Calculation Of Diffuse Luminaires Using Radiance System And Backward Ray Tracing Method

Krzysztof Wandachowicz

Poznan University of Technology, Institute of Industrial Electrical Engineering
PL-60-965 Poznań, Poland, ul. Piotrowo 3A,
e-mail: Krzysztof.Wandachowicz@put.poznan.pl

1. Introduction

Commonly used analytical method of calculating luminaires [1, 2] makes numerous simplifying assumption which are necessary to render the calculations possible. The most important of these are:

- possibility to do computations solely for reflectors and globes which reflect and transmit perfectly diffuse light,
- equations on the basis of which the computations are done have been derived for very simple geometrical systems (sphere or its part for rotationally symmetrical globes and reflectors and infinitely long cylindrical surface for reflectors with line light sources) and each departure from such shapes produces errors difficult to evaluate,
- the part of the luminaire forming a holder completely absorbs the luminous flux incident on it which, combined with limited possibility to allow for proper dimensions and shape of the holder, may produce incorrect results,
- lamps, sockets and other elements inside a luminaire are not taken into considerations as the participants of the luminous flux concealing and interreflections of the flux between the optical parts of the luminaire, which results in erroneous assumption of the illuminance distribution along the reflector or globe surface.
- the globe or the reflector surface must be uniform in terms of the reflection properties,
- it is usually assumed that the light source in the luminaire is characterized by uniform distribution of luminous intensity and even if the real distribution of the applied lamp may be taken into consideration, such distribution must rotationally symmetrical.

Furthermore, in addition to the simplifying assumptions specified above, also very troublesome are computations for globes complicated in shape due to the difficulties in precise calculation of real globe surface area (when calculating the globe's luminance) and the projected (cosine-weighted) surfaces of globes observed at various angles (when calculating the distribution of luminous intensity)

Significant development of the computing powers of computers witnessed for the least few years resulted in creating new and developing the existing computing methods which make it possible to do computations without some of the above mentioned simplifying assumptions. The most important methods are the following:

- luminous flux method,
- ray tracing method,
- backward ray tracing method.

Moreover, in recent years there has been a rapid development of new calculation techniques, which are used to create computer graphic representations and visualization of interiors [3, 4, 5]. Using the achievements of such techniques a new calculation method has been developed on the basis of the backward ray tracing method, which makes it possible to determine luminance distribution in interiors [6]. Interesting results achieved in this study encourage to expand the developed method onto the systems involving optical elements (globes, reflectors), light sources and other active participants in shaping the luminous intensity distribution.

2. Backward ray tracing method

The backward ray tracing method assumes that the radiation is propagated along line paths called rays, and traced rays are subject to multiple reflections with the set system geometry and set properties of the system surface [4]. The process connected with the propagation of radiation is described by geometrical optics laws.

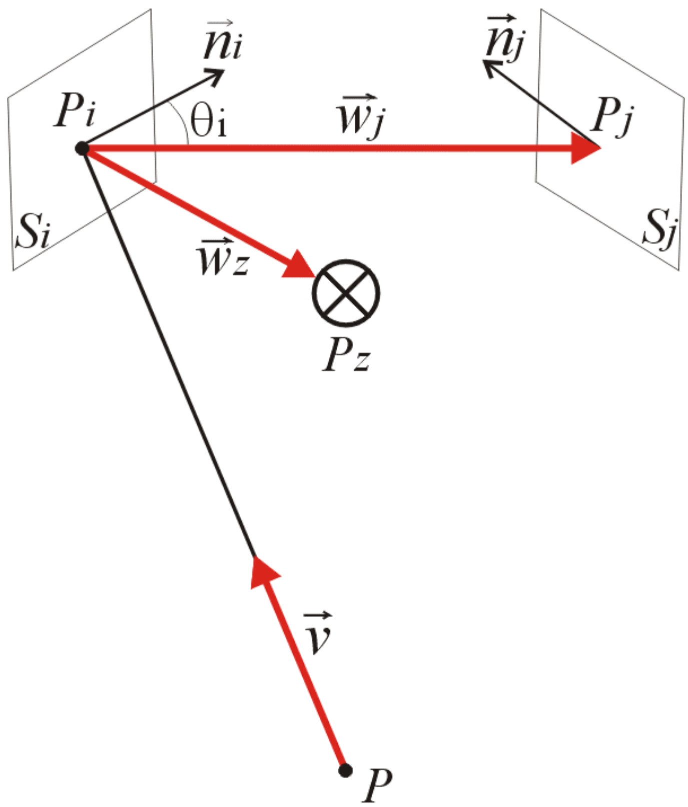

Fig. 1 Geometrical interpretation of the assumed model.
The observer is located in point P, while the light source in point Pz. Surfaces occurring in a given system are marked as S_i, S_j.

I the backward ray tracing method the rays start to be traced from the point of view of the observer placed in a given environment, taking into account any possible reflections or refractions of radiation resulting from rays intersecting with the surfaces occurring in a given system (Fig. 1). In the reflection point new secondary rays are formed. Each newly formed ray is traced in the same manner until it becomes sufficiently suppressed or until it fails to meet any objects on its track. In each hit point the direct component resulting from the illumination of a given point by a light source is calculated. For further reflections in further nodes the value resulting from determining the direct component of a given node and from the summed values determined in other nodes is calculated. This process ends after summing up the values from all nodes, whereby we obtain the luminance value for the surface around the point hit by the primary ray.

The basis of the method is the assumed geometrical system model (Fig. 1) and the equation (1), which enable determination in the direction "v" of the luminance $L_r(P_i,-\vec{v})$ of the surface element S_i [6].

$$
\begin{aligned}
L_r(P_i,-\vec{v}) = & \sum_z q(P_i,-\vec{v},\vec{w}_z)\cdot g(P_i,P_z)\cdot L(P_z,-\vec{w}_z)\cdot\left|\cos\theta_z\right|\cdot\omega_z \\
& +\frac{\pi}{N}\cdot\sum_{j=0}^{N-1} q(P_i,-\vec{v},\vec{w}_j)\cdot g(P_i,P_j)\cdot L(P_j,-\vec{w}_j)
\end{aligned}
\qquad (1)
$$

where:
q – luminance coefficient,
g – factor dependent on the system geometry, assumes the value of 0 when points P_i and P_j are mutually invisible or the value of 1 when on the line connecting these two points there is no obstacle.

In the equation (1) two parts may be distinguished: the part responsible for determining the direct component and the part responsible for determining the indirect component. Both components may be determined having regard to real reflection characteristics of the materials described using the luminance coefficient.

3. Description of the optical system elements of luminaires

Necessary for the purpose of computations is proper description of the shapes of the optical system elements of luminaires. In particular, it is necessary to describe the shapes of the following elements:

- reflector,
- globe,
- light source solid (filament, arc tube, bulb),
- bases, sockets, holders and other elements placed in the luminaire.

Description of a luminaire is produced using CAD type software. From among the available three-dimensional models only the surface models and solid models are applied. By means of surface models (flat surface - polygon) it is possible to create elements complicated in terms of shape the surfaces of which (often times curved) are subjected to the process of division into a number of small flat elementary surfaces (Fig. 2). Real surfaces of paraboloid reflectors or globes with complicated shapes are then replaced with a surface consisting of a set of discrete flat surfaces [7].

The solid models whose surface curvature is described by means of mathematical equations may be used for describing the shapes of optical elements of luminaires but only to a limited extent. The proposed method assumes the possibility to use the following solid models: sphere, cylinder and cone [5]. Furthermore, from among flat figures circles and rings may be used. Using all the above models it is possible to create not only the surfaces of reflectors and globes, but also arc tubes and bulbs solids as well as other elements actively participating in creating the luminous intensity distribution.

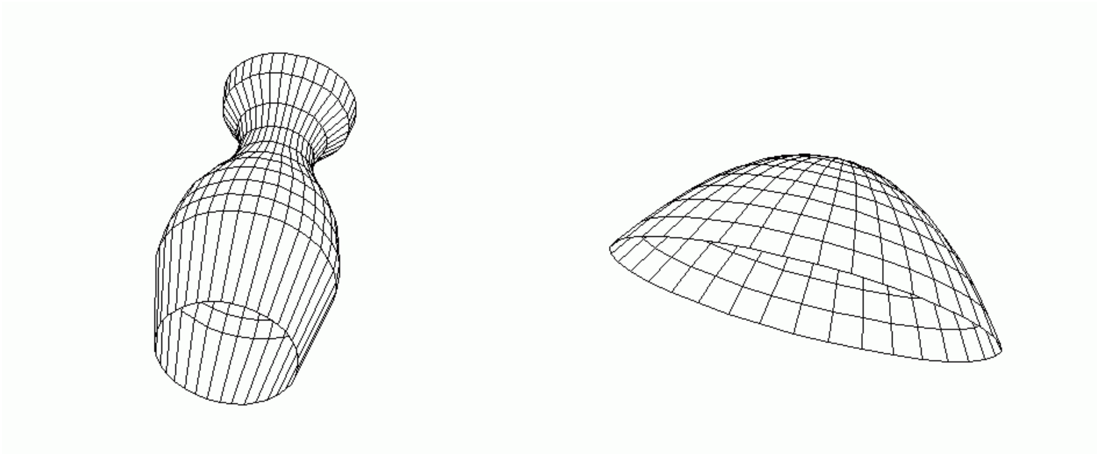

Fig. 2 Illustration of reflector and globe with surfaces divided into discrete elements.

4. Computations using the backward ray tracing method

Using the backward ray tracing method it is possible to do computations where the searched value is the luminance distribution on the globe or reflector surface or the luminous intensity distribution. The first of the above named values (luminance distribution) may be calculated by direct adaptation of the method developed for computing luminance distribution in interiors [6]. In this particular case, adaptation will consist only in adjusting the computation process control parameters to the requirements of the optical systems of luminaires, determination of correct amount of traced rays and proper description of the reflection characteristics of materials and lamps used in computations [7].

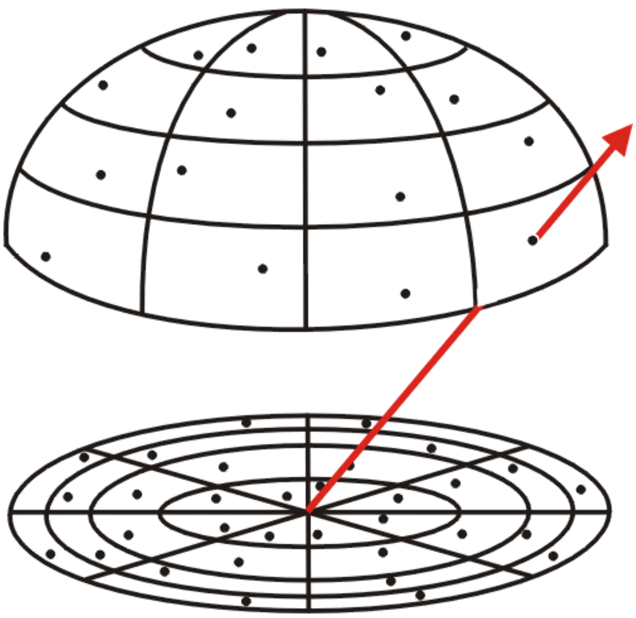

Fig. 3 Hemisphere divided into domains. Dots represent points of intersection of traced rays with the surfaces of the hemisphere domains (one of the traced rays is shown).

Calculation of the luminous intensity distribution requires (in addition to what has been mentioned above) more complicated modifications. The backward ray tracing method applied here is a combination of the deterministic method (predetermined and identical directions of traced rays for repeated calculations) and scholastic technique where the rays are traced on a random basis in selected directions [5]. At the intersection of the traced ray and the surface (e.g. surface S_i, Fig. 1) secondary rays are being generated and emitted to the hemisphere viewed from a given point. The hemisphere is divided into domains in such a way, that the projections of these domains on the horizontal plane have identical surface area [5]. One ray passes through each domain (Fig. 3). Within the boundaries of each domain the ray directions are selected on a random basis. Thanks to such manner of selecting the traced rays directions and of dividing the hemisphere, the directions of such rays are uniform distributed despite the Monte Carlo method.

Luminous intensity of the luminaire $I_{\gamma,C}$ in a specified direction γ,C is calculated from the inverse-square law (2):

$$I_{\gamma,C} = E_i \cdot r^2 \qquad (2)$$

where:
E_i - illuminance in point "i" (Fig. 4a) on the plane perpendicular to the line crossing the light center of the luminaire and point "i",
r - distance between the light center of the luminaire and point "i" (Fig. 4a).

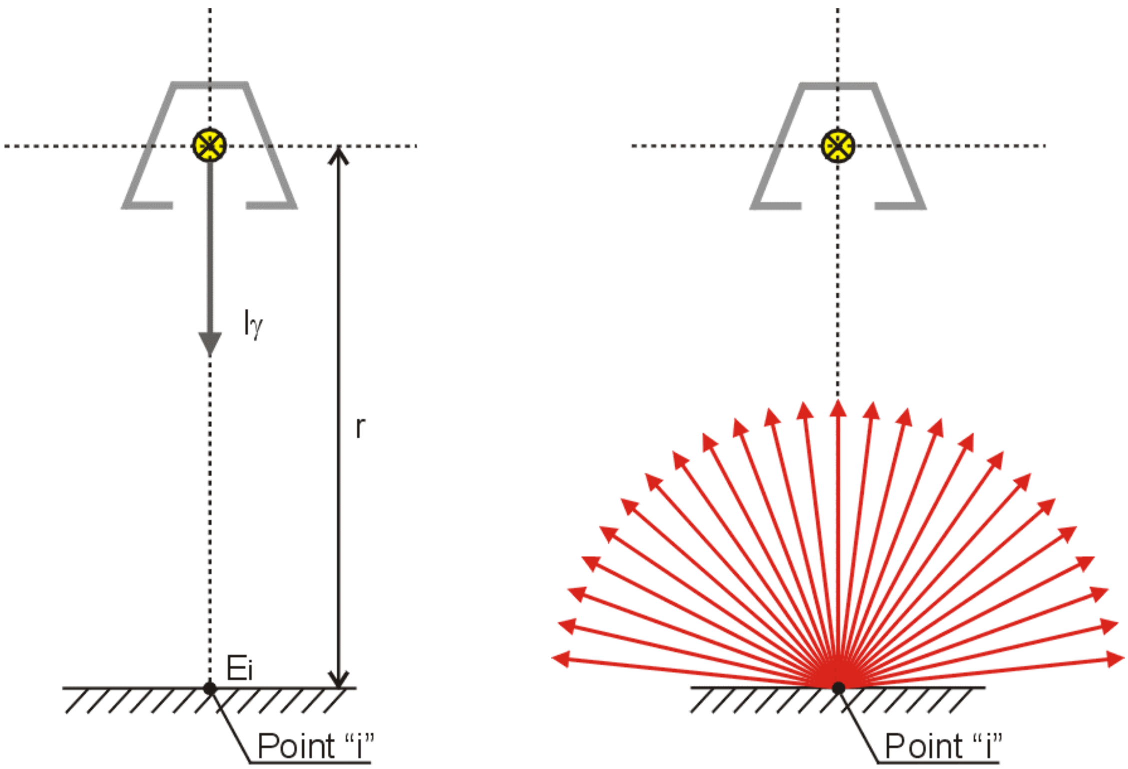

Fig. 4 a) Calculating the luminous intensity I_γ in point „i". b). Calculating the illuminance in point "i". From among twenty five emitted rays, only three will hit the luminaire.

The illuminance E_i in point "i" is calculated using the backward ray tracing method and the illuminance equivalent definition [8] (3) where the integral is replaced with luminance summation L_{Sj} on all surfaces S_j. Luminance L_{Sj} is connected with the elementary beam of radiation propagating in the solid angle $d\omega$ and incident on surface S_i into direction w_j (Fig. 1).

$$E_i = \int_{\omega} L_{Sj} \cdot \cos\theta \cdot d\omega = \sum_{Sj_1}^{Sj_k} L_{Sj} \cdot \cos\theta \cdot d\omega \qquad (3)$$

The secondary rays emitted to the hemisphere (as described in Fig. 3) hit surfaces S_j and return the luminance value of these surfaces. The sum of luminance product L_{Sj} and angle of incidence cosine θ give the illuminance value at point „i".

Application of the above method to calculate the illuminance at point "i" from the luminaires will result in a limited number of rays hitting the luminaire and returning the luminance value of the globe or reflector in the hit point. This happens because the luminaire has proportionally small sizes in relation to the distance at which the measurement point are located (e.g. point "i"). Such proportions result from the necessity to ensure that the distance to a light source is greater than five times the largest dimension of the source (Fig. 4b). Hitting the luminaire with a small amount of rays produces incorrect illuminance values. Therefore it is necessary to do additional preliminary calculations to obtain a precise result. The so-called substitute surface is introduced [5] which, in case of the globe, has the shape of a sphere surrounding the entire luminaire while in case of the reflector it has the shape of a circle or rectangle enclosing the luminaire in the reflector opening (Fig. 5).

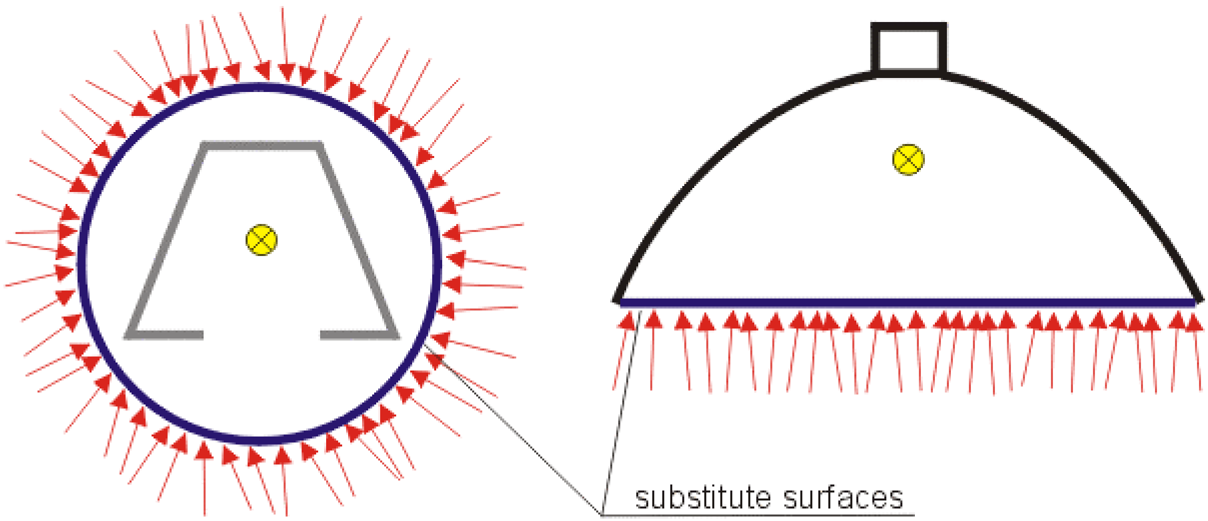

Fig. 5 The substitute surface (blue line) for the globe (sphere) and paraboloid reflector (circle).

Preliminary calculations consist in emitting a large number of rays towards the substitute surface. These rays are emitted from the entire hemisphere and intersect the substitute surface at various angles (θ_i within the range from -90^0 to $+90^0$ as shown on Fig. 1, Fig. 3 and Fig. 5). After passing through the substitute surface, the rays hit the luminaire elements and the secondary rays tracing process takes place. As a result of this process the luminance distribution $L_{\gamma,C}$ towards directions γ,C is calculated for the substitute surface surrounding the luminaire. The substitute surface becomes the so-called secondary light source and participates in the process of calculating the direct component.

After the preliminary calculations are over, the next process is activated where from point “i” towards the luminaire a beam of rays is emitted (as shown in Fig. 3 and Fig. 4b). Some rays will hit the substitute surface and will return the value of previously calculated luminance $L_{\gamma,C}$. Luminances $L_{\gamma,C}$ connected with rays emitted towards directions γ,C are, from the point of view of real course of rays (from the light source to the observer), luminances of elementary beams of rays incident from various direction to point „i” and propagating at solid angles $d\omega$ which, after being summed up, give the value of the illuminance E_i at point „i” (3).

5. Calculations of luminaires with a diffusing globe

The first verification of correctness of the applied method has been carried out for an ideal spherical globe and open globe with a holder (Fig. 6). The globe diameter was 30 cm, and the assumed globe transmittance coefficient was 0.6, reflectance coefficient was 0.3 and the luminous flux of light source Φ_o equaled 1350lm.

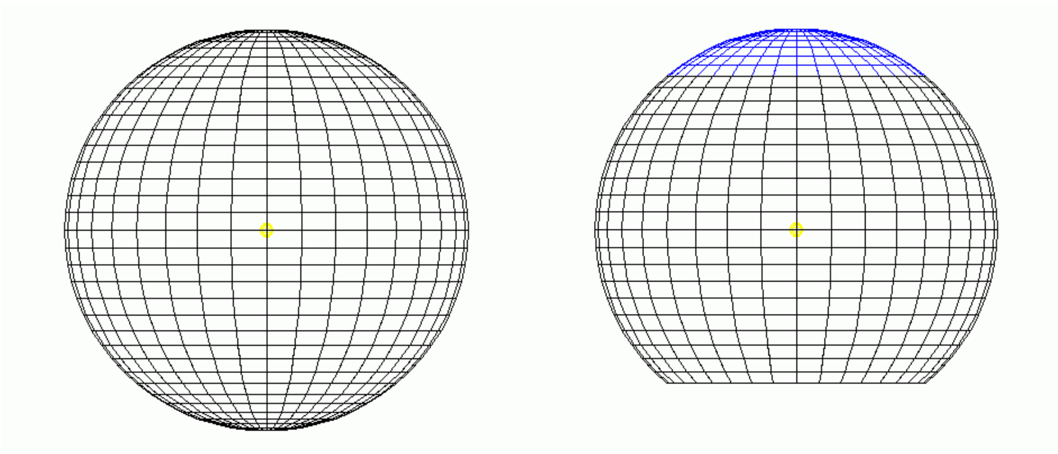

Fig. 6 Ideal spherical globe with the diameter of 30 cm and open globe with a holder. The objects marked blue colour are holders, the light source as a sphere is marked yellow.

The luminance of the globe surface, luminous intensity distribution, has been calculated and on this basis the luminous flux of luminaire has been obtained. The obtained results (Table 1) have been compared with the calculations done using the analytical method. When analyzing the results it may be concluded that the results obtained by the calculations done using the ray tracing method and calculations done using the analytical method, which is a reference in cases contemplated hereby are almost the same. Therefore, one may presume that a similar degree of preciseness will be possible in case of systems involving more complicated shapes where the simplifying assumptions specified in the introduction have not been applied.

Table. 1 Luminance of the globe surface "L" and the luminous flux of luminaire „Φ" calculated using the analytical method and the ray tracing method.

		Analytical method	Ray tracing method
Luminance of the globe **L**	Ideal spherical globe	**1 303** [cd/m^2]	**1 306** [cd/m^2]
	Open globe with a holder	**1 184** [cd/m^2]	**1 187** [cd/m^2]
Luminous flux of luminaire **Φ**	Ideal spherical globe	**1 157** [lm]	**1 166** [lm]
	Open globe with a holder	**1 011** [lm]	**997** [lm]

Another example for which the calculations were done is the diffusing open globe (Fig. 7). Models similar in shape and reflection properties to socket and fixings have been placed in the luminaire. The light source is the incandescent general-purpose lamp with a clear bulb and the power of 100W, which is shown as a sphere with the diameter of 2 cm and which is assigned a real luminous intensity distribution. The luminance distribution on the luminaire globe surface (Fig. 9) and luminous intensity distribution (Fig. 8) have been calculated.

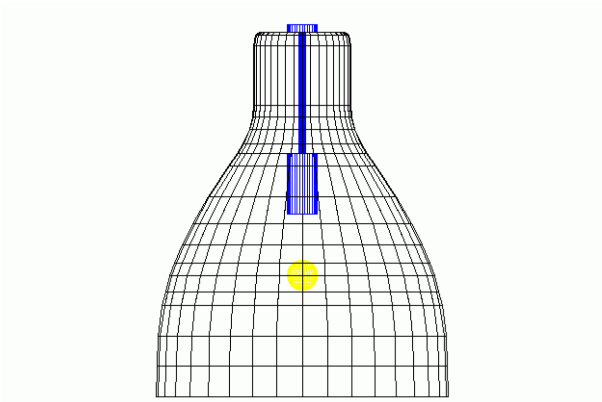

Fig. 7 The luminaire with diffusing open globe (transmittance coefficient τ=0.6, reflectance coefficient ρ=0.3). The objects marked blue colour are holders, the light source as a sphere is marked yellow.

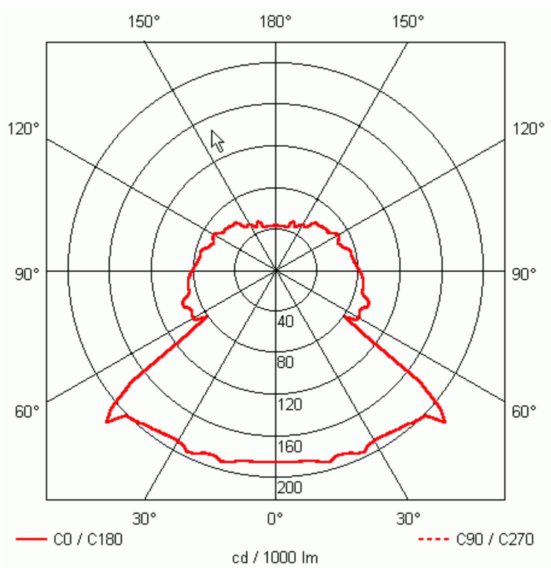

Fig. 8 The luminous intensity distribution of luminaire (Fig. 7) with diffusing globe.

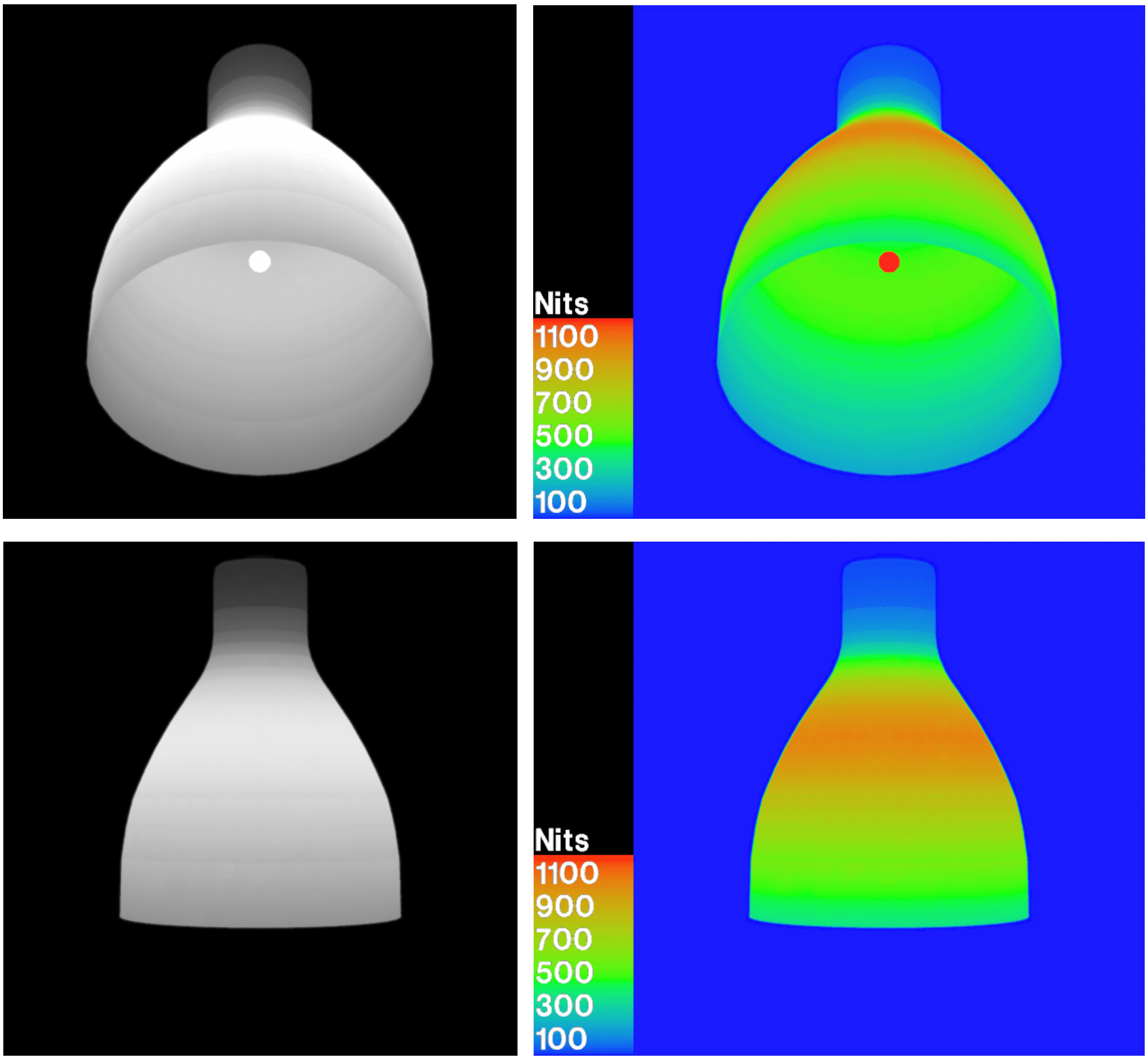

Fig. 9 Visualization of the luminance distribution on the surface of diffusing luminaire, there are presented two views on the pictures. “False color” option of Radiance system can show luminance distribution (1 Nit = 1 cd/m^2).

6. Summary

The proposed method which uses the backward ray tracing technique makes it possible to calculate luminaires of complicated geometry having regard to real luminous intensity distribution of applied lamps. The first, reference check calculations have been carried out for diffusing globes and reflectors. The proposed method assumes describing reflection characteristics of materials by means of luminance coefficient q (1). In connection with the above and basing on the study results [6] it may be assumed that calculations for globes and reflectors with specular reflection and mixed reflection will be possible. The above issues will be further studied.

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