Research Paper Building & Energy

TOPIC – Empirically Establishing Optimum Shape of PMMA Rod For Daylight Harvesting

*** Prof. Pavan Godiawala**	B.E. Mechanical, M.Sc. Manufacturing Management. Department of Fashion Technology, National Institute of Fashion Technology Gandhinagar
Prof. Dr. Noopur Anand	M.Sc. Textile and Clothing; PhD; Department of Fashion Technology, National Institute of Fashion Technology New Delhi
Dr. Jayantilal Mathurbhai Patel	B.E.-M.E. Mechanical Engineering, PhD. Department of Mechanical Engineering, L. D. College of Engineering; Ahmedabad

ABSTRACT

For a daylight transmission a comparison is made between cylindrical PMMA rod and cuboidal PMMA rod for light transmission. Universally it has been observed that cylindrical PMMA rods are preferred for better transmission efficiency. On different diameter of cylindrical and cuboidal rods, experiments were conducted and based on the experimental results it has been proved that there is a possibility to transmit diffused light in exposed surface of cuboidal PMMA rod in open environment where diffused light is also available with direct sun light and cuboidal rods give substantially more efficiency than circular rod of same size. This increase of efficiency with size has an exponential growth. By adopting this shape for higher efficiency light transmission daylight can be transmitted in interior part of the buildings for lighting purposes and in turn curtail pollution and high electricity running cost along with increased wellbeing of the occupants. To a certain extent it also answers the inconsistent availability of direct sunlight throughout the day and across the weather, due to its ability to transmit diffused light.

KEYWORDS Day lighting, Lighting, Sustainable Energy, Energy harvesting, PMMA rod

I. INTRODUCTION

An array of benefits that sun light beholds has led to profound research in the field of daylight harvesting and innovations. The world has seen it all from a simple louver and blind system to the most sophisticated solar tracker fitted optical fiber system. These systems have enabled to the mankind to achieve a production of 4,699.2TWh in 2012 clean energy from solar power, of which solar energy contributes 2.2% which is 104.5 TWh.Considering the total global energy production of 22,613.0 TWh this is a miniscule amount of energy being produced in sustainable manner.

Since the concern of depleting fossil fuel and in turn affected environment is a major concern. Trend shows there is a growth in energy produced from three segments solar, wind and bio fuel. The positive aspect here being the mean annual growth rate of solar energy production has been 50.6% from 2002 to 2012 and is the fastest growing energy source. Harvesting energy from solar power is not just showing a positive growth but is exponential in nature and has been reported to grow at a rate of 65.5%in the year2011-12.

Solar energy finds immense utility in areas of electricity production, thermal power and cooking thus replacing the usage of fossil fuel in a big way.The major contributor to solar energy generation is photo voltaic cellwhich converts solar power to electricity but PV cells have their own limitations and are not very eco-friendly in terms of disposal after their life term of usage is over.An area of recent development in harvesting solar energy is implementing the concept of concentrated solar power to direct sunlight in work space and replace artificial lighting systems. This system has been developing by leaps and bounds but still faces the challenge of lighting areas with densely populated buildings and reaching deep interiors of buildings. Mostly the systems that are available commercially transmit light by vertical structures from roof top, and are pipes that deliver light by the process of multiple reflections. A major breakthrough in this field has been the identification of Polymethyl methacrylate (PMMA) as a potential material with ability to effectively transmit light to a greater length owing to its properties of hightransmittance due to high total internal reflection.Added advantages to PMMA are its physical characteristics of high melting point and its resistance to infrared rays, rendering it a long effective life. Since PMMA rods are effective in transmitting light it is need of the hour to explore in the direction of increasing the effectiveness of light transmission through these rods and identify the optimal shape which can give best efficiency.

II. THEORY

In a process of transmission of light in a transparent material three things take place reflection, transmission and absorption. There are three types of reflections specular, spread and diffused.

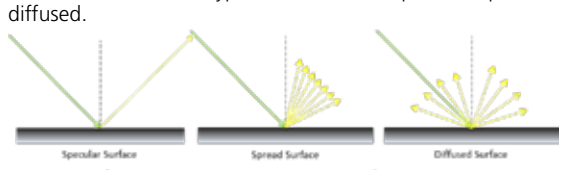


Figure 2.1 – Three reflections depending on surface finish

In case of transmission due to the density of material in which light is travelling the velocity gets changed as per the Snell's law:

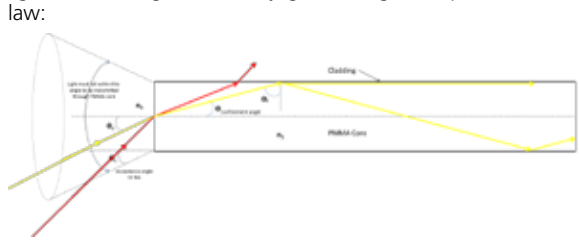


Figure 2.2 – Total Internal Reflection Process

Θ_c– Acceptance angle or critical angle

Θ– Confinement angle
Θ_i– (90 - Θ)
n_0– Refractive index of cladding (in this case "air")
n_1 – Refractive index of core (in this case "PMMA")
The critical angle (Θ_c) can be deduced from Snell's law:

$$NA = n_0 SIN\ \Theta_c = n_1\ SIN\ \Theta \quad [1]$$

$$NA = \sqrt{(n_0^2 - n_1^2)} \quad [2]$$

$$n_1^2 - n_2^2 = 1 \quad [3]$$

As per lambert's law of absorption the light doesn't get transmitted completely but apart of it also gets absorbed. Usually it gets converted to heat.

$$I = I0e^{-\alpha x} \quad [4]$$

Snell's law clearly describes that the light travelling from the material with a higher index of refraction to 1 with a lower index of refraction, the reflected light bends away from the normal. This leads to the light getting reflected along the boundaries. Due to the light reflected between the boundaries it gets transmitted with a minimum loss. This phenomenon is called total internal reflection. The angle at which the internal reflection takes place is known as critical angle Θ_c.To ascertain minimum transmission losses usually boundaries of transmitting material is cladded by material with lower refractive index.

In PMMA rod if the outer boundaries are polished and then buffed with appropriate cloth wheels the surface becomes a specular reflective surface and any light striking on it gets reflected and not refracted to other medium, thus is transmitted further in rod. Here the loss is absorption loss only.

Since in case of daylight harvesting the light source is not a point source and is constantly on a move it becomes a matter of priority to ascertain which angle and which band of incident light will be imbibed by the PMMA rod. Here the concept of numerical aperture comes into play. Numerical aperture (NA) is a dimensionless number denoting the angle, the rays passing through which can be accepted or emitted. Specifically in case of optical fiber studies NA plays an important role to determine the angle of incidence of light so as to achieve maximum transmission through total internal reflection, with minimum loss.

III. EXPLORATION

An empirical path was taken to establish the optimal shape of PMMA rod for daylight harvesting and the process of exploration proceeded logically based on the results and inferences from the preceding experiment. The central setup used for experimenting purpose was Scaled down model of an industrial space which was a box of 12"X12"X12". Based on the observation the industrial work space or office spaces are usually dimensioned 12'X12'X12' and even the lightings are placed at a distance less than 12' and an approximate height of 9'. Same room size was replicated by using a ply wood of 5mm thickness. In this artificial room there were no windows just one opening was created at the top for insertion of the PMMA rods. At the bottom of the box there was a small opening for passing of the lux meter wire. A proper sealing was used so no light was penetrating through anywhere in the box except from desired source for all experimentations. While selecting the inside color it was considered that many of the factories have light color on ceiling and walls so off-white color has been used inside the artificial room.

A light intensity measuring device, Lux meter was used for measuring brightness of light incident on its sensor placed at various coordinates of the model to ascertain the light transmission and spread. The experimental setup has been illustrated in Figure 3.1.

The experiments conducted for initial conceptual clarity to observe the light transmission pattern was conducted in artificial light, whereas all other experiments were conducted in natural sunlight as it is difficult to replicate sunlight in a controlled environment.

Light reading measurements were taken on defined coordinates in the model space to study the illumination of room for a particular PMMA rod. Placement of rod and the considered illumination measurement coordinates are shown diagrammatically below in Figure 3.2.

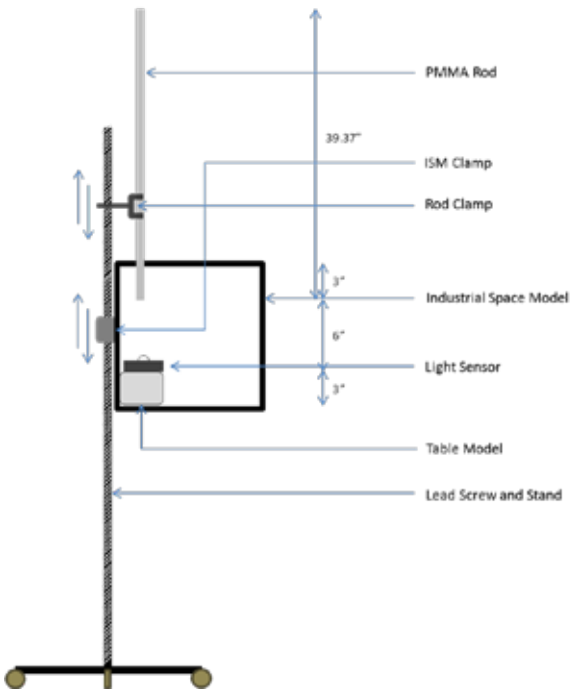


Figure 3.1 – Experimental setup cross sectional side view

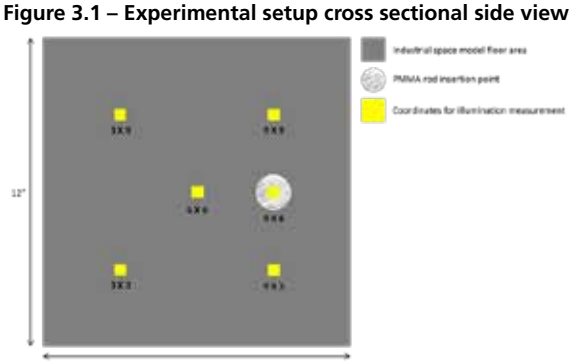


Figure 3.2 – Top view of placement of light intensity measuring points and PMMA rod

At initial stage a comparative study was done to study the performance of PMMA rods in light transmission. This experiment was conducted with artificial light to study the characteristics of the transmitted light through the PMMA rods. For this experiment six PMMA rods were considered with two shapes and two varied sizes of each the considered shapes were cuboidal and cylindrical whereas the face sizes used were 12mm X 12mm and 25mm X 25mm.

These rods were positioned 9" above the surface and artificial light from an LED light source was incident upon it. The transmitted light characteristics were observed, as shown in Figure 3.3.

It was observed that the light transmitted was not uniform from either cylindrical or cuboidal PMMA rods. There was for-

mation of concentric light and shadow rings which made recording of exact luminosity at any point difficult to establish, neither this kind of transmission would be acceptable by industrial standards of lighting.



Figure 3.3 – Light transmitted in a non-uniform pattern through PMMA rods

To quantify the transmission of light through various PMMA rods it was required that the transmitted light must be evenly spread across after emission. This was achieved frosting one end of the rod by sand blasting it. A specimen is shown in the Figure 3.4.



Figure 3.4 – Frost end of PMMA rods after sand blasting

Next study the intensity of transmitted light through PMMA rods was done in natural light at mid-day with frost end rods placed within the space model. The experimental setup was as, the space model was clamped on a vertical stand and the PMMA rods were inserted from top surface, clamped to the same stand. The rods used for this study purpose and their performance are listed in Table 3.1.

The PMMA rods were inserted 3" inside the space model one after the other in the space model and illumination reading noted for previously defined coordinates on the bottom surface and an average reading was considered for comparing the light transmission of the rods. In the duration of the experiment the external illumination level was in a range of 57,300 – 58,800 lux on 5th march 2014 between 2:00PM to 2:45PM. The lux meter was 6" away from the fag end of the 1 mater long PMMA rod.

PMMA Rod (Face dimension)	Average Reading (Lux)	Efficiency %
0.01m Circle	59.17	0.10%
0.01m Square	103.17	0.18%
0.02m Circle	254.17	0.45%
0.02m Square	254.83	0.47%
0.03m Circle	826.83	1.41%
0.03m Square	1243.50	2.17%

Table 3.1 – Transmission efficiency of frosted PMMA rods

It can be clearly inferred from the above data that cuboidal PMMA rod has a substantially better efficiency than cylindrical PMMA rod in terms of light transmission.

An analysis in the above matter can be done by comparing the surface area of the side of PMMA rods on which the light is incident. This comparison shows that the surface area of face of cylindrical rod is 21.5% less than that of the cuboidal rod thus the aperture for previous rod is less than later, hence imbibing less light for transmission. The comparative analysis of surface area of faces of both rods is illustrated graphically in Figure 3.5.

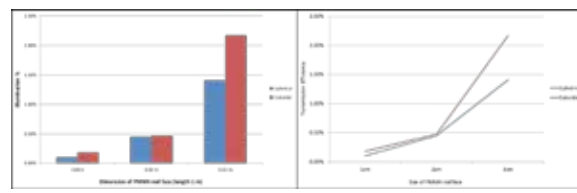
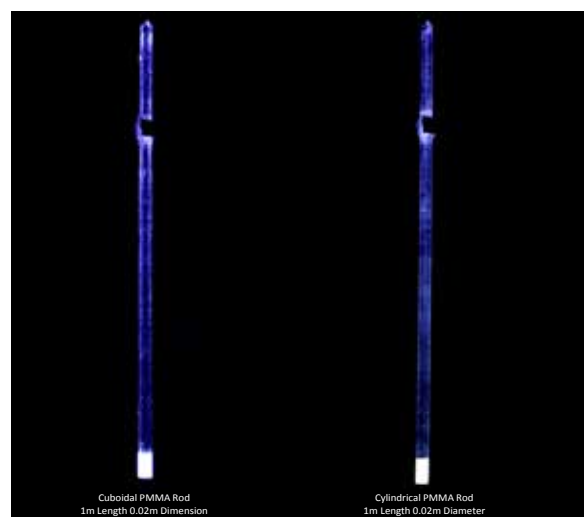


Figure 3.5 – Graphical comparison of frosted PMMA rods' light transmission efficiency

To understand the light transmission in PMMA rod, point source light was passes from cuboidal and cylindrical rod in a dark room and imgae was captured as below mentioned parametrs by an DSLR camera. It was clearly observed that there was higher transmission loss in cuboidal rod from the edges than the cylindrical rod. The illustration of qualitative analysis of the cuboidal and cylindrical rods is shown in Figure 3.6.



Parameters	Specifications	Parameters	Specifications
Input Light	900 lux	Exposure Mode	Manual
Image format	RAW (12-bit)	Metering	Spot
Device	Nikon D3200	ISO	100
Lens	VR 18-55mm f/3.5-5.6G	White Balance	Cool-White fluoroscent 0,0
Aperture	f/22	Colour Space	Adobe RGB
Shutter Speed	30sec	Picture Control	Vivid

Figure 3.6 – Light loss comparison in cuboidal and cylindrical PMMA rods

The next step was to compare the cylindrical and cuboidal PMMA rods in fully covered and full open state to ascertain the effect of diffused light on transmission efficiency. Here the PMMA rods were first fully covered on the side faces by aluminum foil, artificial light incident perpendicular on the top face and intensity of transmitted light observed at the bottom. Same cycle of experiment was repeated with the side faces fully opened. The observed efficiency has been plotted as a graph for analysis in Figure 3.7and the respective value shown in Table 3.2.

Covering of Rod	1 cm	2 cm	3 cm

Fully open Cuboidal	69%	73%	80%
Fully open Cylindrical	56%	69%	78%
Fully closed Cuboidal	55%	72%	79%
Fully closed Cylindrical	65%	76%	83%

Table 3.2 – Observation of fully open and covered cuboidal and cylindrical PMMA rods' light transmission efficiency

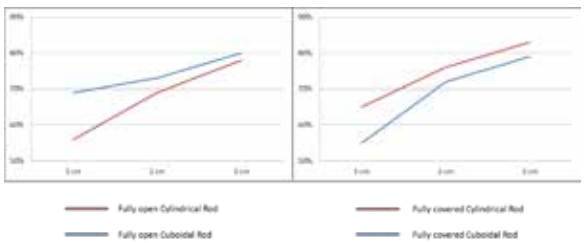


Figure 3.7 – Graphical comparison of fully open and covered cuboidal and cylindrical PMMA rods' light transmission efficiency

For a cylindrical rod the aperture area is $\prod*R^2$ and the rod surface area is $2*\prod*R*L$ and for cuboidal rod the aperture area is W^2 and surface area is $4*L*W$. Here, L is length of the rod, W is width of the rod and R is radius of the cylindrical rod. By calculating the aperture area and the surface area of all the rods it is evident that the difference of area between cuboidal and cylindrical rod is 21.5%, both for surface as well as aperture area.

III. CONCLUSION

PMMA rods of cuboidal and cylindrical shapes have been assessed on light transmittance capabilities and the experimental results seen to be in tandem with the laws of optical physics the cylindrical rod has better transmission efficiency than cuboidal rod when light in directly incident on the aperture. Whereas when diffused light is present along with incident light cuboidal rod shows better efficiency than cylindrical rod. This increase in efficiency of the cuboidal PMMA rod is due to its unique characteristics of imbibing and transmitting the diffused light incident on the lateral surface of the rod at critical angle. Sinceanalytical assessmentof cuboidal rod having 21.5% more aperture and surface area than cylindrical rod contributes to a higher intake and transmitting of light, demonstrating a higher efficiency. This also indicates that intake and transmission is substantially more than transmission loss of incident light in case of cuboidal PMMA rod.

This concludes that the cuboidal PMMA rod with more surface area exposed to diffused light will transmit with better efficiency compared to cylindrical rods of similar dimension. In design of daylight harvesting equipment area which is exposed to sunlight must have cuboidal shape to take an advantage of diffused sunlight transmission along with the incident sunlight transmission and inside the building transmission light transmission device should have cylindrical shape for optimal transmission efficiency, and to a certain extent it will also improve the performance in cloudy sky or overcast sky conditions.

REFERENCES

[ ]Paris.Observ'ER and Foundation Energies pour le Monde, (2013) Worldwide Electricity Production from Renewable Energy Sources, Paris: rue de l'Universite | [ ]Paris.Observ'ER and Foundation Energies pour le Monde, (2013) Worldwide Electricity Production from Renewable Energy Sources, Paris: rue de l'Universite | [ ]Paris.Observ'ER and Foundation Energies pour le Monde, (2013) Worldwide Electricity Production from Renewable Energy Sources, Paris: rue de l'Universite | [ ]Paris.Observ'ER and Foundation Energies pour le Monde, (2013) Worldwide Electricity Production from Renewable Energy Sources, Paris: rue de l'Universite | [ ]Paris.Observ'ER and Foundation Energies pour le Monde, (2013) Worldwide Electricity Production from Renewable Energy Sources, Paris: rue de l'Universite | [ ]Alexander D. Ryer, 1998, Light Measurement Handbook, United States of America, International Light, Inc. | [ ]Born and Wolf, 1999, Principles of Optics, United Kingdom, The Press Syndicate of the University of Cambridge | [ ]Callow, J. &Show, L., (2002).Performance of air-clad optical rod daylighting system. Right Light, n.a., 441 - 446 | [ ]Born and Wolf, 1999, Principles of Optics, United Kingdom, The Press Syndicate of the University of Cambridge | [ ]Born and Wolf, 1999, Principles of Optics, United Kingdom, The Press Syndicate of the University of Cambridge | [ ]Callow, J. & Show, L., (2002).Performance of air-clad optical rod daylighting system. Right Light, n.a., 441 - 446 | [13]Magda Havas, M.; Hutchinson, T. (2008) Environmental and Health Concerns Associated with Compact Fluorescent Lights. [Online] June 2008. Available from: http://gogreen-solutions.com/wp-content/uploads/2012/01/Lighting-Heath-Study-Dr.-Magda-Havas.pdf . [Accessed: 23rd Feb 2014] | [14]Boyce, P.; Hunter, C.; Howlett, O.(2013) The Benefits of Daylight through Windows. [Online] September, 2013. Available from: http://www.usp.br/fau/cursos/graduacao/arq_urbanismo/disciplinas/aut0213/Arquivos_Anteriores/Publicacoes_e_Referencias_Eletronicas/The_Benefits_Of_Daylight_Through_Windows.pdf. [Accessed: 25th Feb 2014] |