Determination of surface forms and optical efficiencies of ellipsoidal reflectors using power LED lighting sources

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New methods are used every day in lighting with rapidly developing technology. The most popular of these is LED lighting. LEDs are more efficient than traditional lighting sources in terms of energy saving, light quality, and lifetime. Optical design is one of the most important and critical processes in luminaire designs using LED lighting sources. Therefore, efficient luminaire designs are required in order to direct light and use it more efficiently. Reflectors are used to diffuse light in the right amount, to the right direction. Obtaining light intensity, luminaire efficiency, and luminance distribution in designing process is important for successful reflector designs. The present study investigated luminance distribution, optical efficiencies of ellipsoidal reflectors using LED lighting sources and conducted optimization of these. In this framework, different reflector surface coating materials were used in ellipsoidal reflectors and luminance distribution profiles were obtained. Additionally, optical efficiency was defined for luminaires formed with these reflectors. The data based on the reflector manufacturing were obtained in accordance with the ellipsoidal reflector analyses. With this method, technical data packages for the prototype production of reflectors using LED lighting sources are created.

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Keywords: LED lighting source, Reflector design, Ellipsoidal reflector surfaces, Optical efficiency, Illumination distribution

1. Introduction

Ray formers were first used in lighting in Argand lamps in 1780. These formers were the first designs of reflectors. These reflectors used in Argand lamps had paraboloid surfaces. With the use of electrical incandescent lamps as light sources, reflector designs with this purpose started as on 1879 [1].

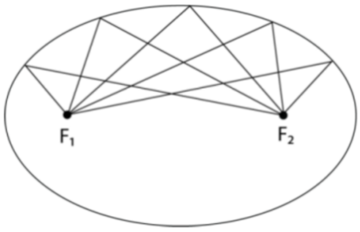
Following the invention of first electrical lamp, many different light sources have been developed. The most popular of these light sources at present is the LED [2]. With the rapid development of LED technology in recent years, LEDs are widely used in our daily lives. Due to low energy consumption, long lifetime, small size, flexibility in design, and high colour rendering, power LEDs are superior to traditional light sources and so they are preferred over them. Because of their total cost and environmental friendly features, many consumers now prefer LEDs instead of traditional fluorescent lights [3]. In order to enhance the performance of lighting systems using LED light sources, secondary optical designs are required in LED lightings. Secondary optical designs are required to reorganize direct output of LED in order to obtain desired lighting [4]. With appropriate reflector designs, needed light is directed and energy can be saved. Moreover, incorrect designed reflectors can produce glaring and disturbing lights, and light pollution.

Therefore, reflector design is important for eliminating these disadvantages [5]. Reflectors are widely used in luminaires, flashlights, exterior lighting, and car headlights for the specified light intensity and luminance distribution. Ellipsoidal reflectors are useful in projectors or when the light is needed to be directed on a specific field in narrow angles [6].

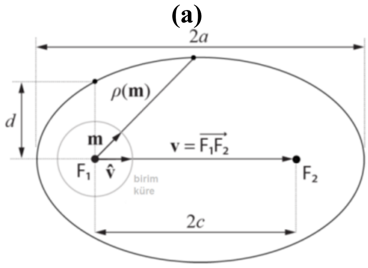
Specific to lamp, well-designed reflectors are useful to lighting, human health and environment. For this reason, the present research designed different ellipsoidal reflectors for lambert and angle LED sources. For the surfaces of ellipsoidal reflectors designed in the present research, different materials with different specular reflectivity, and semi-specular reflectivity were used, and these were compared. Light intensity distribution, luminance distribution and luminaire efficiency of the reflector designs were obtained with the computer design software. The computer design software used in the present research is Photopia, 2015 version. Additionally, specular luminance distributions of the ellipsoidal reflector designs were also studied using this software. The present research contributes to lighting by presenting the effects of different ellipsoidal reflectors with different sizes and surfaces on luminance distributions.

2. Designing methods

2.1 Ellipsoidal reflectors in reflection processing



(a)



(b)

Fig. 1 (a) When a light source is placed on a focal point (F_1), all lights travel on the other focal point (F_2) (b) Parameters of ellipsoidal on polar coordinates.

The classical equation for ellipsoidal on polar coordinates is given as follows;

$$\rho = \frac{a(1-e^2)}{1-e\mathbf{m}.\hat{v}} \quad , \quad e = \frac{c}{a} \tag{1}$$

where a is for x axis, e is for eccentricity ($0 < e < 1$), $\hat{v}$ (unit vector) is the direction of major axis of ellipsoidal, and **m** (unit vector) is the direction of polar radius of ambient. $\mathbf{m}.\hat{v}$ equals to the cosine of polar angle (θ). e is defined as the eccentricity [7].

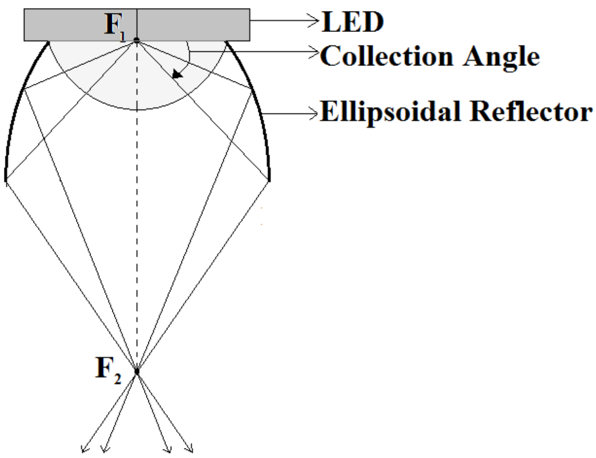


Fig.2. Ellipsoidal reflector obtained with LED source.

Fig. 2 presents the working principle of ellipsoidal reflectors obtained with LED light source schematically. F_1-F_2 in the figure refers to the distance between two focal points forming the ellipsoidal. Rays coming from the LED light source placed on the F_1 focal point of ellipsoidal to the reflector reflect on the ellipsoidal reflector and travel through F_2 focal point. Then, every ray collected on F_2 focal point is distributed back to the plane to be enlightened in the direction they come. Another parameter affecting luminance distribution in ellipsoidal reflector lighting is the collection angle. The angle scanned by the collection angle is presented in Fig. 2. Accordingly, the form of the reflector changes depending on the increasing and decreasing collection angle.

2.2 Designing theory and applications

Three-dimensional (3D) lighting problem can be solved with well-set design techniques by degrading to two-dimensions (2D) in cases of rotational or reciprocal symmetry. Reciprocal symmetrical reflectors are suitable for linear sources such as florescent tubes. Since LED light source is used in the present research, rotational symmetrical reflectors were designed in accordance with ellipsoidal parameters. In order to create a design based lighting, a 2-dimensional curve should be obtained first. Then, this 2-dimensional curve is rotated on the symmetrical axis, and a 3-dimensional volume is obtained. Geometrically, 2-dimensional curve is obtained by mapping rays from the target source and providing correct flux transfer. The form of the reflector is designed with a first order differential equation that can be solved with numerical integral techniques [8].

Pre-specified far-field lighting distribution is presented in Fig.3. As in the figure, point source is in the centre (O). A ray coming with α angle according to the optical axis is reflected in β direction by a reflector r distant away from the centre.

The relationship between source angles α and target directions β can be obtained by using the cumulative flux emitted by the source up to the angle α and setting it equal to angle β. It can be written that the accumulated flux distributed from the source up to α angle equals to the total flux accumulated to β angle [9].

$$\Phi_S(\alpha) = \Phi_T(\beta) \tag{2}$$

Accumulated flux distribution of the source to the angle α is computed by the equation as follows;

$$\Phi_S(\alpha) = \int_{\alpha_{min}}^{\alpha} I_S(\theta)d\Omega = 2\pi\int_{\alpha_{min}}^{\alpha} I_S(\theta)sin\theta d\theta \tag{3}$$

Total flux accumulated at the centre is calculated as follows in far-field case;

$$\Phi_T(\beta) = \int_{\beta_{min}}^{\beta} I_T(\theta')d\Omega' = 2\pi\int_{\beta_{min}}^{\beta} I_T(\theta')sin\theta' d\theta' \tag{4}$$

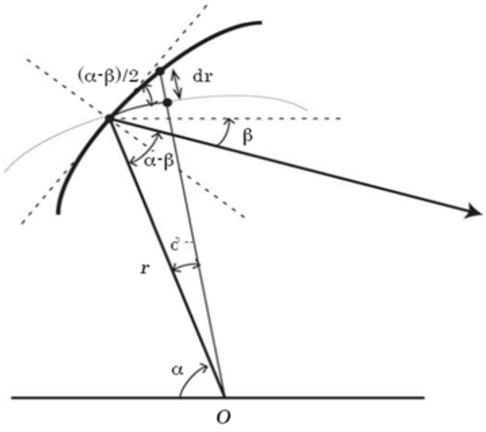


Fig.3. 2-Dimensional reflector profile structure for a far-field problem using detailed numerical integration method by Elmer [10].

An expression for dr can be derived. The displacement r depending on angles α and β is used for this derivation. After integrating the expression dr, the following relationship is obtained;

$$r(\alpha) = r_0 \exp\left(\int_{\alpha_0}^{\alpha} \tan\left(\frac{\alpha-\beta}{2}\right) d\alpha\right) \quad (5)$$

In this equation, α_0 is the polar angle of lower edge of the reflector. The value r_0 adjusts the size of the reflector by determining the distantce from the source to the edge of reflector in the minimum angle (α_0).

A similar method is used for near field. In this case, β is the function of the radius r of the reflector, and target coordinates are (y, z). For this reason, β is defined in a non-linear equation as follows.

$$\beta = \tan^{-1}\left(\frac{r\sin\alpha - y}{z + r\cos\alpha}\right). \quad (6)$$

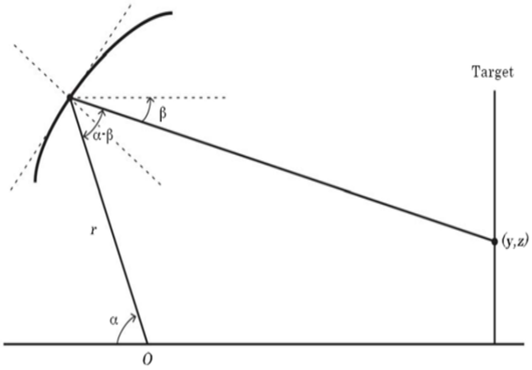


Fig.4. 2-D reflector profile structure for a near-field problem using detailed numerical integration method by Elmer [9].

Geometrical near-field approximation is denoted in Fig.4. In near-field case, location target angle between the source and target establishes a relationship between α and target points (y; z). Comparison between accumulated source and target flux distributions is given as follows;

$$\Phi_T(y) = \Phi_S(\alpha). \quad (7)$$

In near-field, distribution of flux accumulated in the target is given by;

$$\Phi_T(y) = \int_{y_{min}}^{y} E_T(y')dA = 2\pi \int_{y_{min}}^{y} E_T(y')dy' \quad (8)$$

where the function (y=f(α)) is the location between the source and the target. When average reflectivity of reflector surface is γ, the location of the flux between the source and the target is given by [5];

$$\Phi_T(y) = \gamma\Phi_S(\alpha) \quad (9)$$

$$\Phi_T(y) = \int_{y_{min}}^{y} E_T(y')y'dy',$$

$$\Phi_S(\alpha) = \int_{\alpha_{min}}^{\alpha} I_S(\alpha')\sin\alpha' d\alpha' \quad (10)$$

$I_S(\alpha)$ is the intensity of source and, $E_T(y)$ is the specified target luminance. This flux conservation may take different forms depending on the geometry of the problem. For a far field target and revolved symmetrical system, target flux in a circular shaped differential solid angle should be calculated, as in equations (9) and (10);

$$\Phi_T(\beta') = \gamma\Phi_S(\alpha'), \quad (11)$$

$$\Phi_T(\beta') = \int_{\beta_{min}}^{\beta} I_T(\beta')\sin\beta' d\beta',$$

$$\Phi_S(\alpha') = \int_{\alpha_{min}}^{\alpha} I_S(\alpha')\sin\alpha' d\alpha'. \quad (12)$$

In this equation, β is the angle of the ray after reflection, and $I_T(\beta)$ is the specified target intensity.

The efficiency of the optical part equals to the proportion of the light flux of luminaire ($\Phi_{luminaire}$) to the light flux total of all light sources in the luminaire. This proportion is defined with the following equation [11];

$$\text{LOR} = \frac{\Phi_{luminaire}}{\sum_{i=1}^{n}\Phi_{source}} 100[\%], \quad (13)$$

where n is the number of the lamps used, Φ_{source} is the light flux distributed from a source. The uniformity of lighting U_E is stated by [12];

$$U_E = E_{min}/E_{average}, \quad (14)$$

where E_{min} and $E_{average}$ refer to the minimum and average lighting in the target field respectively.

At the present study, a 2mmx2mm lambert power LED source produced by CREE company, and a power LED source of 115 degrees angle were used. These sources were selected in accordance with their efficiency factor values (lm/W) and distribution features of LEDs. On this way, contribution of LED sources to energy saving with reflectors was studied. The features of the LEDs used in the present research are given in Table 1.

Table 1. Features of power LEDs used in calculations

Lamp Type	Manufacturer	Colour	Driver Current (mA)	Luminous Flux (lm)	Power (W)	Efficacy Factor (lm/W)
LED XM-L Xlamp 2mm x 2mm lambertian	CREE	Cool White	700	280	2.03	137.9
LED XP-E Xlamp 115 deg	CREE	White	350	100	1.19	84.0

Ellipsoidal reflectors were designed for both LED sources used in the present study. Distances between two focal points of each ellipsoidal reflectors designed were changed parametrically as 20mm, 40mm, 60mm, 80mm and 100mm. According to the changed distances between two focal points, collection angles were adjusted as 30^o 35^o 40^o 45^o and 50^o , and optical efficiency of luminaire and E_{min}, E_{max}, $E_{average}$ values were obtained, and their contributions to the uniformity of lighting were investigated. Different reflectance specular reflector and different reflectance semi-specular reflector materials were used in reflector profiles computed. Reflectance features of the used materials are presented in Table 2.

Table 2. Reflectance features of specular and semi-specular reflectance materials used in calculations.

Manufacturer	Designation	Description	Reflectance (%)
Alanod	322 G/3	specular aluminum	85
ACA Corp.	912MB	semi-spec. alum.	85
Alanod	319 G/2	specular aluminum	88
Satma	2003	semi-spec. alum.	88
Generic	SPEC 96	specular surface	96
ACA Corp.	417ME	semi-spec. alum.	96

As can be seen in Figure 5, as collection angle increases, optical efficiency of luminaire and uniformity values of lighting decrease. As collection angle increases **30^o-50^o** uniformity values of lighting decrease in the interval of **%70-%32**. This can be observed clearly in luminance distribution according to each collection angle.

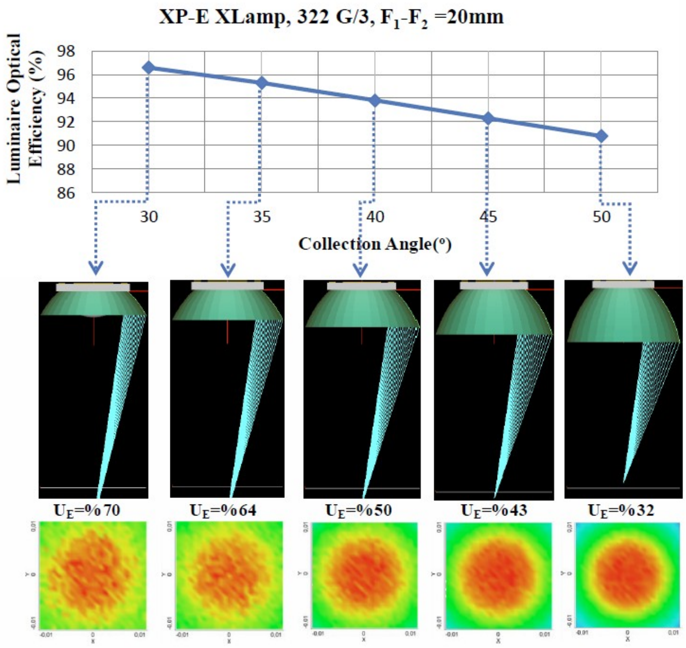


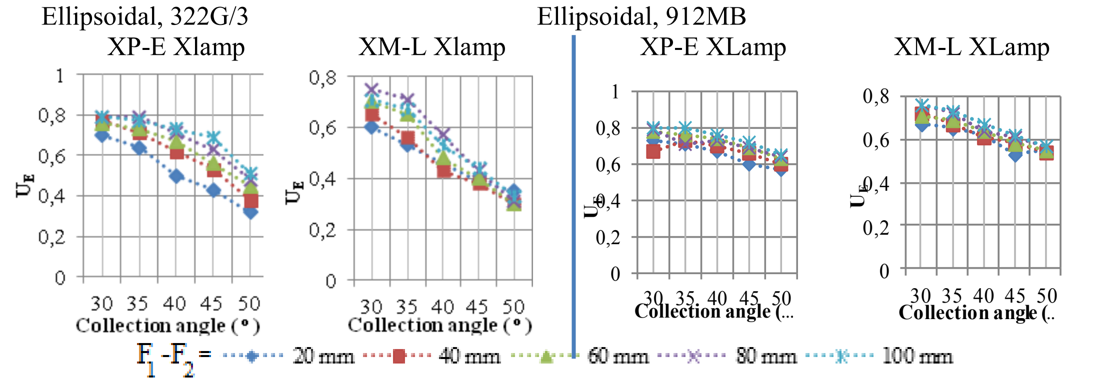
Fig. 5 Examples for the effect of ellipsoidal reflector designed with 20 mm distance between two focal points, and XP-E Xlamp LED lamp, when coated with 85 % reflectance specular reflector material on luminaire optical efficiency according to collection angles. With these values, uniformity values of lighting were given and denoted with arrows.

According to different distances between two focal points and collection angles in ellipsoidal reflectors, a 2mmx2mm lambert power LED source and a 115 degrees angle power LED source were used. For each 6 different materials, ellipsoidal reflectors with 5 different collection angles were analysed. Table 4 presents the analysis results for the ellipsoidal reflector when XM-L Xlamp 2mm x 2mm lambertian power LED was used with 100mm distance between two focal points. The distance between the edge of ellipsoidal reflector and the lightened surface was fixed at 15mm, and analysis results were obtained according to the sizes of LEDs. Since ring gap of ellipsoidal reflectors changed depending on the collection angles, the area of the lighting surface was changed according to each collection angle. On this way, optimized results were obtained in accordance with all rules of the reflector lighting, and the values obtained from the analyses we performed. The computer software was operated on 2.500.000 ray tracing sensitivity, and luminance distribution values were obtained accordingly.

Analysis results for ellipsoidal reflectors are presented in Fig. 6, 7, and 8. The effects of two different LED sources were compared and shown with the reflectance values of reflector materials. Additionally, distances between F_1-F_2 in designed reflectors were changed in mentioned values, and the effects were compared with the uniformity of lighting, collection angle, and the reflectance values of materials used in reflectors. According to the findings, luminaire efficiency of semi-specular reflectors is lower than the specular reflectors, while the distribution of uniformity is higher than the latter. On that way, optimization studies for expedient luminaire designs for the reflector lighting were conducted.

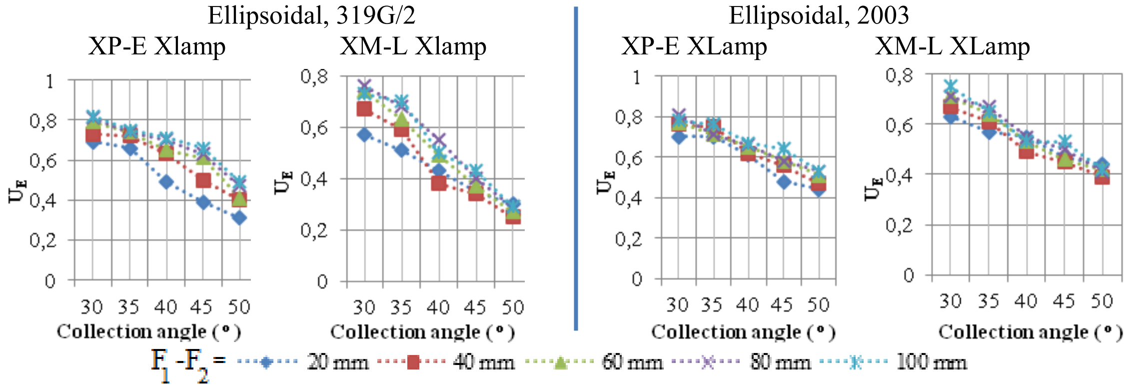
Table 3. The data of uniformity of lighting and optical efficiency values of XM-L Xlamp 2mm x 2mm lambertian power LED in ellipsoidal reflectors for the shape parameters and material types.

Lamp Type	**F_1-F_2 (mm)**	**Collection Angle (^{o})**	**Material Type**	**E_{max} (lm/m^2)**	**E_{min} (lm/m^2)**	**$E_{average}$ (lm/m^2)**	**$E_{min}/E_{average}$**	**$E_{min}/E_{average}$**	**Optical Efficiency of Luminaire (%)**
XM-L Xlamp 2mm x 2mm lambertian cool white (700mA)	100	30	322 G/3	783,118	462,083	650,200	0.71	0.59	95.8
			912MB	652,924	393,720	519,311	0.76	0.60	95.1
			319 G/2	796,055	498,072	678,393	0.73	0.62	97.2
			2003	750,431	474,102	633,301	0.75	0.63	96.2
			SPEC 96	852,200	535,253	715,310	0.75	0.63	99.3
			417ME	771,521	444,979	616,382	0.72	0.58	98.4
		35	322 G/3	907,884	497,830	744,507	0.67	0.55	94.4
			912MB	698,680	414,466	564,213	0.73	0.59	93.4
			319 G/2	951,815	550,244	782,520	0.70	0.58	96.2
			2003	877,228	465,121	714,309	0.65	0.53	94.9
			SPEC 96	998,870	600,766	831,644	0.72	0.60	99.0
			417ME	861,837	490,030	690,978	0.71	0.57	97.7
		40	322 G/3	999,593	436,070	819,792	0.53	0.44	92.8
			912MB	722,366	392,945	588,663	0.67	0.54	91.3
			319 G/2	1,045,694	440,922	872,684	0.50	0.42	95.1
			2003	968,682	407,231	770,859	0.53	0.42	93.4
			SPEC 96	1,130,471	469,911	932,649	0.50	0.41	98.5
			417ME	943,072	430,228	738,395	0.58	0.46	96.9
		45	322 G/3	1,164,175	391,023	890,714	0.44	0.33	91.2
			912MB	806,130	390,234	623,994	0.62	0.48	89.2
			319 G/2	1,266,360	415,602	953,312	0.43	0.33	94.1
			2003	1,121,036	407,343	823,162	0.49	0.36	91.8
			SPEC 96	1,359,016	439,964	1,022,970	0.43	0.32	98.3
			417ME	1,047,575	396,703	790,227	0.50	0.38	96.2
		50	322 G/3	1,208,012	295,753	899,776	0.33	0.24	89.5
			912MB	828,866	354,021	617,492	0.57	0.42	86.8
			319 G/2	1,304,159	282,648	965,460	0.29	0.22	93.0
			2003	1,201,425	345,690	814,347	0.42	0.29	90.0
			SPEC 96	1,407,527	299,504	1,038,686	0.29	0.21	97.9
			417ME	1,094,938	360,887	786,681	28	0.33	95.3



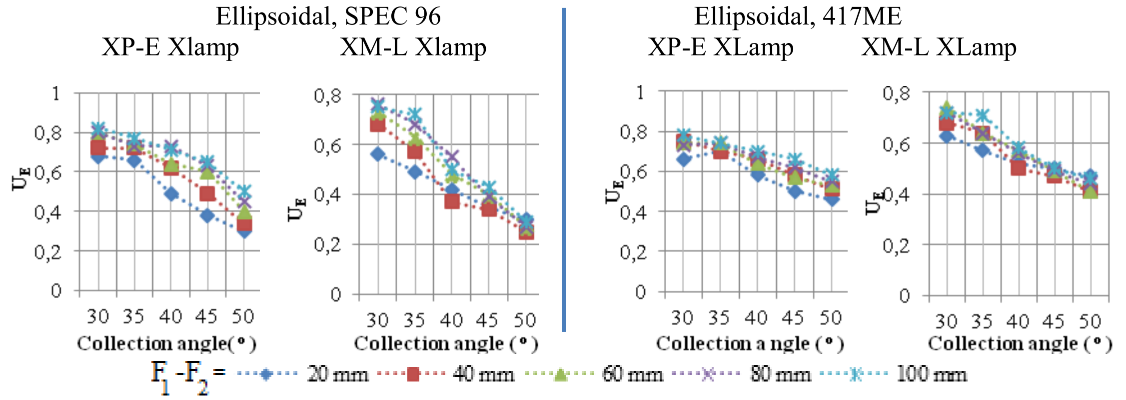
(a) **(b)**

*Fig.6. Uniform lighting values of ellipsoidal reflectors with 30°,35°,40°,45°,50° collection angles, and 20, 40, 60, 80, 100 mm distance between two focal points for XP-E Xlamp and XM-L Xlamp power LEDs **(a)** 85 % specular reflectance **(b)** 85 % semi-specular reflectance*



(a) **(b)**

*Fig.7. Uniform lighting values of ellipsoidal reflectors with 30°,35°,40°,45°,50° collection angles, and 20, 40, 60, 80, 100mm distance between two focal points for XP-E Xlamp and XM-L Xlamp power LEDs **(a)** 88% specular reflectance **(b)** 88% semi-specular reflectance*



(a) **(b)**

*Fig.8. Uniform lighting values of ellipsoidal reflectors with 30°,35°,40°,45°,50° collection angles, and 20, 40, 60, 80, 100mm distance between two focal points for XP-E Xlamp and XM-L Xlamp power LEDs **(a)** 88% specular reflectance **(b)** 88% semi-specular reflectance*

3. Discussions and evaluations

Analysis and findings of ellipsoidal reflectors were evaluated and compared using the tabulated data which were obtained in Table 4, Fig. 6, 7, and 8. As seen from the data, as the distance between two focal points in ellipsoidal reflectors increases, uniformity of lighting increases, and E_{max}, E_{min}, $E_{average}$ values decrease accordingly. As collection angle values decrease, without changing the distance between two focal points of the ellipsoidal reflector, uniformity of lighting and optical efficiency of luminaire increase. In this case, the effects on uniformity of luminance; E_{max}, E_{min}, $E_{average}$ values decrease.

Optical efficiencies of ellipsoidal reflectors with specular reflectance materials are higher than the ellipsoidal reflectors with semi-specular reflectance materials with the same reflectance coefficients. Without changing the distance between two focal points and collection angles of ellipsoidal reflectors with specular and semi-specular reflectance materials; as the reflectance values of the material increase, E_{max}, E_{min}, $E_{average}$ values and optical efficiency of luminaire increase, while the uniformity of lighting decreases.

Since the lumen value of XM-L Xlamp is higher than XP-E Xlamp used in the present research, flux on luminance plane per square meter is higher, and so E_{max}, E_{min}, $E_{average}$ values are higher as well. When the distances between two focal points and collection angles are the same in ellipsoidal reflectors, optical efficiency of luminaire for XP-E Xlamp 115 deg white (350mA) power LED lamp is lower than XM-L Xlamp 2mm x 2mm lambertian cool white (700mA) power LED lamp. Additionally, taken all parameters of ellipsoidal reflectors are the same, uniformity values are higher in ellipsoidal reflectors for XM-L Xlamp than the ellipsoidal reflectors for XP-E Xlamp for all reflector materials. It is unavoidable that the uniformity of lighting increases as the distance between the source and the lightened area increases, because light flux of LED sources placed in the first focal point reflects from the reflector, and converges on the second focal point, then starts to diffuse towards the area to be lightened in incidence direction. Therefore, the distance between the reflector and the lightened area affects the uniformity of lighting directly.

4. Conclusion

At previous researches ellipsoidal reflectors were designed for traditional lighting lamps. However, none of ellipsoidal reflectors for LED lamps which are being currently developed and determined their features at present, were designed.

The present research investigated the effects of ellipsoidal reflectors using LED sources, for different reflector surface materials on the luminance distribution. Numerous variances were tried to obtain optical efficiencies and luminance distribution with the distances between two focal points in ellipsoidal reflectors. For some certain distance, both optical efficiency and luminance distribution values started not to change. Best results for uniformity of lighting were determined for ellipsoidal reflectors using power LED sources. In this case, the highest luminaire optical efficiency values were obtained. As designing ellipsoidal reflectors, numerous collector angles were tried, and the best results were reported. The present research revealed that, as collection angle increased, uniformity of lighting and luminaire optical efficiency decreased. With higher luminaire optical efficiency, the light wasn't wasted in the reflector. On this way, energy used for lighting was saved with optimum results. The findings of the present research contribute to obtaining desired results for luminance distribution and optical efficiency of luminaire, and provide a guide for reflector design. The present research may be a guiding resource for luminaire design for ellipsoidal reflector.

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