# Determination of illuminance distributions of aspherical reflecting surfaces using power LED sources

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Power LED lighting technology has been improving quite fast. Therefore, conventional lighting components have been currently replaced with LED lighting technology due to its advantages. In the reflector design, to obtain and control the probable characteristics of reflector surfaces such as luminous intensity, luminance distribution, and luminaire efficiency are very important. In this case, reflecting surface forms were computed to get optimum luminous intensity distributions and luminaire efficiencies providing uniform luminosities. On that way, different power LEDs and Fresnel lenses were used for this purpose. In paraboloid reflectors, the effects of variations of reflector surfaces and materials on luminous distributions were determined. The effects of variation illumination distances between the location of luminaire and illumination planes on luminance distributions were computed using multiple LED sequences. Luminance and luminous intensity distributions of reflector surfaces were simulated using computer software programs. This study was also implemented to prepare prototypes of paraboloid reflectors for the manufacturing aims.

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## 1. Introduction

The necessity to govern the light emitted from candles or lights led to the invention of reflector configuration. Beforehand 2,000 years, people observed that a mirror shaped as a parabola focus light, thereby markedly boosts its intensity, and even set objects ablaze. Today, a great deal of applications such as auto headlights, road lights, projection presentations, and restorative illuminators necessitate an exact control of light. At all events, the light given off from a light source can be directed to a desired target distribution with a reflective surface [1].

The power LED lighting is more notable in terms of power economy and non-mercury lighting. They will occur of the common lighting, such as white heat bulbs, mercury lamps, gas-electric arc lamps, halogens and CFL’s. Currently, power economy is becoming more and more vital as a fresh concern in the world. Some advantages of power LED lighting are energy efficient, long life, rugged, LED’s light instantly in nanoseconds; cold doesn’t affect it [2]. The other advantages of power LEDs are a wide colour scope, that they will work even in subzero temperature and that the colour do not wash out like other light sources like fluorescents, making them ecologically friendly perfect display. Besides they don’t feature hazardous substances such as mercury etc. Also their driver current are controllable [3].

The appropriate power LED reflecting surface provides some benefits from the advantages of LED lighting technology. For this purpose, power LEDs with different angles, paraboloid reflecting surfaces and different reflecting surface materials were examined and compared with each other. Paraboloid reflectors for power LEDs with different angles were prepared. In this case, their luminous intensity distribution, luminaire efficiency, and luminance distribution were tested using the computer software program, Photopia Version 2014. The design considerations of uniform luminosities were determined. Then, the power LED sequence were prepared and experimental studies were carried out. In this way, design conditions of components of power LED luminaires, Fresnel’s lenses were investigated for power LED coupling purposes.

## 2. Examining Paraboloid Reflectors

The parabola is a spesific case of curvature that has a focal spot to which parallel light emissions will be reflected. The opposite is also true; if you position a light source at the focal point, it will create a parallel light emission. The easiest and most proper way is to acquire the principal properties of the paraboloid reflectors from the mathematical statement of the parabola in polar coordinates. Figure 1 indicates the coordinate system.

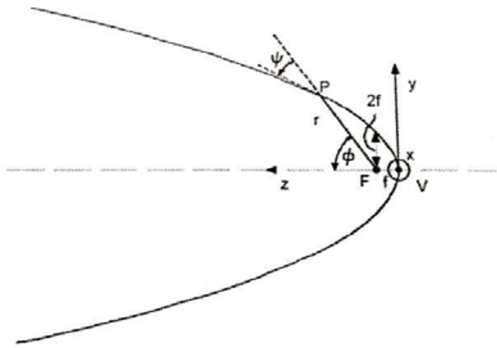


*Fig.1. The parabola in polar coordinates with origin at the focal point.*

The focal length f is the distance VF from the vertex to the focal point. On the equality of the parabola is give by

$$r = \frac{2f}{1 - \cos f} = \frac{f}{\sin^2 \frac{f}{2}} \quad (1)$$

This result is given in elementary texts on coordinate geometry, and it might be verified by transforming to polars the more familiar cartesian form with axes as shown in the Fig. 1. [4].

$$z = \frac{y^2}{4f} \quad (2)$$

## 3. Methods

At present, computers have greatly simplified processes, but concepts remain the same. On this way, as designing reflectors at the first step we used the point source reflector design process. Then, we simulate whole flux quantities of reflectors. All flux reflectors garhered should be equivalent to the required amount of flux on the target. In this case, our aim is to shape the source flux into the desired target distributions. Two steps were carried out on the computations in the following;

1. Map the flux emitted by the source into the target,
2. Generate the reflector shape that achieves the mapping.

Foremost, we need the point source to transmit the angular dispersion of the magnetic field. This angular flux distribution or intensity distribution $I_s(\theta)$ can be converted into a cumulative flux distribution Φsource by integrating the intensity on the emission angle θ of the source. In this case, the cumulative source flux distribution is given as follows;

$$\phi_{source}(\theta) = \int_{\theta_{min}}^{\theta_{max}} I_s(\theta')\, d\Omega = 2\Pi \int_{\theta_{min}}^{\theta_{max}} I_s(\theta') \sin\theta' d\theta' \quad (3)$$

where $d\Omega = 2\Pi \sin\theta d\theta$ is a differential annulus shaped solid angle, and $\theta_{min}$ and $\theta_{max}$ are the limits that define the collection angle of the reflector. In this case, the cumulative target flux distribution is presented in the following;

$$\phi_{target}(y) = \int_{y_{min}}^{y} E_t(y')\, dA = 2\Pi \int_{y_{min}}^{y} E_t(y') \sin y' dy' \quad (4)$$

where $dA = 2\Pi \sin y' dy'$; $y = f(\theta)$ ;source angle $\theta$ and target location y; $E_t(y')$ prescribed target illuminance.

In our study, an average reflectivity ρ is at the reflector surface, and the flux conservation between the origin and the object can be given by [1];

$$\rho \Phi_{source}(\theta) = \Phi_{target}(y) \quad (5)$$

$$\rho \int_{\theta_{min}}^{\theta} I_s(\theta') \sin\theta' d\theta' = \int_{y_{min}}^{y} E_t(y')\, y' dy' \quad (6)$$

where ρ is the average reflectivity of the reflector, $I_s(\theta)$ and $E_t(y)$ is the source intensity and the prescribed target luminance respectively. For instance, for a far-field mark and a rotationally symmetric system, one needs to compute the target flux contained within an annular shaped differential solid angle. In this case, it can be given by;

$$\rho \int_{\theta_{min}}^{\theta} I_s(\theta') \sin\theta' d\theta' = \int_{\beta_{min}}^{\beta} I_t(\beta') \sin\beta' d\beta' \quad (7)$$

where β is the ray angle after reflection and $I_t(\beta)$ is the target prescribed intensity. [5-9].

## 4. Analysis and discussion

In our study, the power LEDs having different light collection angles were used. Types of the LEDs of that power LEDs, name of the producing company, values of source currents, flare angles, color, power and lumen are given in Table 1 below.

*Table 1. Data of power LEDs used*

| Lamp Type | Manufacturer | Drive Current (mA) | Degree | Color | Watts | Lumens | Lumens/W |
|---|---|---|---|---|---|---|---|
| LED XR-E XLamp | Cree | 350 | 75 | white | 1.155 | 80 | 69.3 |
| LED XR-C | Cree | 350 | 90 | white | 1.225 | 60 | 49.0 |
| LED XP-C XLamp | Cree | 350 | 110 | white | 1.160 | 70 | 60.3 |
| LED XP-E XLamp | Cree | 350 | 115 | white | 1.190 | 100 | 84.0 |

Paraboloid reflectors having different light collection angles were designed for the LEDs used. Light collection angles were determined as 20°, 25°, 30°, 35°, 40° and 45°. Materials with various reflection coefficients were used for the paraboloid reflectors having those light collection angles, and the regularity of light distribution were examined. Information about the materials having various reflection coefficients are given in Table 2.

*Table 2. Data of the materials having various reflection coefficients used.*

| Manufacturer | Designation | Description | Reflectance (%) |
|---|---|---|---|
| Generic | SPEC 70 | specular surface | 70 |
| Generic | SPEC 80 | specular surface | 80 |
| Generic | SPEC 86 | specular surface | 86 |
| Generic | SPEC 92 | specular surface | 92 |
| Generic | SPEC 95 | specular surface | 95 |
| Generic | SPEC 99 | specular surface | 99 |

In the case of using each one of 6 different reflectors having different light collection angles discussed, 6 different materials and 4 separate power LEDs were analyzed. As an example, the values of obtained quantities and distributions of illuminations for XR-E XLamp75° are given at the Table 3. As the regularity of light distribution was being evaluated, the emission area of light that came out reflecting from the reflector was taken into account On that way, it was not considered the total area illuminated by the light come out directly from the reflector. That is, as required by the geometry of paraboloid reflector, minimum ($E_{min}$), average ($E_{avg}$) and maximum ($E_{max}$) of illumination levels were detected in that part of the total illuminated area, which was about as big as the opening of the reflector, and regularity in the distribution of illumination was assessed within the context of $E_{min}/E_{max}$ and $E_{min}/E_{avg}$ levels.

2,500,000 ray tracings were used while assessing the illumination distribution. Paraboloid reflectors having different light collection angles were analyzed in every kind of materials with the aim of contrasting the regularity of the distribution of illumination.

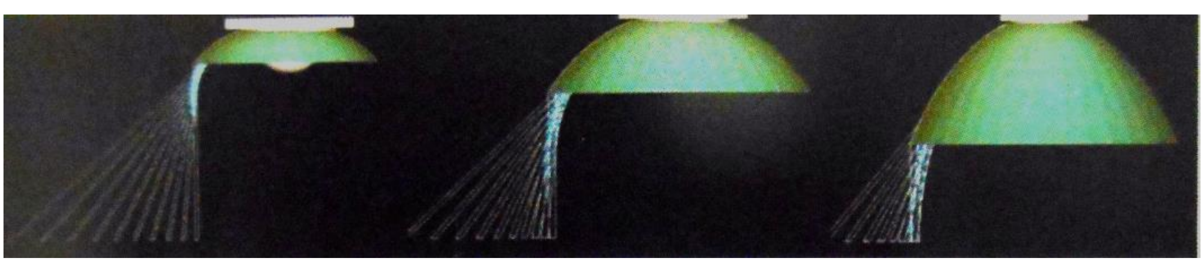

*Fig.2. Examples for the reflectors analyzed. Collection angles of paraboloid reflectors are $20^0$, $30^0$ and $35^0$ respectively.*

*Table 3. Values concerning the quantity and distribution of illumination formed in the case that Cree 1.2W 75$^0$ power LED was used on Paraboloid Reflector*

| Lamp Type | Collection Angle ($^0$) | Material Type | $E_{min}$ (lm/m$^2$) | $E_{max}$ (lm/m$^2$) | $E_{avg}$ (lm/m$^2$) | $E_{min}/E_{avg}$ | $E_{min}/E_{max}$ | Luminare Optical Efficiency(%) |
|---|---|---|---|---|---|---|---|---|
| CREE 1.2W 75$^0$ | 20 | SPEC 70 | 58,220 | 109,419 | 82,458 | 0.71 | 0.53 | 99.6 |
| | | SPEC 80 | 58,263 | 111,750 | 83,076 | 0.70 | 0.52 | 99.7 |
| | | SPEC 86 | 58,289 | 113,149 | 83,448 | 0.70 | 0.52 | 99.7 |
| | | SPEC 92 | 58,316 | 114,547 | 83,819 | 0.70 | 0.51 | 99.8 |
| | | SPEC 95 | 58,329 | 115,247 | 84,005 | 0.69 | 0.51 | 99.8 |
| | | SPEC 99 | 58,346 | 116,179 | 84,252 | 0.69 | 0.50 | 99.9 |
| | 25 | SPEC 70 | 52,761 | 105,750 | 80,237 | 0.66 | 0.50 | 99.2 |
| | | SPEC 80 | 52,898 | 107,967 | 81,368 | 0.65 | 0.49 | 99.3 |
| | | SPEC 86 | 52,979 | 109,297 | 82,047 | 0.65 | 0.48 | 99.5 |
| | | SPEC 92 | 53,061 | 110,628 | 82,727 | 0.64 | 0.48 | 99.7 |
| | | SPEC 95 | 52,641 | 112,250 | 83,077 | 0.63 | 0.47 | 99.7 |
| | | SPEC 99 | 52,687 | 113,135 | 83,560 | 0.63 | 0.47 | 99.9 |
| | 30 | SPEC 70 | 46,208 | 85,340 | 68,594 | 0.67 | 0.54 | 98.7 |
| | | SPEC 80 | 46,658 | 86,302 | 69,499 | 0.67 | 0.54 | 99.1 |
| | | SPEC 86 | 46,904 | 86,880 | 70,042 | 0.67 | 0.54 | 99.3 |
| | | SPEC 92 | 47,099 | 87,457 | 70,585 | 0.67 | 0.54 | 99.6 |
| | | SPEC 95 | 47,220 | 87,746 | 70,857 | 0.67 | 0.54 | 99.7 |
| | | SPEC 99 | 47,383 | 88,131 | 71,219 | 0.67 | 0.54 | 99.8 |
| | 35 | SPEC 70 | 36,188 | 66,595 | 56,439 | 0.64 | 0.54 | 97.3 |
| | | SPEC 80 | 36,486 | 66,595 | 57,284 | 0.64 | 0.55 | 97.8 |
| | | SPEC 86 | 36,664 | 66,595 | 57,791 | 0.63 | 0.55 | 98.1 |
| | | SPEC 92 | 36,843 | 66,595 | 58,297 | 0.63 | 0.55 | 98.4 |
| | | SPEC 95 | 36,932 | 66,595 | 58,551 | 0.63 | 0.55 | 98.5 |
| | | SPEC 99 | 37,051 | 66,595 | 58,889 | 0.63 | 0.56 | 98.7 |
| | 40 | SPEC 70 | 29,572 | 59,932 | 48,982 | 0.60 | 0.49 | 91.7 |
| | | SPEC 80 | 29,994 | 62,987 | 49,986 | 0.60 | 0.48 | 92.2 |
| | | SPEC 86 | 30,246 | 64,820 | 50,588 | 0.60 | 0.47 | 92.4 |
| | | SPEC 92 | 30,499 | 66,653 | 51,191 | 0.60 | 0.46 | 92.7 |
| | | SPEC 95 | 30,625 | 67,569 | 51,492 | 0.59 | 0.45 | 92.8 |
| | | SPEC 99 | 30,794 | 68,791 | 51,893 | 0.59 | 0.45 | 92.9 |
| | 45 | SPEC 70 | 20,937 | 53,944 | 39,244 | 0.53 | 0.39 | 83.8 |
| | | SPEC 80 | 21,336 | 57,904 | 40,430 | 0.53 | 0.37 | 84.2 |
| | | SPEC 86 | 21,575 | 60,294 | 41,141 | 0.52 | 0.36 | 84.4 |
| | | SPEC 92 | 21,814 | 62,686 | 41,853 | 0.52 | 0.35 | 84.7 |
| | | SPEC 95 | 22,221 | 63,542 | 42,204 | 0.53 | 0.35 | 84.8 |
| | | SPEC 99 | 22,382 | 65,094 | 42,677 | 0.52 | 0.34 | 84.9 |

Luminare Optical Efficiency (%): The ratio can show how well the luminaire is designed and how much light was lost in its optical systems. The more reflective-efficient materials have luminare optical efficiency. Light output ratio of luminaire (LOR) takes into account for the loss of light energy both inside and by transmission through light reflectors. It is given by;

(8)

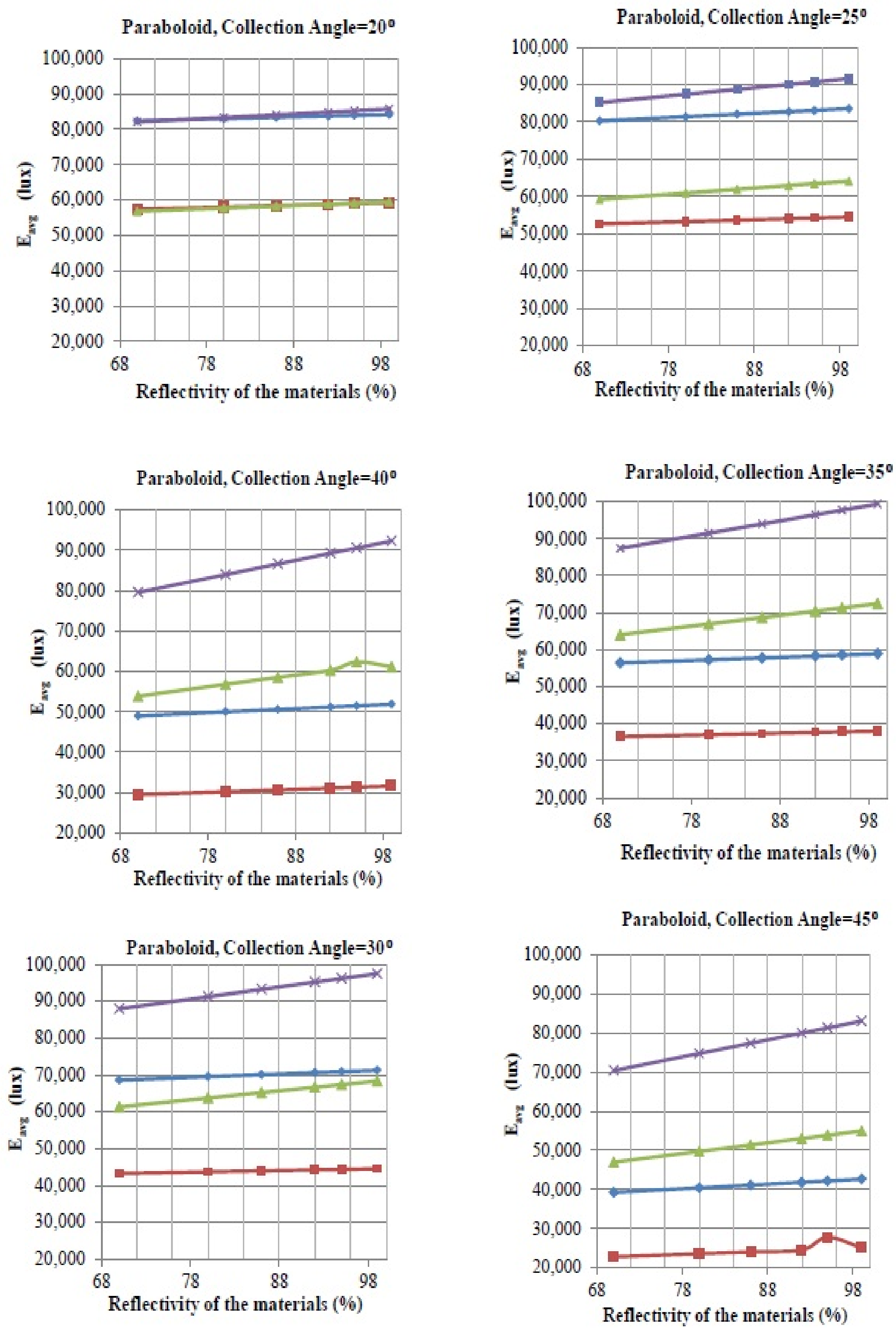


*Fig.3. Examples to the illumination distributions obtained from the paraboloid reflectors having the various collection angles. The variations of average illumination levels with the reflectivity of materials for the power LEDs having different angles.*

As seen in the Fig. 3 and Table 3 on which the results for the sample situations can be commonly given as follows;

- The collection angle of the paraboloid reflector increases as considering all the instruments and LED types used,
  - ❖ The illumination level ($E_{min}$, $E_{avg,}$ $E_{max}$) decreases since the size of the reflective surface increases,
  - ❖ The regularity of the illumination distribution decreases.

- The value of the reflection coefficient reduces in consideration of all the collection angles and LED types used,
  - ❖ The illumination level ($E_{min}$, $E_{avg,}$ $E_{max}$) decreases
  - ❖ The regularity of the distribution of illumination increases

- The most regular distribution of illumination occurs with the use of XR-E XLamp75$^{o}$ power LED in consideration of all the collection angles of paraboloid reflector and the materials used, and XP-C XLamp110$^{o}$, XP-E XLamp 115$^{o}$ and XR-C 90$^{o}$ comes respectively.

- The optical light output ratio of lighting device decreases as the collection angle of the paraboloid reflector increases in consideration of all the instruments and LED types utilized.

- The highest optical efficiency rates occurs with the use of XP-E XLamp 115$^{0}$ power LED in consideration of all the collection angles of paraboloid reflector and of the materials used, and comes XP-C XLamp110$^{0}$, XR-E XLamp75$^{0}$ and XR-C 90$^{0}$ respectively.

- The illumination distributions shaded plots were examined. The most uniform luminous distribution of illumination occurs with the use of XR-E XLamp75$^{o}$, XR-C 90$^{0}$, XP-E XLamp 115$^{0}$ and XP-C XLamp 110$^{0}$ comes respectively. The plots of these examplee are denoted in Fig. 4.

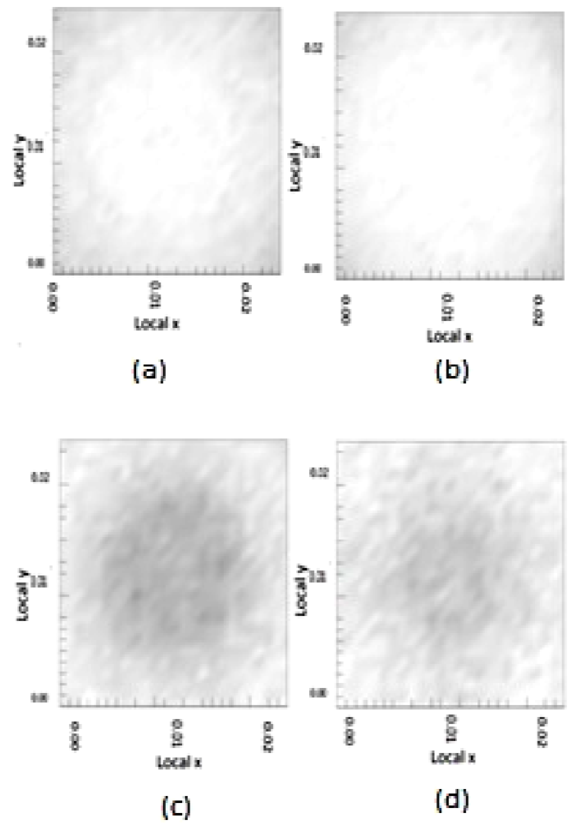


*Fig.4. The illumination distributions occurring with the application of 30$^{o}$ collection angle and Spec70 reflection instrument on paraboloid reflector with XR-E XLamp 75$^{0}$, XR-C 90$^{0}$, XP-C XLamp 110$^{0}$ and XP-E XLamp 115$^{0}$ respectively.*

In the analyses multi LED sequences were formed with the purpose of testing the usability of the designs devised. The collection angles and materials with which the power LED was became most efficient according the results obtained from the analyses were used. Some illumination level measurements in different distances were carried out. The LED sequences formed average illumination values are given in Table 4. LED sequences (5x10) were formed taking into account the multiple source shadow effect it can be seen at Fig.5.

*Table 4. Illumination distributions of power LEDs obtained in different distances after they sequenced*

| Lamp Type | Collection Angle ($^0$) | Material | Distance (m) | $E_{avg}$ ($lm/m^2$) |
|---|---|---|---|---|
| Cree 1.2w $75^0$ | 20 deg | Spec 70 | 2.65 | 273.262 |
| | | | 2.80 | 244.252 |
| | | | 3.00 | 214.327 |
| Cree 1.2w $90^0$ | 25 deg | Spec 70 | 2.65 | 275.360 |
| | | | 2.80 | 249.472 |
| | | | 3.00 | 215.562 |
| Cree Xp C-Lamp $110^0$ | 20 deg | Spec 70 | 2.65 | 238.255 |
| | | | 2.80 | 212.680 |
| | | | 3.00 | 154.698 |
| Cree Xp C-Lamp $115^0$ | 25 deg | Spec 70 | 2.65 | 402.980 |
| | | | 2.80 | 359.780 |
| | | | 3.00 | 312.598 |

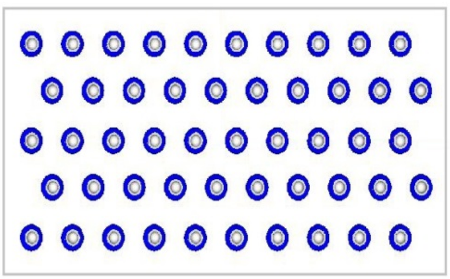

*Fig.5. Example to the sequence of LEDs*

To obtain better illumination distribution, collimating lens connections were made in the multiple LED sequence. Fresnel lenses were used. Lens making formula is applied for paraxial approximation.. Lens maker's formula as afunction is given by;

$$f = f(n, R_1, R_2, t) \tag{9}$$

where; $f$ is the paraxial focal length of the Fresnel lens, $n$ is index of refraction of the lens material; $R_1$ is the radius of lens surface nearest the LEDs; $R_2$ is the radius of other lens surface, t is thickness of the lens**.** As known that the paraxial focal lenght is the function of these parameters.

The thickness of the Fresnel lens is reduced as the number of steps is increased. Typically Fresnel lenses are planned with the minimal number of stairs needed to achieve the desired thickness because additional light losses may come along the inner faces and joining the vertices. All the same, for plastic lenses, a thin lens design is desirable where excessive lens thickness will result in sink distortions. Thence, the performance and moldability of a lens are sold-off when choosing the optimal number of stairs [10].

The variation of surface distance and illumination distribution for the power LED of 1.2W $75^0$ manufactured by Cree Company in USA is given in Table 5. The properties of Fresnel lens used; the prism steps number is 10, the refraction index of acrylic is 1.491, the lens thickness is 3mm, revolve segment number is 180.

As seen from the Table 6, as the distance between the surface and the reflector increases, the regularity of the illumination distribution decreases.

*Table 5. The surface distance and illumination distribution for the Fresnel lens designed for the power LED of 1.2W, $75^0$ .*

| Lamp Type | Size (mm) | Distance (m) | $E_{min}$ ($lm/m^2$) | $E_{max}$ ($lm/m^2$) | $E_{avg}$ ($lm/m^2$) | $E_{min}/E_{avg}$ | $E_{min}/E_{mx}$ |
|---|---|---|---|---|---|---|---|
| CREE 1.2W $75^0$ | 350x700 | 2.65 | 197.20 | 401.770 | 290.280 | 0.68 | 0.49 |
| | | 2.80 | 171.080 | 371.810 | 261.320 | 0.65 | 0.46 |
| | | 3.00 | 105.20 | 336.720 | 226.760 | 0.46 | 0.31 |

## 5. Conclusion

Illumination devices should be designed properly to be able to take advantages of power LEDs effectively. In order to get successful results from power LEDs, determination of reflector design parameters for providing required conditions such as illumination distribution, lumious intensity, and optical efficiency is quite important. Forming surfaces of reflectors for desired reguirements can be changed as well. Some kinds of illumination design programs were used for this purpose. The distribution of luminous intensity and illumination to be formed for reflector properties are simulated. Waste of time, money and labor can substantially be prevented monitoring the results to be gained in the process of design with the help of those simulation programs oriented to the analysis of the illumination device. On this way, making certain amount of prototype devices in designing process may not be needed.

This study includes certain parts of the results reached to examine the effects of different choices relating to the reflector's format, properties of instruments, and LEDs on the illumination distributions. The optimum circumstances by assessing the results in terms of regular distributions of illuminations and light outputs of devices were obtained.

Illumination distributions and the light output of the device occurred in the case that multiple angled LEDs are used on the paraboloid reflectors were examined and evaluated.

The results presented have a leading role on designing of reflectors which will be ensure the achievement of circumstances required in terms of the illumination distributions and lighting device outputs.

## References

[1] J. P. Roland, Collage of Optics and Photonics at the University of Central Florida Orlando, Chap.1. 2010.
[2] M. Arik, F. J. Petrosk, S. Weary Thermal and Thermomechanical Phenomena in Electronic Systems, pp. 113, (2002).
[3] E. M. Sa, F. L. M. Antunes, A. J. Perin, IEEE Power Electron Specialists Conference, pp. 4196 (2008).
[4] R. Winston, J. C. Minano, P. Benitez, Elsevier Academic Press, USA, pp. 467 (2005).
[5] N. Boldyrev, About Calculation of Asymetrical Specular Reflectors, Svetotekhnika 7, Russia, pp. 7-8, 1932.
[6] V. Komissarov,The Foundations of Calculating Specular Prismatic Fittings, Trudy VEI , 43th ed., pp. 6-61. 1941
[7] J. S. Schruben, Formulation of A Reflector Design Problem For A Lighting Fixture, 62nd ed., J. Opt.Soc. Am. 1932.
[8] W. Elmer, The Optical Design of Reflectors, Wiley, Newyork, 2nd ed., TLA Lighting Consultants, 1980.
[9] O. Kush, Computer-Aided Optical Design of Illuminating and Irradiating Devices, Aslan Publishing House, Moscow,1993.
[10] Anon., Lumileds, "Secondary Optics Design Considerations for Superflux LEDs", www.lumileds.com (11.12.2014).

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