive lighting systems [6-12].

Thanks to the use of LED sources, it is possible to reduce the weight and dimensions of the luminaire [13-14] and increase energy efficiency [15-17]. Small dimensions and the luminous surface of a single LED source [18-20] provide great opportunities for shaping the complex luminous surface of the luminaire. This is achieved by grouping sources on multi-source matrices. It allows for the construction of light and optical systems of luminaires of complex shape. It is also possible to use an individual optical system for each light source or a common one for the entire panel. Thanks to the above features, the use of LED sources makes it easier to shape various types of light distribution.

In the developed solution the reflector is an element that forms the distribution of the luminous flux in the modeled luminaire. The shape of the focus profile determines the direction of reflection of the rays emited from the light source. In turn, the reflection properties of the material determine the degree of concentration of the rays reflected from the surface. There are three types of reflection: directional, diffuse and directionally-diffuse. The shape of the profile must correlate with the reflection characteristics of the material.

The main objective of the research is to analyze the suitability of materials with different reflection properties for use in an optical system with a variable photometric characteristic and to assess the possibility of obtaining specific characteristics of luminous flux distribution.

Luminaire with variable luminous intensity distribution

The object of the research is a luminaire with a variable luminous intensity distribution [4-5], which should enable the formation of different distribution types: a rotationally-symmetric, with two axes of symmetry and an asymmetric distribution. Due to the formation of a rotational-symmetric luminous intensity distribution, the light-optical system is built on a circular plan (Fig.1).

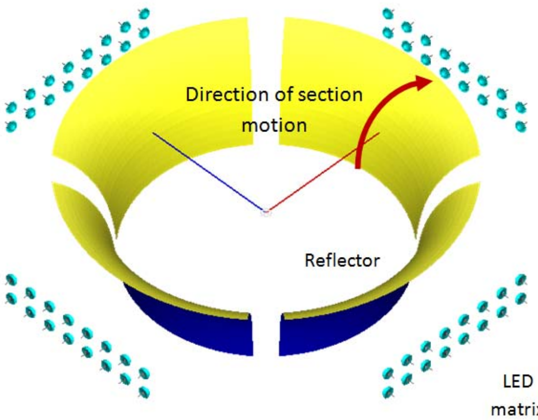

Fig. 1. Light-optical system of a luminaire with a variable luminous intensity distribution

The possibility of transforming a distribution type into a symmetrical and asymmetrical one requires the separation of several independently controlled sections of the light-optical system. In the analysis presented below, it was assumed that the position and luminous flux of the light sources are unchanged, while the modification of the luminous intensity distribution is carried out only by changing the position of the reflector. Its sections are inclined around an axis at the base of the segment in the direction of the light sources (Fig.2).

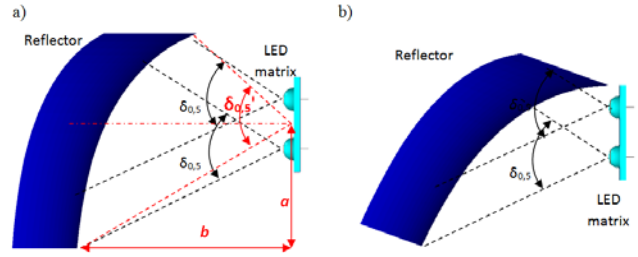

Fig. 2. Illustration of changing the inclination of the reflector: a) minimum inclination, b) maximum inclination

The base focusing profile is a single parabolic curve that provides the expected angles of reflection of rays from the light source under certain geometric conditions, including the dimensions and relative position of the light source and reflector profile. It is also possible to create a parabolic profile built from more base profiles. The profile curve is the starting point for modeling the reflector surface.

The research was carried out on the basis of a reflector with a parabolic monocurve profile. The assumed reflection angles of the rays coming from the center of the light source range from 0° for the upper end of the profile to 60° for the lower end, counting from the optical axis of the system. The values correspond to the adopted beam angles of distribution in the wide variant, with the base inclination of the reflector equal to 0°. The narrow variant is obtained with the reflector inclined at an angle of 20°. The shape of the reflector during the tests remained unchanged, subsequent results of the luminous intensity distribution were obtained by changing the characteristics of the optically active surface of the reflector, resulting from the properties of the material used.

The model of the light-optical system and its simulation were made in the Photopia software [24]. Photopia has a CAD module that allows to support the graphical modeling of the light-optical system, using the geometric relationships between the elements of the system. It also makes it possible to track the course of rays on the path of the light source - reflector and reflector - space, thanks to the use of the Monte Carlo method of random tracking of elementary fluxes when determining photometric solids. Thanks to this, it enables a wide spectrum of analysis of light and optical systems.

In the course of the research, luminous intensity distributions were determined for various variants of the system with defined optical properties of the reflector. The results were analyzed based on the shape of the obtained luminous intensity curves and characteristic parameters (maximum and axial luminous intensity, beam angle).

Simulations were carried out with materials with a specular surface (providing directional reflection and high luminous intensity amplification) and a diffusing surface. The analysis covered characteristic materials with different structures and surface diffusing properties, influencing to a different extent the obtained luminous intensity distribution.

The next stage was the analysis of materials with a surface that ensure directional diffuse reflection. The use of materials with different levels of surface matting was analyzed, which affects the degree of scattering of reflected radiation. Similar properties are ensured by materials with a mirror surface with an embossed diffusing macrostructure, with a diversified structure.

The analysis of the influence of the material properties on the possibility of using a system with variable luminous flux distribution was carried out with the use of various materials [21-23]: with a mirror surface, diffusing, directionally diffusing and with a mirror surface with a diffusing macrostructure.

Analysis of reflector surface properties using mirror materials

The basic reflector material is a material with a mirror surface ensuring directional reflection (Fig. 3a). The course of the rays coming from the light source and reflecting from the reflector with a mirror surface is shown in Fig. 3b. Mirror materials are used when high luminous intensity amplification is expected and at the initial stage of reflector modeling, in order to obtain the first approximation of the shape and subsequent ones as close as possible to the expectations.

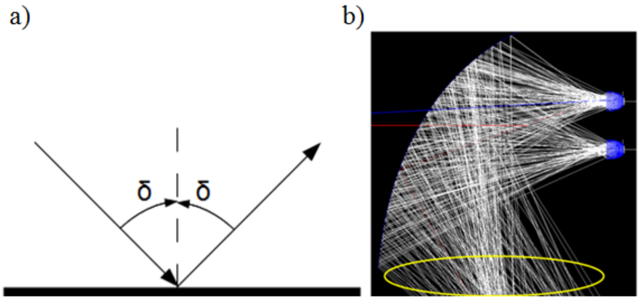

Fig. 3. Directional reflection mechanism (a) and visualization of ray traces after reflection from a reflector with mirror surface (b).

Selected results of the analysis of luminous intensity curves for two extreme distribution variants (reflector inclination 0° and 20°) of the luminaire with a reflector with a mirror surface are shown in Fig. 4. With wide and small distribution angles γ, the luminous intensity reaches low values, which may lead to the formation of a dark zone directly under the luminaire and problems with obtaining a uniform distribution of the illuminance on the illuminated surface. The second observed disadvantage is the lack of rotational symmetry of the distribution, visible in the wide and narrow variant. These problems are mainly due to the directional nature of the material reflection.

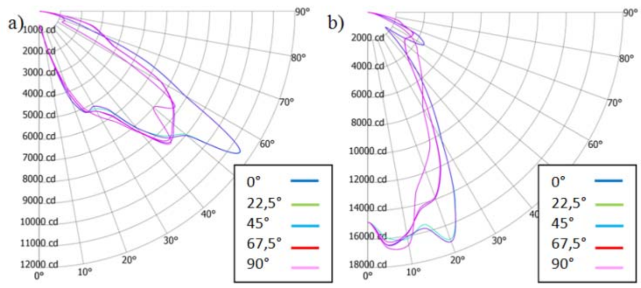

Fig. 4 Luminous intensity curves of the luminaire with the use of a reflector with a specular surface: a) wide light distribution, b) narrow light distribution

Analysis of reflector surface properties using diffusing materials

In further studies, materials with different reflective properties were used. Simulations were carried out with materials with a diffusing surface (Fig. 5a), for the unchanged shape of the reflector. The course of the rays from the light source and reflecting from the reflector with a diffusing surface (on the example of the R1 material) is shown in Fig. 5b. The results of the analysis of the light distribution curves for the two extreme positions of the reflector (inclination 0° and 20°) of the luminaire with a reflector with a diffusing surface are shown in Fig. 7-9. The analysis included characteristic materials with different structures and surface diffusing properties, affecting the obtained luminous flux distribution to varying degrees.

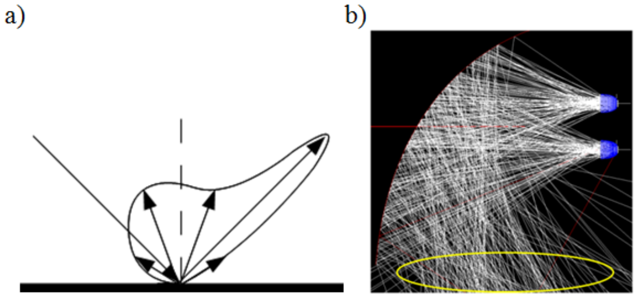

Fig. 5. Diffusing reflection mechanism (a) and visualization of ray traces after reflection from a reflector with diffusing surface (b).

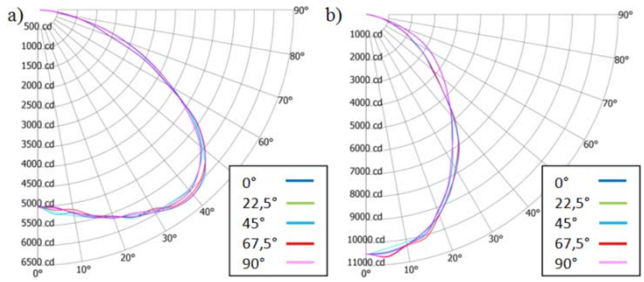

Fig. 6. Luminous intensity curves of the luminaire with the use of a reflector with a diffusing surface R1: a) wide light distribution, b) narrow light distribution

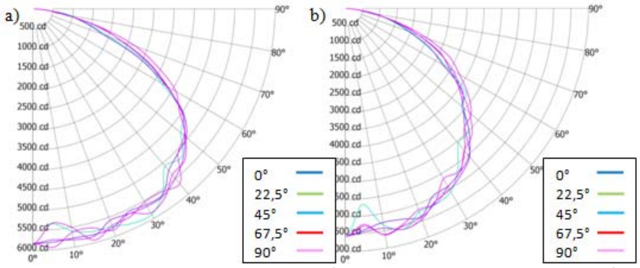

Fig. 7. Luminous intensity curves of the luminaire with the use of a reflector with a diffusing surface R2: a) wide light distribution, b) narrow light distribution

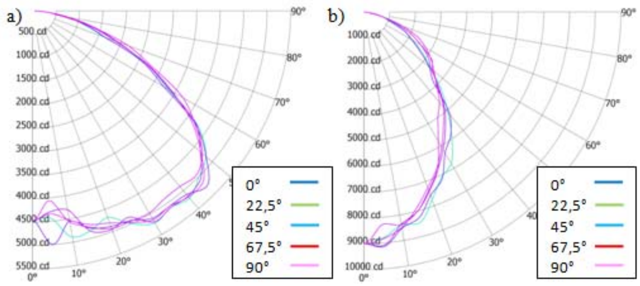

Fig. 8. Luminous intensity curves of the luminaire with the use of a reflector with a diffusing surface R3: a) wide light distribution, b) narrow light distribution

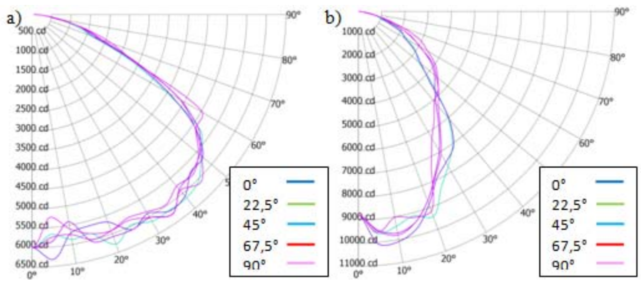

Fig. 9. Luminous intensity curves of the luminaire with the use of a reflector with a diffusing surface R4: a) wide light distribution, b) narrow light distribution

The use of diffusing materials allows to significantly smooth the luminous intensity curves. The disadvantage of this configuration is too little direction of the reflection, and thus the inability to ensure sufficient controllability of the light distribution. The distribution in the narrow variant is insufficiently focused (variants R1 and R2). In the R3 and R4 variants, a greater concentration of the distribution can be seen, but the shape of the diffuse distribution has also changed.

Analysis of reflector surface properties using materials with a directionally diffusing surface

Another analyzed solution is a group of materials with a surface ensuring directional-diffuse reflection (Fig. 10). The use of materials with different levels of surface matting, which affects the degree of scattering of the reflected radiation, was analyzed. The results of the analysis of light distribution curves for selected characteristic materials with different directional-diffuse reflection properties (K1-K6) are shown in Fig. 11-16. The degree of scattering of the reflected light is too high, which makes it impossible to ensure the required controllability of the light distribution. The results of the conducted analysis indicate that materials of this type are not suitable for use in the analyzed optical system.

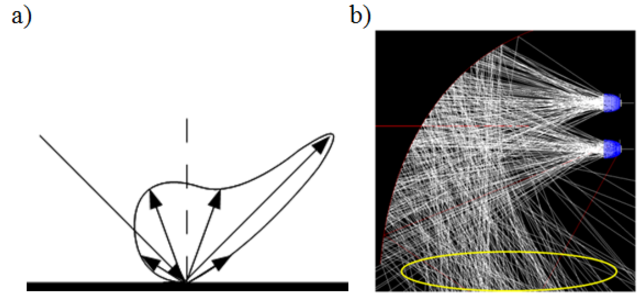

Fig. 10. Directionally diffuse reflection mechanism (a) and visualization of ray traces after reflection from a reflector with directionally diffusing surface (b).

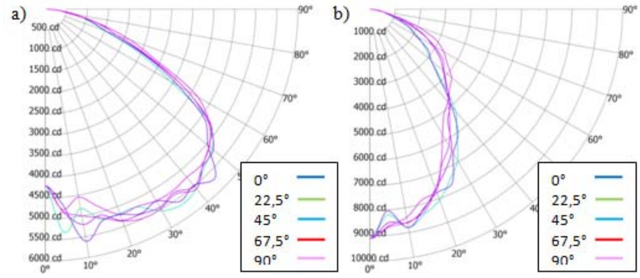

Fig. 11. Luminous intensity curves of the luminaire with the use of a reflector with a diffusing surface K1: a) wide light distribution, b) narrow light distribution

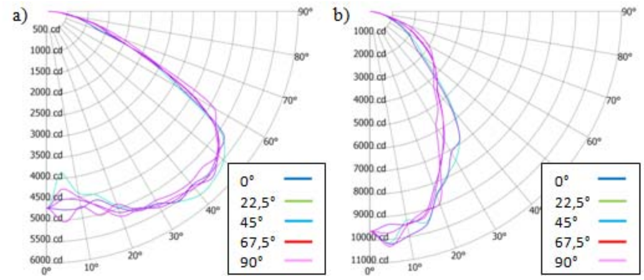

Fig. 12. Luminous intensity curves of the luminaire with the use of a reflector with a diffusing surface K2: a) wide light distribution, b) narrow light distribution

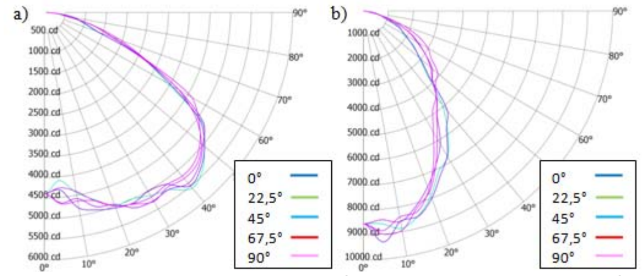

Fig. 13. Luminous intensity curves of the luminaire with the use of a reflector with a diffusing surface K3: a) wide light distribution, b) narrow light distribution

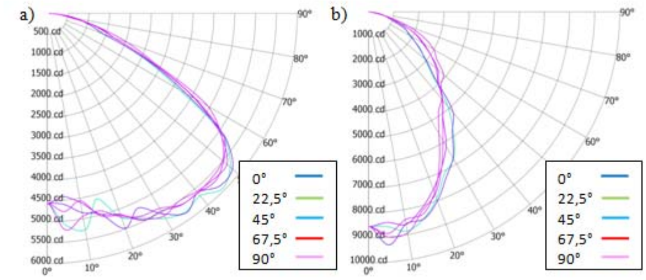

Fig. 14. Luminous intensity curves of the luminaire with the use of a reflector with a diffusing surface K4: a) wide light distribution, b) narrow light distribution

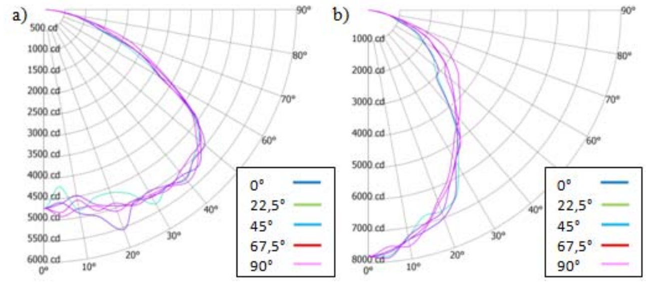

Fig. 15. Luminous intensity curves of the luminaire with the use of a reflector with a diffusing surface K5: a) wide light distribution, b) narrow light distribution

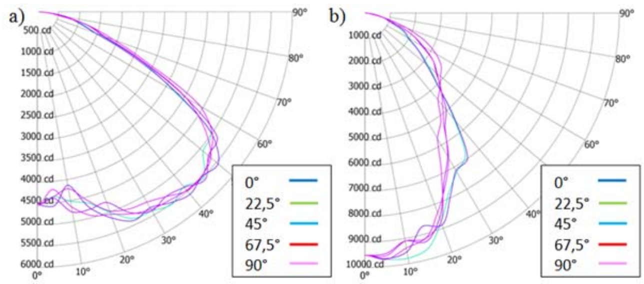

Fig. 16. Luminous intensity curves of the luminaire with the use of a reflector with a diffusing surface K6: a) wide light distribution, b) narrow light distribution

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3.4. The use of materials with a mirror surface with a diffusing macrostructure

Another group of analyzed materials are materials with a mirror surface with an embossed diffusing macrostructure, with a diversified concave or convex structure, in the shape of a honeycomb, round or irregular, with an element diameter of 5-7 mm and a depth of 1.5-2.0 mm.

The results of the analysis of the luminous intensity curves for the two extreme positions of the reflector (inclination 0° and 20°) of the luminaire with a reflector with a mirror surface with a diffusing macrostructure for selected characteristic materials (M1-M5) are shown in Fig. 17-21.

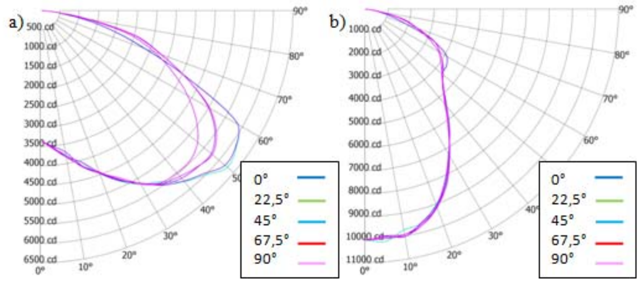

Fig. 17. Luminous intensity curves of a luminaire using a reflector with a mirror surface with a diffusing macrostructure M1: a) wide light distribution, b) narrow light distribution

In the M1 variant (Fig. 17) in the wide distribution, a slight decrease in luminous intensity is visible for small angles. On the other hand, narrow distribution shows too little focus of the light beam. In the M2 variant (Fig. 18) in the wide distribution there is a clear decrease in the luminous intensity for small angles. Narrow distribution shows a greater degree of focusing the light beam than in the case of the M1 variant.

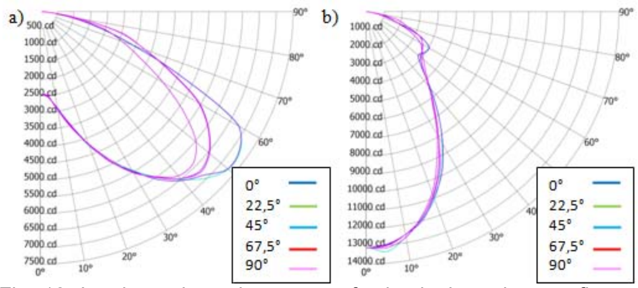

Fig. 18. Luminous intensity curves of a luminaire using a reflector with a mirror surface with a diffusing macrostructure M2: a) wide light distribution, b) narrow light distribution

In the M3 variant (Fig. 19), unfavorable effects are visible both in the wide distribution (large reduction of luminous intensity for small angles) and in the narrow distribution (increased spread of the light beam). Variant M4 (Fig. 20) has features similar to variant M2.

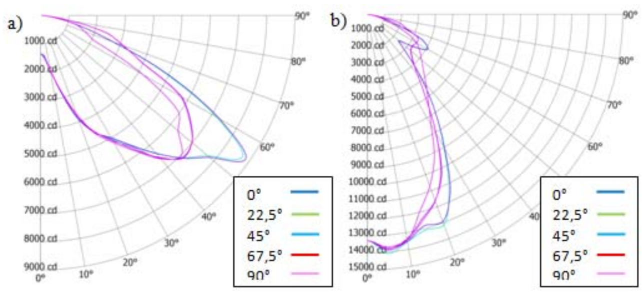

Fig. 19. Luminous intensity curves of a luminaire using a reflector with a mirror surface with a diffusing macrostructure M3: a) wide light distribution, b) narrow light distribution

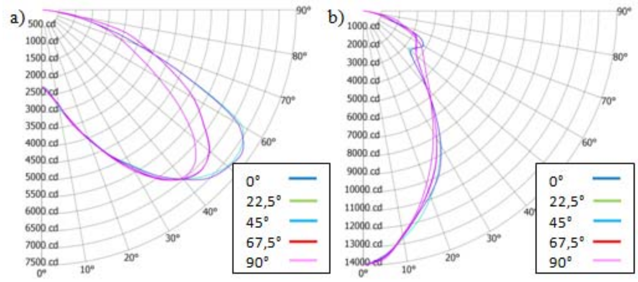

Fig. 20. Luminous intensity curves of a luminaire using a reflector with a mirror surface with a diffusing macrostructure M4: a) wide light distribution, b) narrow light distribution

In the M5 variant (Fig. 21), the wide distribution is characterized by a slight decrease in luminous intensity for small angles, similarly to the M1 variant. However, the narrow distribution shows a greater concentration of the light beam than the M1 variant, similar to the M2 and M4 variants. The results of the conducted analysis indicate that the use of a material with a mirror surface and the M5 diffusing macrostructure gives the most favorable effects in the tested system.

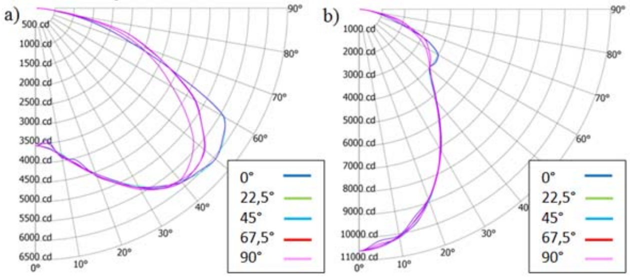

Fig. 21. Luminous intensity curves of a luminaire using a reflector with a mirror surface with a diffusing macrostructure M5: a) wide light distribution, b) narrow light distribution

The scale of deformation of the optically active reflector surface (M1-M5 materials) had a significant impact on the axial luminous intensity of the luminaire for the wide beam variant. In order to achieve the highest level of lighting uniformity in the immediate surroundings of the luminaire, a diffusing macrostructure with significant surface deformation should be used.

Conclusion

The material analysis of the optically active reflector surface allowed to assess the suitability of materials with different reflective properties for use in a light-optical system of the luminaire with a variable luminous intensity distribution. The results of the analysis show that:

1) The suitability of specular surface materials for use in systems with relatively large beam angles is limited. It makes it impossible to obtain a sufficiently uniform distribution, and thus also a uniform distribution of illuminance on the working surface.

2) The materials with the diffusing surface are not suitable for use in the analyzed optical system with variable luminous intensity distribution. The degree of diffusion of the reflected light is too high, which makes it impossible to ensure the required controllability of the luminous flux distribution.

3) Materials providing directional diffuse reflection are not suitable for use in the analyzed optical system. Similar to diffusing materials the degree of diffusion of the reflected light is too high.

4) The most favorable effects in the tested system are achieved by the use of a material with a mirror surface with a diffusing macrostructure. Thanks to this, it is possible to achieve both controllability of the direction of light radiation and its uniform distribution on the working plane.

In order to obtain the appropriate light beam spread over a wide range of beam angles in the target system, it is necessary to correlate the appropriate reflective properties of the material with the properties of the focusing profile of the reflector. The presented test results refer to the properties of the material, while the properties of the focusing profile of the reflector are the subject of further research on the luminaire with variable luminous intensity distribution.

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REFERENCES

[1] Barbosa J.L.F., Calixto W.P., Simon D., High power LED luminaire design optimization. *Proceedings of the IEEE 16th International Conference on Environment and Electrical Engineering*, Florence, Italy, 7-10 June 2016, pp. 1-6.
[2] Barbosa J.L.F., Simon D., Calixto W.P., Design Optimization of a High Power LED Matrix Luminaire. *Energies*, 2017, 10, 639.
[3] Barroso A., Dupuis P., Alonso C., Jammes B., Seguier L., Zissis G., A characterization framework to optimize LED luminaire's luminous efficacy. *Proceedings of the 2015 IEEE Industry Applications Society Annual Meeting*, Addison, TX, USA, 18-22 October 2015, pp. 905-913.
[4] Leśko M., Baran K., Wachta H., Różowicz A., A Concept of an Adaptive Luminaire with Variable Luminous Intensity Distribution. *Proceedings of the VII Lighting Conference of the Visegrad Countries (Lumen V4)*, Trebic, Czech Republic, 18-20 September 2018, pp. 1-4.
[5] Leśko M., Różowicz A., Wachta H., Różowicz S., Adaptive Luminaire with Variable Luminous Intensity Distribution. *Energies*, 2020, 13, 721.
[6] Cao X., Zheng D., Intelligent LED lighting system and sensor technology. *11th China International Forum on Solid State Lighting (SSLCHINA)*, Guangzhou 2014, pp. 129--132.
[7] Chew I., Kalavally V., Tan C.P., Parkkinen J., A Spectrally Tunable Smart LED Lighting System With Closed-Loop Control. *IEEE Sensors Journal*, Vol. 16, No. 11, pp. 4452-4459, June 1, 2016.
[8] Durmus D., Davis W., Optimising light source spectrum for object reflectance. *Optics Express*, 2015, 23, pp. A456-A464.
[9] Georgiev K., Hristov K., Dimitrov M., Pachamanov A., Training stand with control systems for street, tunnel and industrial lighting. *Second Balkan Junior Conference on Lighting (Balkan Light Junior)*, Bulgaria, Plovdiv 2019, pp. 1-4.
[10] Mahajan S.A., Markande S.D., Design of intelligent system for indoor lighting. *International Conference on Computing Communication Control and Automation (ICCUBEA)*, Pune, 2016, pp. 1-4.
[11] Onaygil S., Erkin E., Smart Lighting Solutions for Residences Using IoT Infrastructure: Advantages, Disadvantages and Effects on Energy Saving. *Seventh Balkan Conference on Lighting (BalkanLight)*, Varna 2018, pp. 1-5.
[12] Vázquez D., Alvarez A., Canabal H., Garcia A., Mayorga S., Muro C., Galan T., Point to point multispectral light projection applied to cultural heritage. *Proceedings of the SPIE 10379, Nonimaging Optics: Efficient Design for Illumination and Solar Concentration XIV*, San Diego, CA, United States, 7 September 2017, p. 103790K.
[13] Khanh T., Bodrogi P., Vinh Q., Winkler H., LED Lighting. Technology and Perception. *Wiley-VCH Verlag GmbH*, Germany, Darmstadt 2015.
[14] Van Driel W.D., Fan X.J., Solid State Lighting Reliability. Components to Systems. *Springer*, 2013.
[15] Handbook Energy Labelling for Public Lighting. *NL Agency and the "Dutch Institution of Illuminating Engineering",* 2010.
[16] Huang S.C., Lee L.L., Jeng M.S., Hsieh Y.C., Assessment of energy-efficient LED street lighting through large-scale demonstration. *International Conference on Renewable Energy Research and Applications (ICRERA)*, 2012.
[17] Kirpichnikova I.M., Volkova O.S., Maliugina A.A., Combined lighting system energy efficiency evaluation by the light flux regulation. *International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM)*, St. Petersburg 2017, pp. 1-5.
[18] Liu S., Luo X., Led Packaging for Lighting Applications. Design, Manufacturing and Testing. *Chemical Industry Press, Wiley*, 2011.
[19] Cree Product Characterization Tool: http://pct.cree.com/
[20] Seoul Semiconductor Product Data Sheet, www.seoulsemicon.com
[21] ACA Corp: https://acacorp.com/lighting/
[22] Alanod: https://alanod-westlake.com/products/
[23] Almeco Group: https://almecogroup.com/en/pages/377-reflecting-surfaces-for-lighting
[24] Photopia: https://www.ltioptics.com/en/index.html