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## SHAPING OF PANEL MATERIALS IN LIGHT DIRECTION DESIGN

The paper presents the methodology of the analysis of the materials used in solar energy conversion, and an elaborated example with simulations of obtained results. Material properties are selected in relation to the need of sunlight illumination applications in civil constructions. This process is presented , starting from the analysis of some aspects of solar radiation, through the calculations of lens curvature and leading to the execution of simulations in different conditions. Graphical presentation of the phenomenon, it can visualize the process of shaping curves. The materials such as glass, polymers, metals, and gases have been discussed. Particular attention was paid to the results of the transmission of materials, their reflection and absorption of solar radiation. Moreover, the research problems of illumination and reflection in multi-layer structures used for civil constructions have been presented.

*Keywords:* reflective materials, illumination channels, surface shaping, reflection, non-imaging optics.

## 1. Introduction

Natural light is necessary to provide effective biochemical processes in most living organisms not excluding human beings. The interaction with solar radiation energy reduces risks of various illnesses, improves heart operation and influence the length of life. These properties are justified by stimulation of D vitamin and NO contents. The latter content improves blood circulation and through widening of arteries increases the amount of blood, oxygen and other nutritive agents that reach heart muscle.

Moreover there are other advantages of the use of solar energy to light building interiors, such as: labor effectiveness increase and undoubtedly electric energy savings. To achieve desired effects, some design solutions can be applied, including for example: intelligent windows, roof skylights, pipe skylights, heliostats or Hybrid Light Systems (HLS). The efficiency of operation of heliostats and skylights depends most on material reflectance of either reflective or transmitter elements. Heliostats employ special driven mirrors systems tracking sun position during daytime. Pipe skylights consist of a dome, a light transmitting tube and a diffuser. The material covering the inner part of a tube plays the most important role in these systems. In construction both design solutions can be combined. The paper considers building interior constructions and materials used for additional natural light supply and effects possible to achieve in different materials used in lighting channels. That is why efficient computational methodology is developed for natural light transport systems.

The general purpose for the series of research is to design and construct an experimental system of light concentration and direction in the Faculty of Technology Fundamentals, LUT to illuminate the dark areas in the building interior with natural light.

## 2. Discussion of the application of natural light reflection and transmission phenomena

Solar radiation intensity is the most important characteristic value describing the availability of the source of energy. It is an instantaneous value of radiation density gained at a flat surface unit vertical to the direction of radiation and its unit is W/m$^2$. The maximal amount is called solar constant of 1366 [W/m$^2$]. At our regional scale total insolation intensity does not exceed 1100 [W/m$^2$].

The technology of solar energy concentration considered as promising in buildings is the use of Fresnel's lens and reflection surfaces. Such construction is based on complex step lens consisting of concentric rings of appropriate curvature radius to make parallel beam thanks to equal focal lengths. They are especially used in PV systems but the sector of non-imaging phenomena is also promising for this construction and technology.

The condition noted in the form of the equation of reflectance as eq.1 is always met in solar active materials

$$R(\lambda) = 1 - A(\lambda) - T(\lambda) \qquad (1)$$

where:

$R$ − material reflectance

$A$ − light absorption in a material

$T$ − transmittance in particular wave lengt)

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The ability of emission is possible in materials exclusively within the range of its absorption ($E(1) \leq A(1)$). The description uses for convenience the following concepts:

– mean spectrum in relation to eye sensitivity(*opt*),
– solar radiation gain spectrum (*slo*)
– black body emissivity spectrum at particular temperature (*temp*) [1], and
– reflection coefficient determined as the ratio of incident radiation to the reflected radiation $R = I_o/I_p$.

Moreover, some important in our consideration phenomena occur in two areas of the interaction between radiation and insolated material. These interactions are related with the changes of radiation properties and with the changes of illuminated material. The first area covers reflection, refraction, dispersion, change of wave length and polarization. The material can be changed energetically or structurally resulting also in biological and chemical changes. These phenomena depend on size, structure and geometry, the ratio of incident radiation to this geometry characteristics and the relation between wave energy and induction value of material particles. The most important phenomena influencing radiated material surface are: absorption, luminescence, photoemission and heat transfer.

Reflection phenomena nature from flat surfaces and from spherical surfaces have been used and modeled for the purpose of computations. This procedure is presented in Fig. 1 and can be described pointing out the rays that coming out of the lighting point, go further after their reflection from the flat surface in the way as if they were send out from an apparent image of the original point. The lighting point is located beside the reflecting surface on its vertical. The reflection from spherical surfaces is reproduced by means of a section. The rays coming out as vertical to the sphere surface are not bended. In the axial area, the following is assumed:

1) the vertical surfaces are reproduced as vertical too but optically coupled
2) the ratio of the image size to the object size in the coupled pair of surfaces is constant and called a transverse magnification
3) the ratio of convergence of coupled rays is also constant and called an angle magnification [2]

The light reflection from a smooth surface is directional and light is polarized. The polarization depends on the angle of radiation and on the type of material. The total polarization from the dielectric surface occurs only at particular angle called Brewster's angle when the incident ray and the reflected one form 90° angle. The coefficient of refraction and the Brewster's angle are related as $n = \operatorname{tg}\alpha_B$.

The mentioned phenomena form the basis to carry out modeling within the non-imaging optics for the purpose of natural lighting systems.

Natural reflection is usually directional and diffused at some extent, but if the surface is rough it can be even diffused in all directions (Lambert type). Mirror coatings and polishing help avoid this type of reflection.

Moreover collinear and off-specular unusual reflection can occur. The level of diffusion depends on spectrum distribution and incident direction. The sub-surface reflection occurs in opaque materials in a layer several times wider than the wave length and spatial reflection occurs in the whole volume of semi – opaque materials. That is why in most of considered cases of reflection some number of simplifying assumptions, to these complex phenomena, have to be taken into account.

The following 3 properties characterize reflections: reflection coefficient, reflection factor and the function of reflection coefficient distribution. The reflection factor can be described by Eq. 2:

$$R = k = \frac{W_1}{W_{2,id}} \qquad (2)$$

where:

$k$ – non-dimensional value indicating the degree of smooth surface perfection expressed within the range 0-1,

$W_1, W_{2id}$ – the same physical values measured in identical measurement conditions determined for the real surface and the perfect (ideal) surface, respectively.

The mentioned coefficient of reflection is determined as the ratio of the same physical values measured in particular conditions ($W_1$ – beam reflected into semi space, $W_2$ – incident beam from particular direction)

$$\rho = k = \frac{W_1}{W_2} \qquad (3)$$

The function of reflection coefficient distribution is quotient of two different physical properties selected in the way as to become a kernel of the total equation describing the considered phenomenon:

$$\dot{\rho} = g = \frac{dW_1}{f(W_2)dw} \qquad (4)$$

where: $W_1 = \int g(W_2)\, d\omega$, and $\int d\omega \leq 1$

The geometry of material surface is very important to the characteristics of reflected radiation. Even if the surface seems totally smooth, actually it can have chaotic or regular micro – roughness or both. They can be caused by natural oxidation, sand treatment, spray or rolling. Surface roughness is described by international standards.

For example, $R_a$ range is an arithmetic mean of module of deviation $h(x)$ from the mean line on the $L$ section.

$$R_a = \frac{1}{L}\int_0^L |h(x)|\, dx \approx \frac{\sum_1^n |h_i(x)|}{n} \qquad (5)$$

The range $R_z$ is an arithmetic mean of 5 highest and 5 lowest points in the profile in the $L$ section.

$$R_z = \frac{\sum_1^5 |h_{pi}| + \sum_1^5 |h_{vi}|}{5} \qquad (6)$$

In general optics the following materials are used: oxide optical Glass, halogen Glass, fluoride Glass, optical ceramics,

mono- and poly-crystalline materials, polymers and liquid crystals. In mirror optics, pyroceramic materials based on $SiO_2$ – $Al_2O_3$ – $LiO_2$ – $TiO_2$ are used. They can be characterized by low thermal expansion coefficient, low short wave light transmittance and yellow dye. They can be applied in mirrors of long diameters, even up to 4 m [3].

Intelligent systems apply smooth surface of good electric conductors (usually metals) for directional reflection, with the reflection coefficient approaching $\rho \cong 90 - 95\%$ and in some cases more than 99%. This reflection is accompanied by absorption but the depth is smaller than incident radiation wave length and the conversion into heat is low, however the color can change slightly but less intensively at incident angles of 90°.

Highly reflective metal surfaces such as Al i Ag show bright silver color in white light because the number of photons reemitted by these metals is more or less the same as in the incident beam. Because photons of short wave length are not reemitted by Au and Cu, that is why they have red-orange dye. The other metals of low corrosiveness such as rhodium and platinum have lower reflectance. All metals have low thermal emissivity $E_{temp}$.

Dielectrics reflect either in diffused or in directional way and the coefficient increases along the incident angle. For glass it is $\rho \cong 5\%$.

Light penetrates glass 7 times deeper than metals and thus it is treated as transparent material. Light is selectively absorbed there and it is a kind of a combination of wave length of transmitted beams. The absorption occurs in the result of atom vibrations around their positions and of the excitation of electrons in bands or among them above $E_g$ threshold value.

Technical mirrors made of flotation glass contain iron oxides that reduce $T_{slo}$ in the range of selected wave length. The glass, at waves longer than 0.4 μm, shows uniform transmittance of about 80% but at longer waves of $\lambda \approx 1$ μm shows lower transmittance of $T_{slo}$ between 30% and 60%, but $T_{opt}$ is not changed. The reflectance of boundary surface between air and glass is about 4% within the range of 0,4 μm < $\lambda$ < 2 μm, assuming at the same time that the maximal transmittance of glass in the same range is 92% [1].

The application of thin coatings in the use of solar energy sector is performed to modify optical or other physical properties of the base material. Reflexive coating and transparent insulation layers can be composed of polymers similar to glass but less resistant to degradation. Light diffusion in polymers occurs between crystal and amorphous phases. Appropriate selection of material for high reflective mirrors suggests the assumption that the considered mirrors are made of polished Ag coatings.

## 3. Determination of surface shape for non imaging effects

### 3.1. Determination of angles for mirrors

Non-imaging surfaces is a general name for the surfaces used to reflect light (not necessarily natural) without the result of image. They are mainly used to direct and transport sunlight rays to additionally lighten building interiors. The most frequently used and efficient construction to collect, focus and transmit a beam of solar rays is a system of two concave spherical mirrors and a receiver. The main mirror is designed to concentrate the light and its name is a refraction concentrator but the other one is to direct the beam to receivers of any of the purposes, i.e.: photovoltaic, thermal or lighting. Such systems, however, are not free from disadvantages. The most visible one is shading of the main mirror by a reflective concentrator which is located on the way of the beam. There is also another problem to avoid i.e.: the generation of dark areas in the bottom spherical mirror by the receiver of light [4].

The principle aspect in design is an appropriate shape of mirror surfaces in order to maximize both beams – the collected beam and the concentrated one. The first one depends on the size and shape but the second one mainly on its shape. As a rule, if all edge rays are well traced then the others are also managed [5]. This is presented in Fig. 1 where the rays reflected from subsequent points: M, T and K, S hit the target receiver. The general formula describing the mirror surface is Eq. 7:

$$y = \alpha + \beta + \chi x + \delta x^2 + \varepsilon x^3 + \phi x^4 + \tag{7}$$

where: $\alpha, \beta, \chi, \delta, \varepsilon, \phi$ are values describing the mirror top point, mirror curvature center, mirror focus etc. The values can be determined as much as needed to solve computational problems. For the purpose of the presentation of this example and because of numerous variables, a simplified method is described in the paper. The method shows the determination of the arc curvature along ST distance. The accuracy of computations is not influenced this way. The initial definition of coordinates makes possible to define the bottom mirror:

$$M(-R, \frac{R^2}{4L}),\ K(-r, \frac{r^2}{4L}),\ K'(-r, \frac{r^2}{4L}),\ F(0, L),\ P(0, \frac{r^2}{4L}). \tag{8}$$

The following formulae (Eq. 9-15), to determine inclination angles of particular curves, can be used to plot the mirror curvature.

On ST distance the formula $y = sx + \lambda s$ used and the values: $s_1, s_2, s_3, s_4$ define inclination angles of reflected rays, $s_c$ nd $s_d$ re inclination angles of tangent lines to ST curie, respectively in points S and T [4].

$$s_1 = \frac{L}{r} - \frac{r}{4L} \tag{9}$$

$$s_2 = \frac{L}{r} - \frac{R}{4L} \tag{10}$$

$$s_3 = \frac{\left(4L^2 - r^2\right)\left(4L\lambda - r^2 - 4Lkr\right)}{16L^2 R\left(\lambda - L\right)} \tag{11}$$

$$s_4 = \frac{4L\left(4L^2 - R^2\right)\left(\lambda - L\right) + \left(4L\lambda - R^2 - 4Lkr\right)}{16L^2 R\left(\lambda - L\right) - 4Lr\left(4L^2 - R^2 - 4LRk\right)} \tag{12}$$

$$s_c = s \tag{13}$$
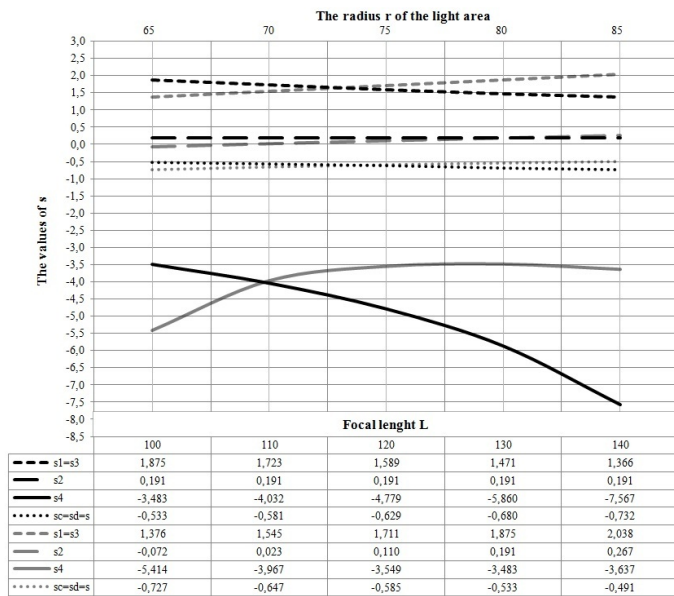
$$s_d = s \qquad (14)$$

$$s = -\frac{1}{s_1} \qquad (15)$$

The relations between (Eq. 9-15) are used for curve simulations for the reflective concentrator and the refraction concentrator. Their mutual relation is then composed as presented in Eq. 16.

$$\left| \frac{s_1 - s_c}{1 + s_1 s_c} \right| = \left| \frac{s_4 - s_d}{1 + s_4 s_d} \right| \qquad (16)$$

TABLE 1

Simulation of s coefficient vs. focal *L* and radius *r*



| | 100 | 110 | 120 | 130 | 140 |
|---|---|---|---|---|---|
| ▪ ▪ ▪ s1=s3 | 1,875 | 1,723 | 1,589 | 1,471 | 1,366 |
| ▬ s2 | 0,191 | 0,191 | 0,191 | 0,191 | 0,191 |
| ▬ s4 | -3,483 | -4,032 | -4,779 | -5,860 | -7,567 |
| ⋯ sc=sd=s | -0,533 | -0,581 | -0,629 | -0,680 | -0,732 |
| ▪ ▪ s1=s3 | 1,376 | 1,545 | 1,711 | 1,875 | 2,038 |
| ▬ s2 | -0,072 | 0,023 | 0,110 | 0,191 | 0,267 |
| ▬ s4 | -5,414 | -3,967 | -3,549 | -3,483 | -3,637 |
| ⋯ sc=sd=s | -0,727 | -0,647 | -0,585 | -0,533 | -0,491 |

The graph presented in Tab. 1, demonstrates the waveform of inclination angles determining mirror curvatures: $s_1, s_2, s_3, s_4, s_c, s_d$ *n* dependence on the focal and on the radius. This simplified simulation distinguishes different $s_3$ waveform within the range of *L* from 100 to 140 mm and the range of *r* from 65 to 85 mm.

### 3.2. Simulation of results

The simulation of shape at different locations of lenses is presented in Fig. 1, in dependence on gradual elongation of the radius *r* length in the concentrating and transmitting system of natural light. The computations are carried out by means of a simplified model for a half of the top reflexive lens. The simulation tool is AutoCad and the scale is maintained.

The coordinates of points: M, K, K', P, F, previously determined by means of Eq. 8, is coefficients from Eq. (9-16) and the line described by $y = sx + \lambda$ ave been the basis to find points: S and T. These points define the location and the angle of the top lens. The hypothetic shape of the bottom mirror was determined on the basis of computed coordinates of M, K, K'. The figure presents only the edge rays pointing the refraction concentrator and only five values of the radius, from the series of computations, for the visibility of this image. Computations assume radius lengths *R* = 225 mm for the bigger mirror, focal lengths 140 mm, and radius lengths within the range of *r* = 65 − 85 mm for the target receiver, presented every 5 mm. The presented image is the resultant of all and makes the visualization of geometric effects, clear.
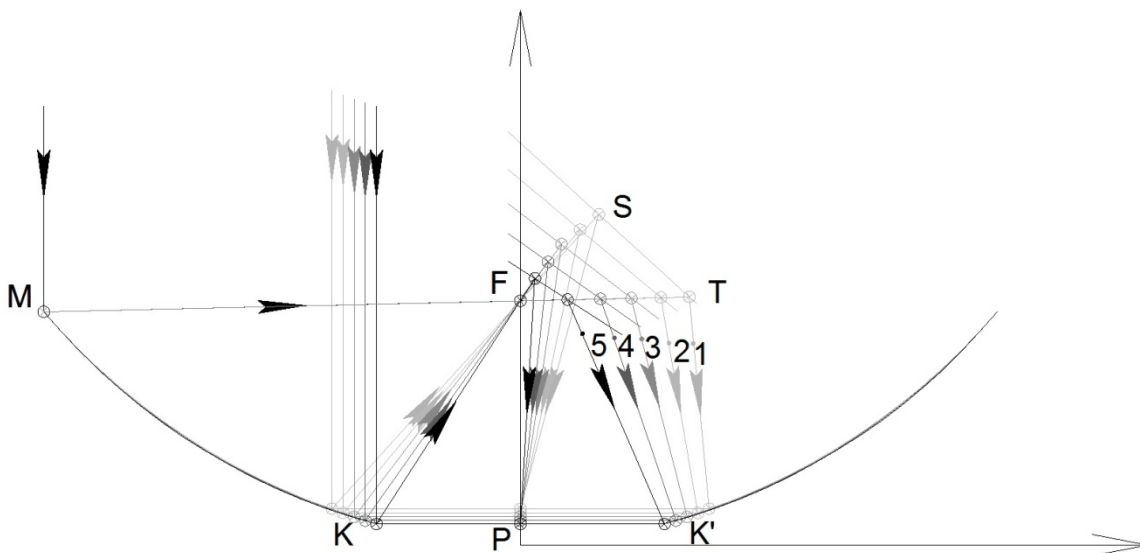


Fig. 1. Curves of mirror surfaces at different radius lengths: 1 − *r* = 85 mm, 2 − *r* = 80 mm, 3 − *r* = 75 mm, 4 − *r* = 70 mm, 5 − *r* = 65 mm

### 4. Conclusions

The results within this research presentation indicate that direction of light at changeable radius of PV reciver area determines the shape and the location of both mirrors. Moreover, the angle of reflection value (from the main mirror) is changed along the focal and radius length in ranges, such as the reflection. The top lens is tilted from the Y-axis at smaller angle to

the X-axis. Thus the purpose for the sharpening of surface curves is to eliminate the dark (shadowed) areas to improve the uniformity of illumination in rooms. The non-imaging surface can be determined by means of s coefficients which has been graphically presented and is important for design purposes. The presented method is simplified and if this model was applied approximately a quarter of the beam would be diffused around would miss the target area to illuminate. The cubic simulation and the simulation of reflection coefficients is then appropriate for technical design in practice but this simplified method can help to established the range of mirrors and their distribution in systems of light direction.The described computational case is met exclusively for the Upper mirror, the shape of which has been constructed by the rotation, around the symmetry axis, of the straight line described by the formula $y = sx + \lambda$. The other possible solution is the construction of the second mirror by means of the rotation of the curve described by the quadratic function formula $y = y_0 - \dfrac{(x+a)^2}{4l}$. The third remaining possible solution is the rotation of another curve but described by a cubic space function of $y = \alpha + \beta(x + \gamma)^3$. There are remaining problems to be solved then, i.e.: what is the optimal shape of the upper mirror created by means of parabolic rotation, so as the whole reflected beam reached the solar energy receiver. This question is to be considered in two separate computational cases, taking into account the possible way of the light beam in established environment boundary conditions. The rules of reflection define the geometry where the first case is the range of direction of reflected beam towards the whole receiver diameter and the second one is when the whole beam fits in the area of the receiver radius. The dispersive influence of the environment can also be taken into the account in more dynamic simulations.

The range of obtained results is relevant to the established purpose for the series of research, i.e. the design of an experimental system of light concentration and direction in the Faculty of Technology Fundamentals, LUT to illuminate the dark areas in the building interior with natural light.

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