

# Optical system design of blackboard light

Xiaoyang He<sup>1</sup>, Yini Zhang<sup>1</sup>, Li Shao<sup>1</sup>, Nianyu Zou<sup>1</sup>, Xiangfeng Li<sup>1</sup>, Bin Hao<sup>1</sup>,  
Chuanxi Wang<sup>1</sup>, Yujun Liu<sup>1</sup> and Ling Yu<sup>1\*</sup>

<sup>1</sup>Dalian Polytechnic University, Dalian, Liaoning Province, 116034, China

\*Corresponding author's e-mail: yuling@dlpu.edu.cn

**Abstract.** In order to solve the problem of insufficient illumination uniformity of the blackboard, this paper provides a design method of the optical system that can achieve uniform illumination of the blackboard. The energy conservation law is used to make the optical system form uniform illumination on the target surface at a specific position. After simulation, the results show that the optical system can make the illumination uniformity of the blackboard reach 0.84.

## 1. Introduction

Classroom lighting is divided into classroom basic lighting and blackboard lighting. In the classroom lighting survey of Shanghai and Jiangsu, it is shown that after the lighting renovation, there are still a large number of classrooms where the uniformity of the blackboard illumination is not up to standard. The main problem is that the lower part of the blackboard is darker [1]. It can be seen that the blackboard illumination of most classrooms lacks a good optical light distribution design, and the problem of illumination and uniformity of the blackboard has not been solved.

The conventional homogenizing optical system uses a bilaterally symmetrical optical lens to perform secondary optical design of the LED. This lens has its limitations: the target surface should be located directly in front of the optical system. When the target surface is above or below the optical system, the uniform light cannot be achieved. Therefore, in the case where the target surface is located under the optical system, an asymmetric uniform optical system design is designed to achieve uniform illumination of the target surface. Above 0.8, the optical system can be used for typical blackboard lighting.

In this paper, the lens surface is transformed into a mathematical model for analysis. By using the Snell's law, the law of edge light and the law of energy conservation, the optical process is analyzed, the surface shape is simulated, and simulation is carried out. The results show that the optical system can achieve the design goals.

## 2. Overview of non-imaging optics

The concept of non-imaging optics was first proposed by Winston in "Principles of solar concentrators of a novel design" [2]. This new concept proposes that non-imaging optics differ from traditional geometric optics in imaging optics. It does not lie in the quality of imaging, but rather emphasizes the energy distribution and transmission efficiency of light. The use of non-imaging optics to control the transmission of light can solve the problem of light energy collection and the allocation of light energy [3].



This design mainly solves the problem of light energy distribution. By controlling the optical process, the light emitted by the LED is evenly distributed to the target surface to achieve uniform light field distribution.

### 3. Method of the study

The optical system is not illuminated directly against the target plane, but at a distance from the target surface. The installation position of the blackboard light is higher than the upper edge of the blackboard and has a certain distance from the surface of the blackboard. The target surface is regarded as the left view of the blackboard, and the part near the z-axis is regarded as the upper edge of the blackboard. Firstly, the light of 30-120° emitted by the light source is analyzed. The optical process of the light mainly passed through the first lens, and then refracted in the optical system and then injected into the target surface through the second lens.

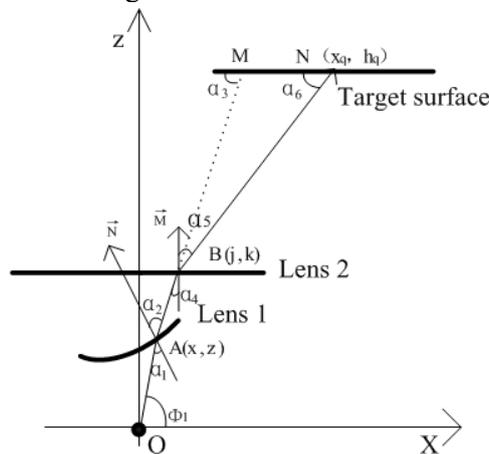


Figure 1. Optical process of light passing through lens one and lens two.

According to the principle of edge ray, a mathematical model is established. The schematic diagram is shown in Figure 1. In the figure, the light-incident surface and the light-emitting surface of the lens are represented by a curve, and the target surface is the blackboard surface, which is convenient for analysis of light. The incident ray  $\vec{OA}$  intersects the lens surface at  $A(x, z)$ , the exit ray  $\vec{BM}$  intersects the target plane with  $M$ ,  $\vec{N}$  and  $\vec{M}$  are respectively the normals of the entrance and exit surfaces. The lens entrance surface is first analyzed. It can be obtained by the Snell's law:

$$n_1 \sin \alpha_1 = n_2 \sin \alpha_2 \quad (1)$$

Where  $n_1$  is the refractive index of the medium where the incident ray is located, and  $n_2$  is the refractive index of the medium where the ray is emitted; therefore,  $n_1$  is the refractive index of the air,  $n_1=1$ ,  $n_2$  is the refractive index of the lens,  $n_2 = n$ , and  $\alpha_1$  is the angle between the incident ray and the normal, and  $\alpha_2$  is the angle between the emitted light and the normal. Take the trigonometric function to the law of refraction, get:

$$\frac{1}{n} \cdot \frac{\tan \alpha_1}{\tan \alpha_2} \cdot \frac{\sqrt{1+\tan^2 \alpha_2}}{\sqrt{1+\tan^2 \alpha_1}} = 1 \quad (2)$$

Let the slope of the normal line  $\vec{N}$  to be  $m_1$ , the slope of the incident ray  $\vec{OA}$  is  $\tan \varphi_1$ , and the slope of the refracted ray  $\vec{AB}$  is  $\tan \alpha_2$ . According to the angle formula, the root of equation (2) is simplified, then:

$$\frac{\sqrt{(\tan \alpha_3 - m_1)^2 + (1 + m_1 \tan \alpha_3)}}{\sqrt{(\tan \varphi_1 - m_1)^2 + (1 + m_1 \tan \varphi_1)}} = \sqrt{\frac{1 + \tan^2 \alpha_3}{1 + \tan^2 \varphi_1}} \quad (3)$$

Substituting equation (3) into equation (2):

$$\frac{1}{n} \cdot \frac{\tan\varphi_1 - m_1}{\tan\alpha_3 - m_1} \cdot \sqrt{\frac{1 + \tan^2\alpha_3}{1 + \tan^2\varphi_1}} = 1 \quad (4)$$

Make:

$$\sqrt{\frac{1 + \tan^2\alpha_3}{1 + \tan^2\varphi_1}} = k \quad (5)$$

Then:

$$m_1 = \sqrt{\frac{k \tan\varphi_1 - n \tan\alpha_3}{k - n}} \quad (6)$$

Substituting (5) into (6), then gives the slope expression:

$$m_1 = \frac{\sin\varphi_1 - n \sin\alpha_3}{\cos\varphi_1 - n \cos\alpha_3} \quad (7)$$

From the equation (7), we can get a first-order ordinary differential equation for the the normal slope  $m_1$ , the angle  $\varphi_1$ , and the angle  $\alpha_3$ :

$$\sin\varphi_1 = \frac{z}{\sqrt{x^2 + z^2}} \quad (8)$$

$$\cos\varphi_1 = \frac{x}{\sqrt{x^2 + z^2}} \quad (9)$$

$$\sin\alpha_3 = \frac{j - z}{\sqrt{(j - x)^2 + (k - z)^2}} \quad (10)$$

$$\cos\alpha_3 = \frac{j - x}{\sqrt{(j - x)^2 + (k - z)^2}} \quad (11)$$

$$\frac{dz}{dx} = \frac{n \sin\varphi_1 - \sin\alpha_3}{n \cos\varphi_1 - \cos\alpha_3} \quad (12)$$

The second lens is analyzed, according to the law of refraction, where  $n_2$  is the refractive index of the lens,  $n_3$  is the refractive index of air;  $\alpha_4$  is the angle between the incident ray and the normal  $\vec{M}$ , and  $\alpha_5$  is the angle between the outgoing ray and the normal  $\vec{M}$ . The reasoning process is the same as the first face lens. From the Snell's law, the expression can be derived:

$$n \frac{k - z}{(j - x) \tan\alpha_6} \cdot \sqrt{\frac{1 + \tan^2\alpha_6}{1 + \left(\frac{k - z}{j - x}\right)^2}} = 1 \quad (13)$$

Among then:

$$\tan\alpha_6 = \frac{h_q - k}{x_q - j} \quad (14)$$

Combining the formula (7) ~ formula (14), Numerical solutions such as Runge-Kutta method and finite difference method are used to solve the solution of simultaneous equations by Matlab programming.

Next, the light of  $0^\circ \sim 30^\circ$  and  $150^\circ \sim 180^\circ$  emitted by the light source is analyzed. This part of the light passes through the prism of the edge and is totally reflected into the target surface, as shown in Figure 2.

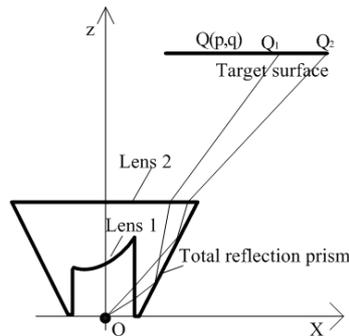


Figure 2. Optical process of light passing through a total reflection prism.

Light propagation follows the law of energy conservation, if without energy loss, the energy output from the light source is equal to the energy of the incident surface [4], then:

$$\iint_{\Omega} I(\theta)d\Omega = \iint_p E(p)dS \quad (15)$$

Where  $\theta$  is the angle between the light emitted by the light source and the optical axis,  $I(\theta)$  is the light intensity value at  $\theta$  point, and  $E$  is the illuminance value at the  $Q$  point. We make the point where the light emitted by angle  $\theta$  hits the target surface on  $Q_2(p_2,q)$ , and the point on the target surface from the angle of  $\theta+d\theta$  is  $Q_1(p_2-dp,q)$ , which can be derived from equation (15):

$$dp = \frac{\sin\theta\cos\theta}{q_2-r} \cdot \frac{I_0}{E_{Q_2}}d\theta \quad (16)$$

Where  $I_0$  is the light intensity of the LED in the optical axis direction;  $E_{Q_2}$  is the predetermined illuminance value of  $Q_2$ , and  $r$  is the distance from the edge of the blackboard to the  $z$ -axis. In equation (16), the ray emitted by the light source has a one-to-one correspondence with the points on the target plane, so a number of corresponding points can be obtained by programming calculation. In the above calculation process, several points can be drawn, and the points of each numerical coordinate are imported into CAD to construct the curve, and the desired face shape can be derived in the modeling software.

#### 4. Simulation

By analyzing the optical process and deriving the model, the model basically meets the design requirements. After improving, the generated model is shown in Figure 3.

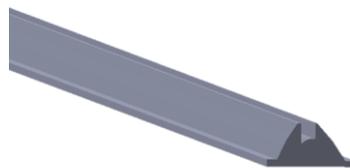


Figure 3. Lens model

The goal is to design an optical system that achieves uniform illumination on the blackboard. Its performance index is: the upper edge of the target surface (blackboard surface) is 15 cm away from the optical system, and the target surface is 35 cm away from the optical system. A single LED light flux of 20lm white light chip, a total of 192 chips, lens material is pmma, refractive index of 1.49. In order to verify the correctness of the model, the simulation trace is performed in tracepro. As shown in Fig. 4, the illumination uniformity of the target surface is better than 0.8, which satisfies the design goal.

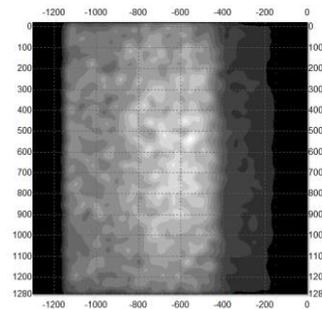


Figure 4. Irradiance analysis chart

After ray tracing, the light distribution curve is shown in Figure 5, and the light traces through the target surface is shown in Figure 6.

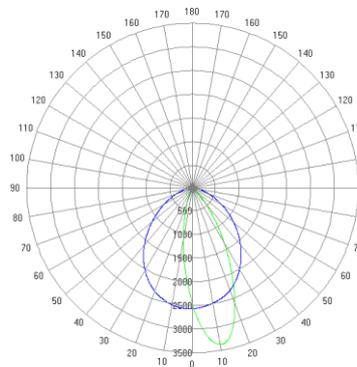


Figure 5. Light distribution curve

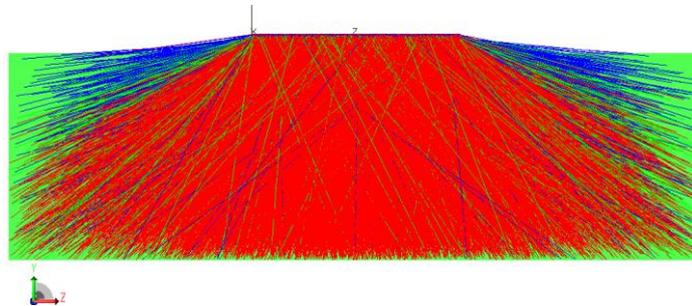


Figure 6. Ray tracing map

The IES file is imported into the classroom model, and the illumination effect of the blackboard surface is analyzed under the classroom basic lighting and the blackboard lighting. According to the standard GB/T 36876—2018 “Sanitary requirements for lighting design and installation of ordinary classrooms in primary and secondary schools”, in the standard, the installation distance of the blackboard luminaire is required [5]. The standard classroom is set to 9 meters long, 7.2 meters wide, 3.5 meters high, The length and width of the blackboard are set to 4 meters and 1.2 meters. The height of the blackboard is 0.1 meters. Set three blackboard lights in front of the blackboard. After adjusting the angle of the blackboard light and the height of the installation, the values of the parameters on the blackboard are as shown in the following table. In the "Standards for Lighting and Lighting Hygiene in Primary and Secondary Schools" [6], the average illumination of the blackboard is required to be greater than 500 lx, and the uniformity of illumination is greater than 0.8. Table 1 shows the values of the lighting parameters on the surface of the blackboard, which can be seen from the table and conform to national standards. Figure 7 is a numerical diagram of the surface of the blackboard, and Figure 8 is a simulation analysis of the environment.

Table 1. Lighting parameter value of the blackboard surface.

Average illumination (lx)	Minimum illumination (lx)	Maximum illumination(lx)	Minimum illumination / average illumination(lx)	Minimum illumination / maximum illumination(lx)
519	438	593	0.84	0.74

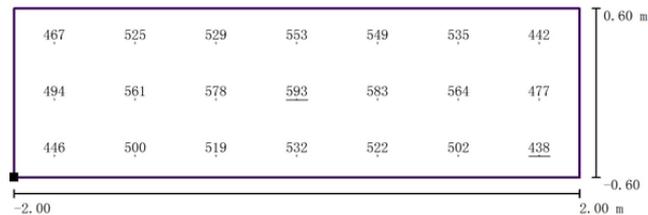


Figure 7. Numerical diagram of the surface of the blackboard.



Figure 8. Blackboard light environment simulation analysis chart.

## 5. Conclusion

In this paper, a non-imaging optical design method is used to design an optical system that can be used for the key illumination of the blackboard. The symmetrical structure of the traditional homogenizing lens is changed, and an asymmetric lens is built for the target illumination surface under the lens to realize the blackboard. The illuminance uniformity reaches the target of 0.8 or more. This can solve the darker problem in most of the lower half of the blackboard. It can be seen from the simulation calculation results that by performing secondary optical design on the LED, a highly uniform asymmetric light distribution can be realized, thereby meeting the design requirements and improving the illumination efficiency.

## References

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