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SPECIAL SECTION

Methods for designing and simulating optical systems for luminaires

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Abstract. This paper presents modern methods for designing optical systems for luminaires in the context of long years of light sources development. It shows that the development of technology for producing increasingly precise optical systems has led to an evolution in the construction of luminaires with increased efficacy and utilizing more efficiently the features of a specific family of light sources. Methods for designing and modelling optical systems with the use of mathematical curves as well as advanced the free-forming method are described. The paper also shows methods for modelling light sources features, especially luminance ones, designed to make precise simulation calculations required in any luminaire design process. Knowledge of luminance distributions of light sources and precise luminance distributions of optical systems for luminaires raises the design process to a very high level, enabling positive modern light source features, such as high luminance and their small dimensions, to be used consciously while minimizing negative ones, such as discomfort glare, caused by luminaires. The paper presents the results of simulation calculations and laboratory measurements for a selected case of luminaire equipped with a discharge lamp of maximum luminance exceeding 30 million cd/m^2.

Key words: lighting technology, optical systems design, luminance modelling, LID calculations.

1. Introduction

In the entire 20th century, the development of lighting technology was relatively slow and easy to predict. In the field of luminaires, solutions with a relatively low complexity degree were dominant in the reflectors market. Compared to general lighting luminaires used indoors and outdoors, basically one group was distinct in terms of the complexity of the optical system. They were the luminaires used in the automotive industry. Illuminating the road surface without dazzling drivers represented a big challenge.

The beginning of the 21st century led to a certain revolution in the field of lighting technology with the appearance of the light sources which, thanks to their features such as high luminance of 10^7 cd/m^2 and small dimensions, facilitated the design of luminaires optimized for specific lighting tasks. Additionally, seamless luminous flux adjustment, enabling the omission of traditional typo-series of light sources, offered designers great opportunities to optimize the luminaire design in all possible applications. And as a result, LED luminaires with high dynamics are currently displacing luminaires with traditional light sources in offices, warehouses, outdoors, in the streets, on bicycle paths, in automotive industry, in architectural lighting solutions, etc. Each of these life areas requires a slightly different approach towards luminaire design to use LED advantages, such as high luminance, and reduce their disadvantages, such as discomfort glare caused by the same high luminance. Most often LED luminaires are designed in a multi-source form, in which the light source with high luminance and surrounded by a square with dimensions not exceeding 1–2 mm is placed inside the lenses with the largest dimension usually close to 10–15 mm. This requires using extremely accurate geometric and luminance models that enable to conduct some precise simulations essential to the luminaire design process. The beginnings of the use of advanced luminance models are associated with the application of high-luminance light sources, such as halogen and discharge lamps (metal halide, xenon, etc.). Naturally, it was possible to develop and use these models thanks to the development of digital recording techniques for luminance images for light sources. The devices utilising this approach are digital cameras called the Imaging Luminance Measuring Devices (ILMD) [1] in the lighting technology. The paper presents the course of the development of light sources and optical systems as well as the advanced methods for designing, modelling and luminance analysis accompanying these methods.

2. Evolution of luminaire construction as a consequence of development of light sources

Although conceptually different, both a light source and a luminaire are an inseparable set of devices performing the task of producing a specific Luminous Intensity Distribution (LID) necessary to complete a specific lighting task. This inseparability, which is probably obvious, also applies to the progress of design solutions of both these elements. However, it should be estimated that it is the light source development that explicitly inspires the luminaire design changes, i.e. the development of their optical systems.

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If we look at the beginnings of the electric lighting era, which was initiated by the appearance of light bulbs, we will see relatively simple optical systems in the area of luminaires, such a simple, rotationally symmetrical reflectors (Fig. 1), with a geometrically justified profile (parabola, circle, etc.). Additionally, if the area of application in traffic lights is omitted, as in lampshades, it was alike – simple geometric forms, diffusing the light rather, with a minimal possibility of shaping the LID. However, it exposed the function of blurring the light source image. Apart from the area of application in reflector systems, where the use of mirror surfaces is highly justified, these first luminaire systems were more likely to use diffuse reflection and transmission. Generally, it should be assessed that the era of luminaire systems with incandescent lamps offered limited chances of shaping the LID. The opportunities to construct more advanced luminaires, allowing us to generate more sophisticated light distributions, were blocked by a low level of optical element production technology limited to producing (spinning, casting) simple geometric shapes.

Fig. 1. Simple shapes of elements for optical systems (spherical lens, paraboloid reflector, etc.) is a characteristic feature of the first luminaires using incandescent light sources

Basically, the appearance of halogen lamps did not change the luminaire design, apart from a chance to minimize to a certain extent the reflector and projector systems. It was a consequence of increasing the luminance of halogen bulb wire that is the parameter and together with the mirror dimension (diameter) determines its maximum luminous intensity.

The appearance and popularization of fluorescent lamps were important impulses provoking change in luminaire design. A long light tube with an incomparably lower luminance (10^3–10^4 cd/m^2) than a bulb wire luminance (10^6 cd/m^2) forced the designers to construct the optics appropriate to the geometry of optical systems, where the rotationally symmetrical optical system appropriate for a light bulb was replaced by linear systems: a parabolic cylinder, trapezoidal cylinder, etc. An important feature of a fluorescent lamp – limited luminance – allowed using the mirror reflectors, since in combination with the large dimensions of a fluorescent lamp (length, diameter), its optical system built on the basis of directional reflection, permitted us to generate more controlled and simultaneously relatively wide luminous intensity distributions, and thus a wide range of applications in interiors, in particular in public facilities.

Apart from increasing the energy efficiency of lighting installations, compact fluorescent lamps did not change the approach towards the optical systems for luminaires as compared to the time of using the light bulbs. And in this case, the reduced luminance of a fluorescent lamp (10^4 cd/m^2) and large dimensions of a luminous solid facilitated some applications using a mirror reflection.

Historically, almost simultaneously with the fluorescent lamp era, high intensity discharge lamps appeared - first mercury, then sodium and, finally, metal-halide. The spectral features of these lamps, as well as some maintenance properties (long warm-up time, no chance of quick re-start, etc.) enabled only some outdoor applications. As for these light sources, their impact on the development of the luminaire system constructions depended on the lamp design. Two versions of these light sources appeared: one with an elliptical diffuse bulb (luminance decrease) and another with a clear, tubular bulb in which a small, high-luminance arc tube (luminance of around 10^7 cd/m^2) was a light source. The former (with the elliptical diffuse bulb), due to the considerable dimensions of the light source, did not allow the designers to use any sophisticated optical systems and was used in the systems with a relatively simple reflector. As a result, low processed luminous intensity distribution was obtained. The undoubted advantage of these systems was limited lamp luminance. A breakthrough in the development of optical systems for light sources was the emergence of high intensity discharge lamps with transparent bulbs, in which the light source was a small high-luminance arc tube [2]. This feature, combined with high luminous efficacy, became an impulse to construct developed and advanced optical systems - the continuous and segmented (faceted) multi-curved mirrors with a dedicated aiming of light reflection and different reflection nature within one structure. It was then when the optical system for the street lighting luminaire represented a highly developed, faceted structure (Fig. 2), where each separate segment of the reflector was responsible for illuminating another part of the space.

Fig. 2. Multi-segment reflector system of street lighting luminaire cooperating with high-pressure lamp arc tube is an example of highly developed optical system technology

The solution described above would not have been possible in practice if, apart from an appropriate light source, there had not been a technological opportunity to produce such a precise and complex geometry for the optical system. Therefore, the development of production technology, especially the use of plastic materials, was another impulse to make progress in the field of optical system construction, and thus to meet the high requirements concerning the shape and complexity degree of the LID. Abandoning traditionally simple and smooth forms of reflectors and covers in favour of textured surfaces was also a consequence of the development, this time not of light sources, but the production technology. This feature of progress allowed us to include the macro- and microstructure of the border surfaces of reflectors and lampshades/covers in a set of elements shaping the LID. Hence, nowadays it is possible to build a flat mirror surface which, thanks to its microstructure, will reflect the light like a curved, concave, or convex mirror. This option is not a consequence of the invention of a new light source, but the effect of the appropriate shaping of the reflective surface microstructure (Fig. 3).

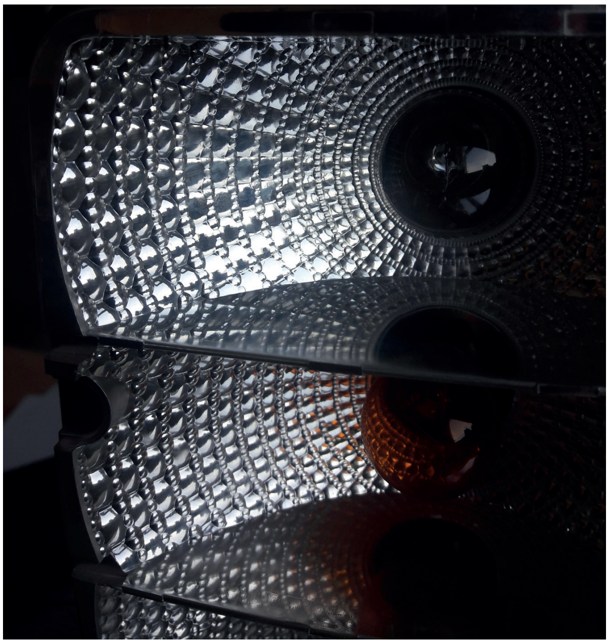

Fig. 3. Diffuse macrostructure – the implementation of this technology has expanded the possibilities of shaping the LID of luminaires

And now in these considerations we have reached the era of light emitting diodes (LEDs), whose development, together with progress in the area of luminaire systems dedicated to these sources, took place at the turn of the 20th and 21st centuries. This innovative type of light sources forced the lighting equipment manufacturers to change completely the way of thinking about luminaires. It resulted mainly from the following LED features:

- a semi-spatial angular area of light emission from an individual LED chip,
- a relatively low power of an elementary LED chip,
- small geometric dimensions of an elementary LED chip.

It was the second feature that has become a reason for abandoning the traditional solution of optical systems for luminaires, because even with the high luminous efficacy of LEDs as a light source, to produce a luminaire emitting a luminous flux at the level of a few or a dozen thousand lumens required designing a multi-lamp (multi-chip) luminaire. The small dimensions of a single LED chip duplicated a few dozen times within one structure of a luminaire, with the luminous flux at the level of a few or a dozen thousand lumens, require a structure of significant dimensions (LED matrix), which from the point of view of the luminaire structure makes it impossible to treat the matrix as one source for which the luminaire will be designed. As a result of such thinking, instead of one luminaire common to all LEDs that shape the final luminous intensity distribution, we are forced to shape the LID separately for each LED chip. The first above mentioned feature of LEDs – the semi-spatial luminous intensity distribution – significantly affected the design of optical systems for LEDs, too. The light beam of an elementary chip can be corrected by placing the optical elements (lenses, reflectors, etc.) in the same part of the area, in which the light is emitted directly from the chip. In practice, this indication translated into building the optical systems for LEDs in such a way that the element shaping the luminous intensity distribution became the lens spatially spanning the radiation zone of the light beam from the LED chip. Therefore, the dominant light reflection as a way of forming luminous intensity distributions in traditional luminaires was replaced by light transmission. That is why a modern LED luminaire is a multi-source luminaire, built on the basis of a tightly-packed matrix of individual chips, covered with a regularly grooved cover consisting of lenses shaping the final luminous intensity distribution. A mental shortcut was used in the abovementioned argument stating that the lenses shape the elementary LID of chips. This optical element made of transparent material (glass, plastic), usually presents a geometrically complex structure that combines the properties of a lens, a reflector and a prism. If we take a brief look at it from the perspective of the history of luminaire development, the problem of constructing the luminaire optical system has not changed. The geometrical scale of the luminaire components has changed. The geometrical dimensions of traditional luminaire elements, measured in centimetres, have been miniaturized and the construction considerations refer to a millimetre scale.

A noticeable and undoubtedly favourable effect of the LED era is a significant improvement in the quality of designing optical systems. A situation noticed in the street lighting can be an example. With the comparable luminous efficacy of traditional high-pressure sodium lamps and light emitting diodes in the street lighting, the designers need to use LED luminaires of significantly lower power than in the case of high-pressure sodium luminaires to illuminate a selected section of the street. At first glance, it is incomprehensible and difficult to explain, but a deeper analysis shows that the LIDs of LED luminaires are closer to the real needs of illuminating the road. The light diffusion beyond the width of the road is lower and it is easier to adjust the level of the designed lighting to the requirements (no unnecessary oversizing of the average luminance), since a rather tough type-series of sodium lamp wattage is currently replacing the flexible adjustment to the needs of LED wattage.

Further, the paper will present some modern methods for luminance modelling of light sources, designing and simulating luminaires based on digital geometric and luminance models.

3. Modern methods of optical system design

Despite basic differences in the materials used and in the manner of operating, both reflector and lens systems, characterized by directional or quasi-directional interaction with light, are designed using the same methods. Nowadays, two basic methods are used to design their shapes. These are the methods that use surfaces based on mathematical curves [3], mainly the so-called conic curves (circle, ellipse, parabola, hyperbola) and named freeforming (known in the automotive technology as FF) or tailoring, which has been developing intensively in recent years. Tailoring reflectors and lenses can be based on algebraic [4, 5], graphic [6, 7] or optimization [8] methods. Regardless of their theoretical background, all these methods are based on a homogeneous luminance distribution and overall dimensions of light sources.

Mathematical surfaces such as spherical surfaces, paraboloid, ellipsoid, parabolic and elliptical troughs are used in simple cases in which it is important to focus the light beam around a direction or on a specific small surface. The required beam divergence is obtained in several ways: by matching the focal length of the mirror or lens to the light source size, by tilting the axis of the forming curve from the axis of the optical system (creating a surface by means of turning the conic curve around the line not parallel to the axis of the curve) or by giving a specific roughness to the surfaces of optical elements.

A luminaire based on a parabola can be an example of using mathematical curves to form reflectors. Three cases are presented in which the parabola tilted by 0, 15 and 30 degrees, respectively, was rotated around the luminaire axis, calibrated so that the inner edge (internal opening) of the reflector was adjacent to the COB diode housing and its centre was in the focus of the parabola. The reflector form was cut to obtain a constant protection angle of 45 degrees. Three different distributions were obtained, all useful in different lighting applications (projector, high bay, downlight) (Fig. 4).

Freeforming is an alternative to using mathematical curves. The basis of this family of optical system design methods is to determine the course of a beam of rays emitted from the light source and reaching the illuminated surface, taking into account a change of their direction when they meet the boundary of the media. On this basis, the tilt of the surface of the system elements is determined at the points of its impact on individual rays. These methods are used to design lens (collimator) systems made of transparent materials more often than to design reflector systems made of opaque (metal or metallised) materials. For the correct course of the design process, it is extremely important to select the right number of rays, for which calculations are made as well as the material parameters, mainly refractive indexes of the materials used.

Designing an optical system with any of the freeforming methods comes down to a solution for each considered ray of

a) b) c)

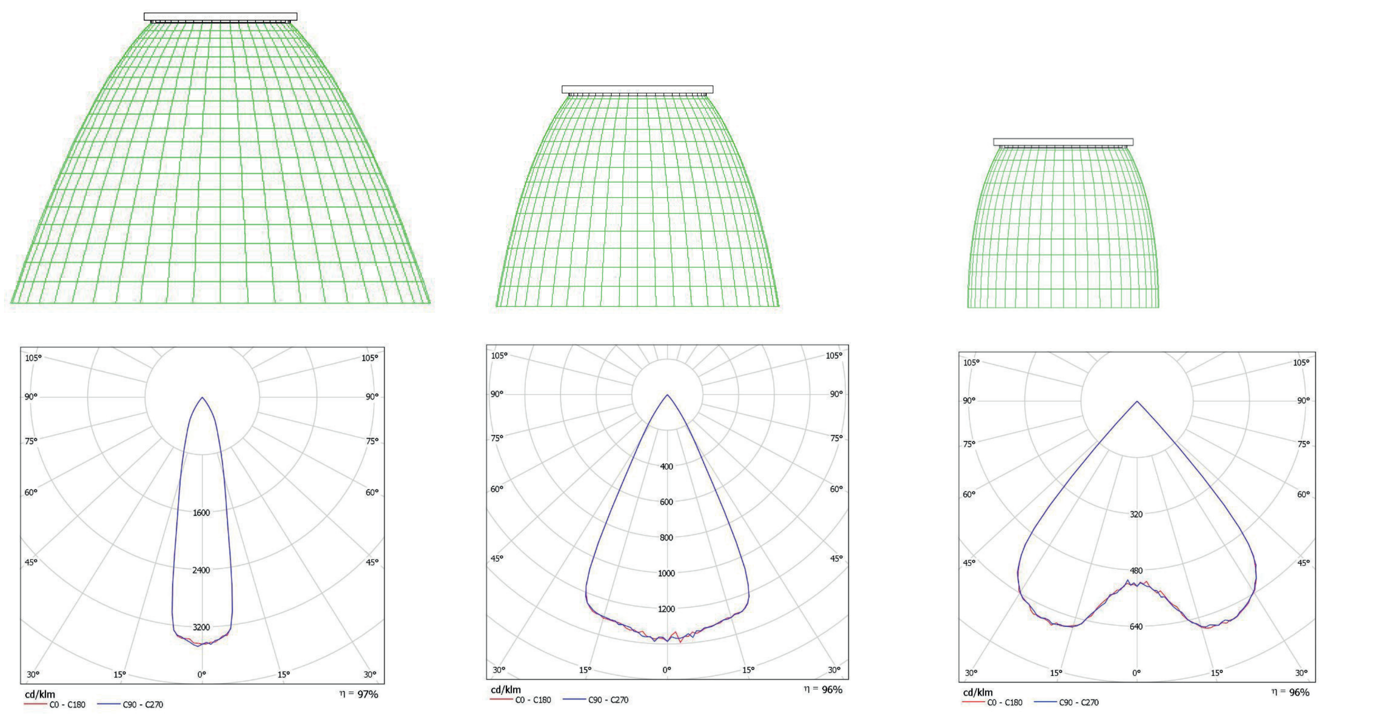

Fig. 4. Shapes of reflectors with a forming of parabola fragment of axis tilted by: a) 0 degree, b) 15 degrees and c) 30 degrees and luminous intensity curves corresponding to them

equation system (1) describing the phenomenon of reflection or refraction of light at the boundary of media [6].

$$\begin{aligned} \boldsymbol{A} \times \boldsymbol{n}_1 &= -\boldsymbol{A}' \times \boldsymbol{n}_1\,, \\ \boldsymbol{A} \times \boldsymbol{n}_1 &= \boldsymbol{B} \times \boldsymbol{n}_2 \end{aligned} \tag{1}$$

where:

$\boldsymbol{A}$, $\boldsymbol{A}'$, $\boldsymbol{B}$ – the light ray versors: coincident, reflected and diffracted,

$\boldsymbol{n}_1$, $\boldsymbol{n}_2$ – the normal vectors up to the boundary of media of lengths equal to refractive indexes n_1 and n_2.

Individual methods differ in the way they describe rays and how they solve the system of equations. In the literature, you can find some descriptions of algebraic methods [4, 5] for solving the above system of equations and graphic methods [6, 7].

Algebraic methods are more susceptible to the automation of the process at the expense of its flexibility. One pattern of light interaction with the optical element is assumed for all analysed rays. When determining the geometry of refractive surfaces, three patterns can be distinguished as follows:

- no refraction of light at one of the boundaries of the medium, usually input, which occurs when the light falls perpendicularly to the refractive surface and the whole refraction is on the other surface (Fig. 5a) [9],
- one surface is set (usually flat), the further course of the rays results from its shape, and to direct it further, it is refracted on the other surface (Fig. 5b) [10],
- passing through the medium is symmetrical, i.e. on each surface there is a half of refraction of the ray between the ray coming from the source and the one falling onto the illuminated surface (Fig. 5c),
- both surfaces are created using the freeforming method [11].

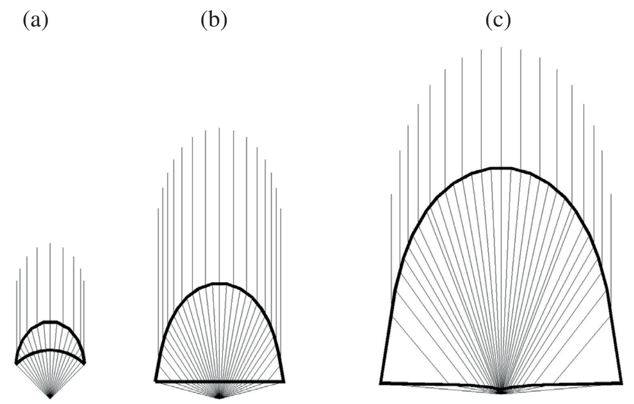

Fig. 5. Diagrams of light passing through lens created with freeforming method according to the patterns: a) spherical surface – freeforming, b) flat surface – freeforming and c) refraction by half an angle on the input surface and half an angle on the output surface

A lack of flexibility in the conduct procedure is a drawback of algebraic methods. If the angles of ray refraction prevent one from using one method, it is impossible to move smoothly to another one. In the event of applying different methods to different rays, it is necessary to decide in advance where a change of the method used must be made. As a result, the designed element must be created as a set of separate elements designed with different methods. They can be combined into one element only at the next stage of the design process.

Descriptive methods allow us to select a way of optical element interaction with the light more freely than algebraic methods. You can freely move between fragments of the optical element surface affecting the course of rays in different manners. However, this means a more labour-consuming method and greater mental involvement on the part of the designer while designing. If one way of proceeding in a certain area begins to give a little unsatisfactory result, it can be replaced with another one at any place. Sometimes, it is worth making the effort of a more laborious design process, especially in difficult systems that, due to the complex way of illuminating, do not undergo the design with algebraic methods. In many simpler cases, graphic methods can be subject to automating the design process, but it is an inefficient solution.

4. Design of asymmetrical optical systems

Asymmetrical lighting is used when a luminaire cannot be located centrally in front of the illuminated surface. In addition to the asymmetrical mount in relation to the illuminated surface, they are characterized, by the asymmetrical LID of the luminaire, too.

An important issue for any type of lighting, including asymmetrical, is supposed to provide its uniformity on the illuminated surface. Apart from the layout of luminaires, a properly designed optical system for any luminaire has a key impact on the lighting uniformity. To achieve uniform asymmetrical lighting, you should focus on the generated luminance distribution on the surface of the object. The obtained luminance distribution has a decisive impact on perceiving the illuminated object, i.e. its dimensions, geometry and surface texture. The luminance distribution should be verified up to date while designing the optical system. It is insufficient and, above all, ineffective to perform numerous time-consuming analytical and geometrical operations, and then checking the luminance distribution obtained in a computer simulation [12]. This leads to a risk of creating the unacceptable structures, and, as a result, requires starting the design work from scratch. The design process of such an optical system should be efficient, considering the current level of technology development in the field of simulation calculations, and production technologies and optic element processing. Designing an optical system should not slow down the entire process of creating new lighting equipment.

During the research [13], a way was found for the effective design of the asymmetrical optical system for luminaires so as to assess the luminance distribution obtained on the illuminated surface during subsequent operations in the range of shaping the optical elements.

In order to solve the problem of current verification of the luminance distribution or illuminance on the illuminated surface (an assumption of the diffusive nature of light reflection was accepted by default), the process of designing the floodlighting can be inspiring. The purpose of floodlighting is to achieve a specific luminance distribution on the illuminated surface of the object. For this purpose, the luminaires with appropriate output and luminous intensity distribution are selected. Then they are in the right places and aimed. Observation of the achieved luminance distribution allows us to accept a given solution or make some changes. The same approach can be used when designing individual optical system elements for the luminaire. It is possible to imagine the illuminated surface and the light source placed at around its edge. It illuminates this surface in a certain way, usually a little uniform, as a rule, unacceptable from the point of view of our design assumptions. That is why the optical system elements (reflecting or transmitting the light), which modify the current lighting effect, are successively introduced. Ultimately, the desired luminance distribution of the illuminated surface is acquired, with specific convergence in relation to the assumptions.

The above comparison to floodlighting was used to create a block diagram of the authors' calculation method. The block diagram is shown in Fig. 6. The diagram presents a selected light source and an illuminated surface with specified parameters. The light source, the illuminated surface and the reference (expected) luminance or illuminance distribution are assumed in advance. Then the iterative process of the material selection, size, aiming and position of the subsequent optical elements relative to the light source takes place. A preview of the resulting luminance or illuminance distribution on the illuminated surface and its comparison with the reference distribution is an inseparable component of these iterations. This facilitates the comparison and evaluation of the previously performed operations and performing the subsequent ones on that basis. Additionally, a preview of the emerging geometry of the optical system is available.

In the developed calculation method, an LED was accepted as a light source. Its model used in calculations consists of three parts. One geometric part and two luminance parts. The geometrical part represents the cross-section of the solid of the light source with a plane. The luminance parts contain two sets of luminance distributions. The first one is the luminance distribution of the LED luminous surface, recorded with the imaging luminance measuring device as part of the device rotation around the LED, with the appropriately selected step. The second set is the luminance distribution also recorded with the imaging luminance measuring device, but on the plane of the measuring screen, which is illuminated only by the light source, with a different light source position from the screen.

With this light source model, the following transformations can be made. If a flat mirror optical element with unlimited dimensions, located near the light source is considered, the luminance distribution created on the illuminated surface can be obtained by simply transforming one of the luminance distributions on the measuring screen, which is part of the light source model. The measuring screen that is in the same direction relative to the light source as the mirror element must be selected. The transformation consists of calibrating each of the discrete luminance values of the measuring screen by a factor dependent on the distance change and mutual position between the light source and the object. Here one time the object is the measuring screen and next time – the illuminated surface. As a result, the luminance distribution created on the illuminated surface is obtained after applying the optical system consisting of the light source and the unlimited mirror surface. Naturally, the obtained results should be added to the luminance distribution coming from illuminating the surface with the light source itself. This distribution also represents one of the luminance distributions recorded on the measuring screen.

The next step is to make this situation real, i.e. to limit the dimensions of the mirror surface used. These dimensions can be limited arbitrarily. While reducing the surface dimensions, each of the discrete luminance values on the object surface, coming from the use of a given mirror element, should be calibrated. The calibration factor will depend on the extent to which the

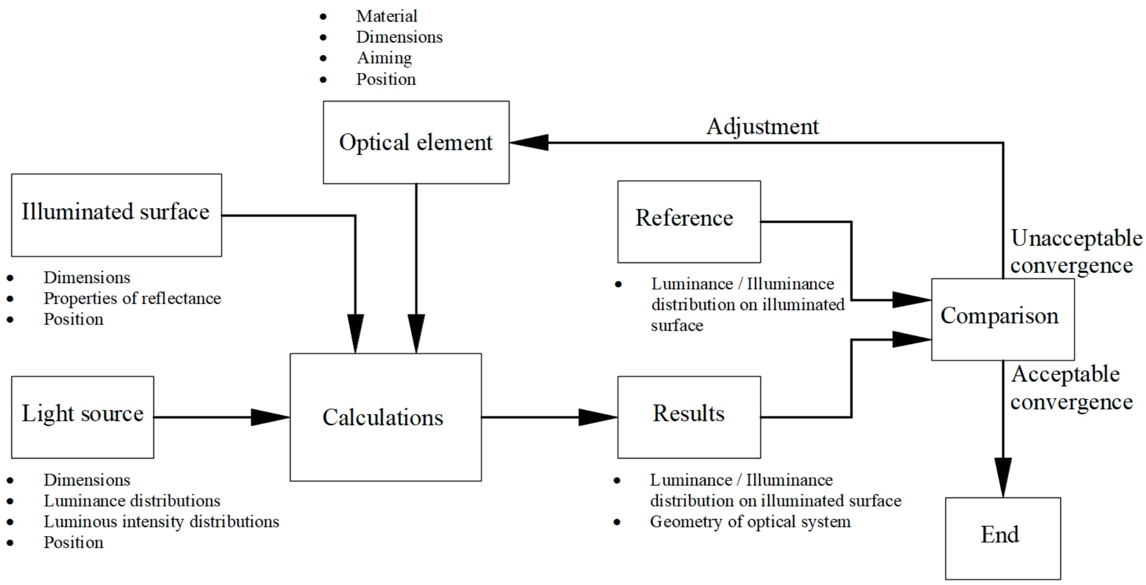

Fig. 6. Block diagram of authors' calculation method

image of the light source visible on the mirror surface from this direction has been reduced. The reduction of this image translates directly into a decrease in luminous intensity and the generated luminance on the illuminated surface accordingly. Due to the volume of this paper, not many details are included about the abovementioned transformations. However, more information is available in other publications [13–15].

This kind of procedure is used for the subsequent flat mirror elements introduced. The next element contacting the previously introduced element is added and the described transformations are conducted so as to obtain the luminance distribution on the illuminated surface, coming from the light source, the already added elements and the currently considered one.

The described transformations in 2D were entered into the Excel spreadsheet and represent a prototype of the calculation method. The spreadsheet view is shown in Fig. 7. Apart from the layer of mathematical functions, the sheet displays the luminance distribution obtained on the illuminated surface and allows us to enter a series of input data. The input data includes: the light source dimensions and two sets of luminance distributions connected with it. This is the data entered at the beginning of the design process. On the other hand, the position, dimensions and aiming of the analysed flat element of the mirror reflector are subject to current changes. This calculation procedure and Excel spreadsheet were used to design a trough-shaped reflector with LED light source [16].

The advantage of this calculation method is the independence of making time-consuming computer simulations while designing to verify the already undertaken design activities. In the case of random optical system analysis, for example in the Monte Carlo method, the simulations whose duration is directly proportional to the accuracy of the obtained results are conducted. If the time is limited, only rough results will be received [17].

The ongoing observation of the luminance distribution being created on the illuminated surface allows us to assess the impact of adding the further optical elements to this distribution. It can be seen what course of luminance distribution they produce and how this course changes together with the change in aiming the elements, i.e. the position of the distribution on the illuminated surface. Additionally, the impact of the slopes of such a distribution can be seen when there is an intention to combine it with the already existing distribution. These slopes are often a critical element that affects the extent to which a uniform luminance distribution on the illuminated surface can be achieved.

5. Methods for modelling geometric-photometric features of light sources

Each project currently underway is subject to computer light simulation before undergoing a stage of prototyping and laboratory tests. The cost of making corrections in physically built prototypes depends on the quality of the simulation result. Therefore, there is a tendency to keep the light simulations for luminaries as real as possible.

Modern computational and simulation methods in the lighting technology are based on computer technology and numerical methods. As a result of the development of software and the increase in computing capabilities of computers, the application of precise methods simulating physical phenomena gives an opportunity to obtain incredibly accurate analysis results. The use of numerical methods, whose big advantage is the multiple repetitions of calculations according to the developed algorithm, always requires the definition of the initial boundary parameters of the system and acceptance of the specific simplifying assumptions. These assumptions apply to every system element existing in virtual memory. As for the lighting technology and luminaires, they are geometric rendering precision and photometric description of light source parameters, respectively [18, 19]. And then come the numerical computational mesh

reflector height [mm]	20
reflector aiming [deg]	141,4
reflector start point x [cm]	-4,00
reflector start point y [cm]	-3,00
direction of increase +x=1, -x=(	0
housing start point x [cm]	5
housing start point y [cm]	9,4
distance to object [cm]	100
arc tube radius [mm]	4,191
distance to screen [cm]	100
reflection index	0,63
L=1, E=0	1
constant level L / E	12

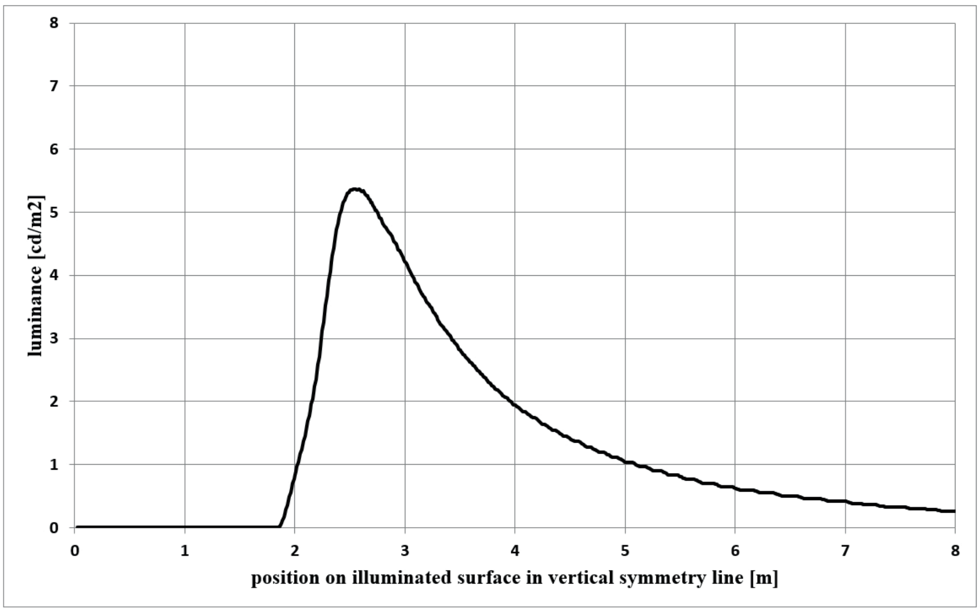

Fig. 7. View of spreadsheet implementing calculation method

density, the geometric rendering precision and the description of the parameters and, for example, the reflection characteristics of materials for reflectors, transmissive materials, etc. The same assumptions accompany the computational environment where such parameters as the number of analysed light rays, the number of iterations, the number of interactions of each ray with the environment, the density of computational mesh division, etc. are pre-defined [20]. Every simplifying assumption accepted at the initial stage of calculations means obtaining the results to a certain extent different from the results of laboratory measurements for the analogous optical systems of luminaires. To make a decision on the acceptable level of accuracy and to identify the reason for any differences, a convergence analysis of the simulation calculation results in relation to the laboratory measurement results that have a direct impact on the photometric characteristics of luminaires should be conducted. A luminous intensity distribution is a basic luminaire parameter that is subject to calculations and that is assumed at the initial stage of each optical system design [21]. The LID itself contains the accurate information about the luminous intensity distribution of the luminaire in each direction of the space. Therefore, it should be considered where the specific value of the luminaire luminous intensity in each direction of the space results from. For all types of luminaires, the luminous intensity results from the product of luminance and the apparent surface area that is covered by this luminance. Obviously, each light source is characterized by a specific luminance distribution which is responsible for the luminance distribution "projected" on the surface of the reflector, lens or cover. It is this luminance distribution, its values and dimensions that are directly responsible for the values of light in each analysed direction in the space.

Historically, basic simulation methods for the needs of photometric calculations were based on the assumption of point of light source (Fig. 8). The development of the methods involved approximating the geometry of the light source by inscribing it in a solid of similar dimensions (Figs. 8a–c). This approach allowed the researchers to determine the basic luminaire parameters, such as maximum luminous intensity and beam divergence angles, with errors directly resulting from the accepted simplifying assumptions (Figs. 8 and 10). The biggest calculation mistakes were caused by the assumption of constant luminance value over the entire surface of the light source approximated by the solid (Figs. 8a–c). This assumption is particularly important and has an impact on the precision of calculations in the case of luminaires characterized by high gains in luminous intensities in specific directions of the space [22]. Most often these luminaires are the spotlights with mirror reflectors and the projectors with lens systems. It should be considered where the observed differences come from. In fact, the design process of luminaires characterized by high gains in luminous intensities (often exceeding x100) is based on the use of high-luminance light sources. Hence, at that point, which is the focus (or "focal point"), part of the light source having the possibly high luminance is placed (Figs. 8b–d). As for the discharge sources, this is the central part of the arc tube. Fig. 8b shows that shifting its diameter by 20% (which means a distance of 2 mm) from the central part of the arc tube causes a 2-fold decrease in luminance, shifting by another 2 millimetres causes a 10-fold decrease in luminance in relation to the maximum value. This relates to a drastic decrease in partial luminous intensity of the luminaire, generated by the image of this part of the arc tube on the optical system surface. The reduction in luminous intensity generated by a given area of the light source is directly related to the fact that a lower luminance value that will be "projected" onto the surface of the reflector or lens needs a proportionally larger surface of the optical system to produce the same value of luminous intensity. A similar effect can be observed for calculations obtained as a result of the assumption of luminance con-

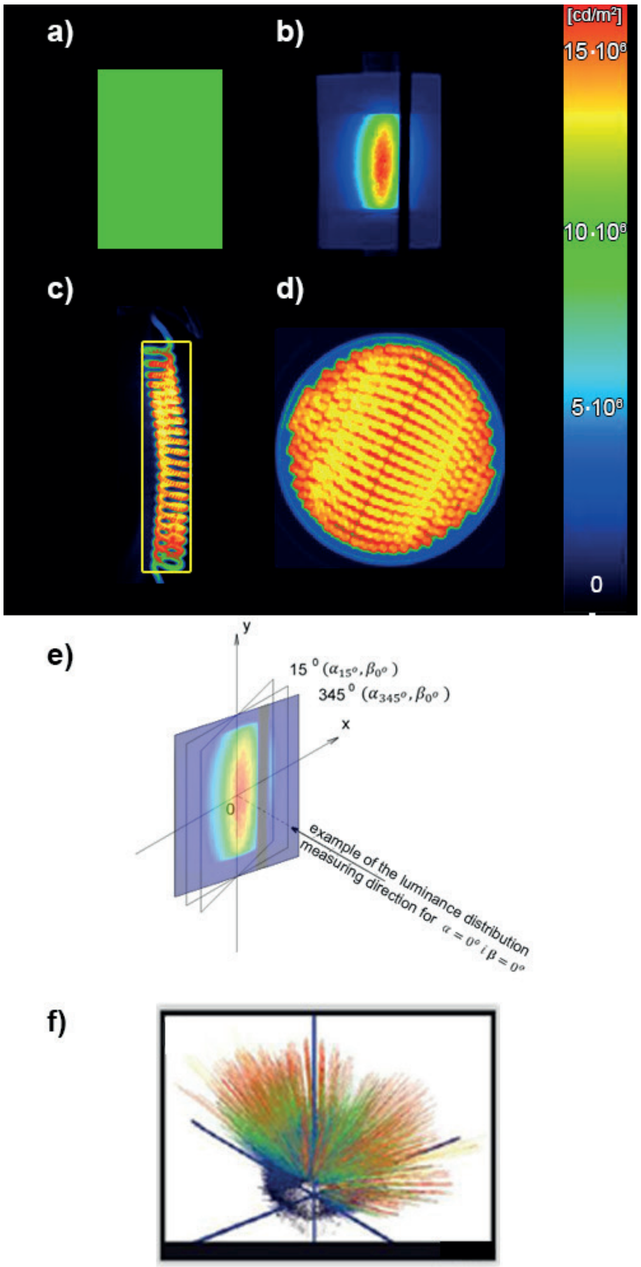

Fig. 8. a)–d) computational luminance models of light sources with use of ILMD [24, 25], e) visualization of implementation of computational bunch of planes model and f) visualization of light source model in accordance with TM-25 (rayfile) f) [26, 27]

stancy over the entire surface of the light source. Calculating the dimension luminance as the ratio (2), the received result of calculations for the luminous intensity of the luminaire system is very close to the reality, but only for the light sources that have a possibly uniform luminance distribution on the entire surface. As far as the high-intensity discharge lamps and LEDs (especially of the COB type) are concerned, an average luminance value that will be correct should be obtained, but there will not be any information about the local maxima, which have a huge impact on the spatial luminous intensity distribution (Fig. 8).

$$L_g = \frac{\Phi_0}{\pi S_g}, \tag{2}$$

where:

Φ_0 – the luminous flux of the light source,

S_g – the dimension surface of the light source.

For this reason, the development of light source models heads towards precise rendering not only of the proper geometry, but also the physical features directly responsible for the photometric parameters of the luminaires built with their use.

Being aware of this fact, light source models can be divided into 4 groups. The first group consists of the models that are extremely geometrically simplified, such as a spotlight and a light source approximated by a solid similar to it, with the assumption of constant luminance over the entire surface, resulting from the ratio of the luminous flux and the dimension surface of the luminous parts (Fig. 8a). In the second group there are the models whose geometry is similar to the geometry of real light sources. These models contain correct or simplified luminance data over the entire surface. An example of such a model is the model implemented in the LTI Photopia calculation software [23]. The whole third group includes very accurate geometric models of light sources along with precise information about luminance distributions on their surface. Basically, this description is not currently found in simulation calculations in the lighting technology. The fourth group covers the luminance models of light sources that ignore or minimize the importance of geometric features of light sources, taking them into account indirectly by using the luminance model developed for millions of preliminary rays containing the detailed data on luminance values and emission points and directions of luminance vectors in space. It should be added that this method for describing the light source is most used in the current lighting technology. This method includes one of several planes proposed by the Lighting Technology Division, WUT, which is based on luminance mapping of the projection of the luminance image of the light source onto the calculation plane corresponding to it. Most often the calculation of luminaire parameters using this method for describing the light source is based on an analysis of "backward ray tracing" (Fig. 9b).

As for the indicated simulation methods, three calculation methods can be distinguished, differing significantly in time and computational complexity. The first method is a classic ray-tracing method, e.g. the Monte-Carlo method [17]. It assumes analysing the course of millions of rays (typically about 10,000,000), sent from randomly selected points on the surface

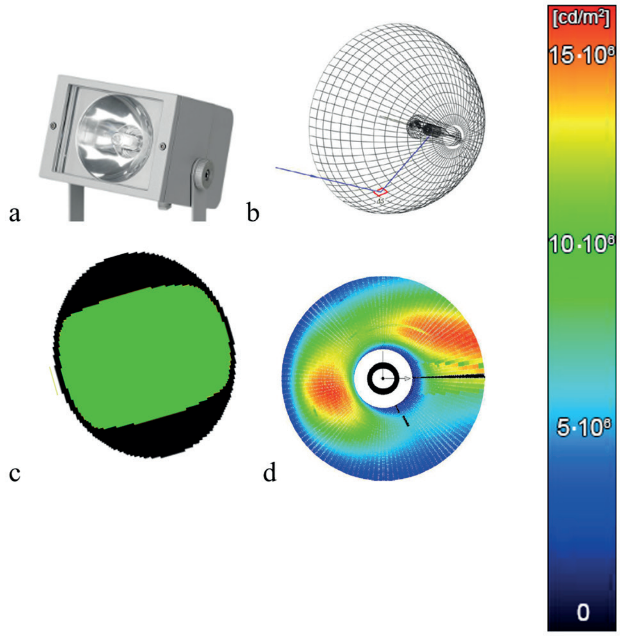

Fig. 9. a) photo of luminaire used in the project, b) visualization of backward ray tracing method, c) calculation result (LPF) for assumption of constant luminance of light source and d) calculation result (LPF) including real luminance distribution of light source [22]

of the light source in random directions in the space. Very often the points and directions result from the points and directions recorded by the light source manufacturers and provided in the IES TM25 rayfile [26]. After drawing a specific ray and direction, its interactions with the environment are checked. The number of interactions considered is usually defined in advance at the beginning of the calculation process and ranges from 25 to 50. The second calculation method is a backward ray tracing method. This method involves sending a beam of parallel rays from the direction of observation towards the luminaire. The rays correspond to the number of the parts (triangles or quadrangles of mesh) the numerical optical system model is divided into. After analysing ray reflections or refractions in the optical system, their relationship with the light source is checked. Then, for each ray that meets the light source, luminance is determined, characteristic of the point on the light source which the ray has met in the space. The value of this luminance, the value of the reflectance index or the value of the material transmission and the size of the discrete element in the direction to which the ray has been sent determines the partial value of luminous intensity in the direction to the space, from which the rays have been sent. This allows for precise visualization of the luminance model of the light source image on the optical system surface, called the Light Points Figure (LPF). LPF is directly responsible for the LID obtained. This method reproduces the reality most accurately in the case of spotlight systems with mirror reflectors and lens systems made of transparent materials such as glass, PMMA, polycarbonate or optical silicone.

The third method is a hybrid method that consists of 2 previous ones. In this method, the backward ray tracing method initially nominates the directions for which the luminous intensity is calculated using the classical ray tracing method. In short, it means using the backward ray tracing method to eliminate the rays sent from the light source that do not participate in creating the luminous intensity or luminance distributions characteristic of the selected direction of observation.

6. Computational precision of dependence of type and detailed features of light source models

The next part of the paper will be devoted to an analysis how the presented simplifying assumptions (Fig. 8) affect the calculated photometric characteristics of luminaires in the process of designing and simulating the luminaire parameters.

Ideally, both LID and luminance distributions obtained in the numerical calculations should be identical to the LID and luminance distributions obtained in the laboratory measurements for the analogous systems existing physically and to the virtual models in computer memory (Figs. 9, 10). For this purpose, a precise three-dimensional model of the optical system and a precise luminance model of the light source should be made. To illustrate the specifics of the results obtained with the simplifying assumptions, some analyses of a virtual model for the luminaire with an actually existing mirror reflector were conducted. For the calculation purposes, all models of light sources presented in Fig. 8 were used. The analysis of Fig. 10 shows that it is possible to achieve very high convergence of measurements and simulations of luminance distributions and values of luminous intensity in the analysed directions. However, this requires the development of a very precise luminance model of the light source and a precise geometric model of the optical system.

Fig. 10 clearly shows that simplifying the real luminance model of the light source and replacing it with the uniform luminance distribution (L_g) eliminates the opportunity to acquire knowledge about the maximum luminous intensity and falsifying the useful beam divergence angle. This simplification disqualifies this method in today's lighting technology. However, it can be noticeable that the use of the luminance model in any of the variants presented in Figs. 8d–f (luminance mapping on the geometric model, method of luminance plane bunch, TM-25 rayfile model) allows us to obtain the simulation calculation results almost nearly 100% close to the results of laboratory measurements. This is done while determining both LID and luminance distributions on the output surfaces of the optical systems (Fig. 9d). The differences between the light curves obtained in the simulation and the luminous intensity curve received in the laboratory measurements do not exceed 4% for the lowest luminous intensity values and 1.5% for luminous intensity values exceeding 0.1 I_{max}. An example of a luminaire with a discharge light source is representative of any light sources for which we can record precise luminance distributions using ILMD (Fig. 8b–d). An in-depth analysis of the results presented in publication [28] proves that the differences in comparison between

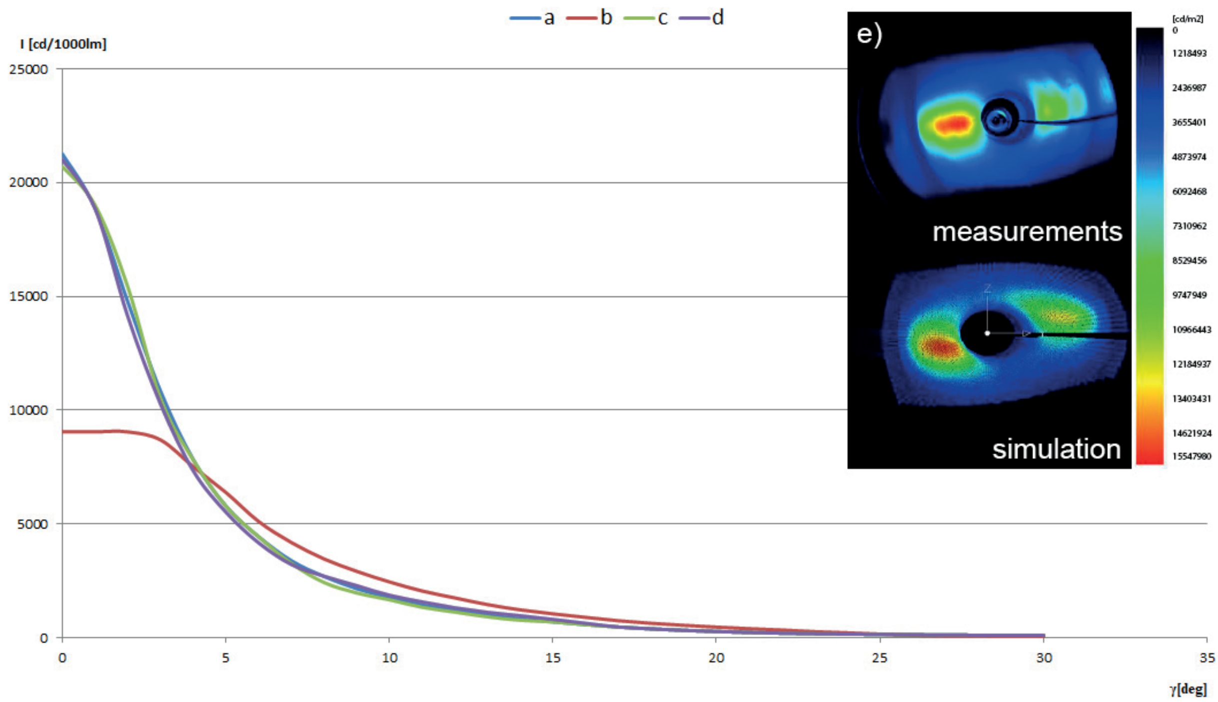

Fig. 10. Comparison of luminous intensity curves for symmetrical rotary paraboloid mirror reflector system with parameters $D = 167$ mm, $f = 16.45$ mm, with a 150 W metal halide lamp ($\Phi = 12700$ lm): a) obtained by means of measurements, b) with simulation results by means of an application assuming calculated constant average luminance on surface of arc tube ($L_g = 5{,}378{,}704$ cd/m^2), c) simulation in the LTI Photopia software with own model, d) with the TM-25 (rayfile) model and e) comparison of LPF obtained as a result of 3d simulation by the author's method and ILMD measurements for the existing luminaire [26, 27]

LIDs obtained as a result of simulations and laboratory measurements do not exceed 3%. Simulations' results and measurements of luminous intensity distributions were compared using the Bergen method [29]. The paper [29] presents the methods related to the differences between two LIDs calculation "(3)" and "(4)", where in the case of no difference, the value $f_{luminaire\_fit}$ should equal 100.

$$f_{luminaire\_fit} = = 100x\left(1-\sqrt{\frac{\sum_{C=0}^{360}\sum_{\gamma=0}^{180}(I_1(C,\gamma)-I_2(C,\gamma))^2}{\sum_{C=0}^{360}\sum_{\gamma=0}^{180}(I_1(C,\gamma)+I_2(C,\gamma))^2}}\right) \quad (3)\ [29]$$

where:

$I_1(C,\gamma)$ and $I_2(C,\gamma)$ – the luminous intensity distributions 1 and 2, respectively, at the angle (C,γ)

$$f_{luminaire\_flux} = \frac{F_1}{F_2} \quad (4)\ [29]$$

where:

F_1 and F_2 – the luminous fluxes calculated from distributions 1 and 2.

For conducted research for LEDs, the differences between luminous intensity distributions, calculated with the Bergen method [29], was $F_{luminaire\_fit} = 98.72$ and $F_{luminaire\_flux} = 0.988$ as for Photopia software and $F_{luminaire\_fit} = 97.61$ and $F_{luminaire\_flux} = 0.970$ as for the method and the author's software presented in the paper [28]. The same convergence of results the authors obtained for both traditional light sources (Fig. 8c), discharge light sources (Fig. 8b) and electroluminescent light sources (Fig. 8d). In addition to the presented high convergence of LIDs, a significantly high convergence of LPF was obtained in each case (Fig. 8e).

As concerns the analysis of simulation results [22, 25], the correct positioning of the light source in the optical system is of utmost importance. The most common differences result from the inaccuracy in rendering the luminous centre of the virtual light source model in relation to the reality. It should be added that these inaccuracies are the differences of merely decimals of a millimetre (usually not exceeding 0.5 mm) and mainly apply to the power LEDs of the light source surface not exceeding 0.1 mm^2, operating in the optical system whose dimension is close to 10 mm. However, this aspect goes beyond the substantive scope of this publication. For this reason, the impact of adjusting the light source in relation to the precision of results obtained from the simulation calculations in relation to the parameter values recorded with the laboratory methods will be ignored.

It must be added that the example of the reflector mirror optical system was chosen to facilitate the visualization of computational methods. The other publications from the Lighting Technology Division at the Warsaw University of Technology prove that the presented methods produce equally good results as far as the lens system analysis is concerned [28].

7. Summary and conclusions

The article presents the development of light sources and luminaires accompanying them in terms of their photometric features. Knowledge and understanding of these features in lighting technology forms the basis of processes related to designing, mathematical modelling and simulation calculations of luminaire parameters. Features such as the dimensions of the light source, luminance and its distribution are the starting point in the design and analysis processes, and determine the design methods and the methods for shaping the luminaire's luminance distributions that result from them and, consequently, the LIDs. The comparison of modern design methods based on mathematical methods and the use of specific curves, most often conic curves, has been enhanced with advanced modelling based on freeforming. As concerns this design method, the only limitations are the assumed production technology of the optical system and the designer's imagination and experience. However, the use of advanced design methods and analysis of luminaires would not be possible without using modern measuring instruments representing the basis for developing the luminance light source models. Therefore, it is necessary to approximate the methods of luminance modelling of the light sources for the needs of simulation calculations, which include point models, geometric models assuming constant luminance on the light source surface and the most advanced models taking into account the real luminance distributions by mapping or rayfile models. The paper also presents the calculation results obtained using the successively mentioned light source models, together with their characteristic feature description. Fig. 10 clearly shows that simplifying the lamp's luminance distribution and approximating it with the dimension luminance resulting from the dimensions of the luminous surface of the light source and the accompanying luminous flux do not lead to obtaining the simulation results at a level even close to the results of laboratory measurements for an analogous luminaire system. However, utilising the advanced luminance model, regardless of the one based on the mapped geometric model or TM-25 rayfile model [26], produces the simulation calculation results at a level identical to the laboratory measurement results. This fact gives a tremendous opportunity to reduce the number of prototypes, significantly decreasing the costs and increasing the speed of designing and introducing such a luminaire model optimized for the specific applications into production. Thanks to this, the designs based on the methods presented in Sections 3–6 have a high degree of optimization to use the special features of light sources. The subsequent design iterations do not require preparing any prototypes, but only must occur in the computer memory using the precise computer simulation results. The analyses presented in the paper refer to the real cases representing the authors' achievements based on long years of experience in designing, creating the original simulation software, light source models and participating in numerous implementation processes. All design and simulation solutions presented in the article are the exclusive achievements of the authors of this publication.

For the purposes of software simulations, the authors' original software developed at the Lighting Technology Division at the Warsaw University of Technology and the commercial software "Photopia" from LTI Optics were used.

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