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Optical Engineering for Day lighting Illumination System

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ABSTRACT

In this research, solar illumination is suggested to be used as an alternative to regular electrical illumination sources. Sunlight rays are collected, concentrated and transported through a system of light guide which distributes the sunlight to interior rooms. Schmidt Cassegrainin arrangement is used in the optical solar system design. Optical solar system consists of a tracking parabolic dish as a primary reflector, suggested to concentrate the solar rays on a secondary reflector, a cold mirror, which splits the solar spectrum into visible light which is reflected, directed into a plastic optical fiber cable, and infrared radiation which is transmitted away from the optical system to avoid melting the plastic optical fiber. An optimum optical design is attained by considering the optimum following parameters: applying different dish rim angles, different dish diameters and different dish reflector materials. Sun spot diameter to plastic optical fiber diameter ratio is a measure of geometrical compatibility of optimum transmitting solar light through the optical system.

Keywords: Sunlight, Parabolic dish, Rim angle, Cold mirror, Plastic optical fiber.

الهندسة البصرية لمنظومة الاستضاءة بالانارة النهارية

الخلاصة

تم في هذا البحث اقتراح استخدام الانارة الشمسية بديل لمصادر الانارة الكهربائية الاعتيادية. تجميع و تركيز الاشعة الشمسية ومن ثم نقلها عبر منظومة بصرية تتضمن دليل ضوئي, ليف بصري بلاستيكي, ليتم توزيعه الى داخل الغرف. يدخل طراز شمت كاسكرين في التصميم البصري للمنظومة الشمسية. تتألف المنظومة البصرية الشمسية من طبق متتبع يعمل كعاكس اولي يقوم بتركيز الاشعة الشمسية على العاكس الثانوي و المعروف بالمرآة الباردة. تقوم المرآة الباردة بفصل الطيف الشمسي الى جزئين: جزء مرئي تقوم بعكسه و توجيهه الى حزمة من الليف البصري البلاستيكي, و جزء الاشعة تحت الحمراء الذي تقوم بتنفيذه بعيدا عن المنظومة البصرية لحمايتها من الانصهار. تم احراز تصميم بصري مثالي من خلال اخذ المعلمات الاتية بنظر الاعتبار للطبق: اعتماد زوايا حافة مختلفة, انصاف اقطار مختلفة و مواد عاكسة مختلفة. تم اتخاذ نسبة قطر بقعة صورة الشمس الى قطر الليف البصري البلاستيكي كمقياس للتوافق الهندسي الامثل لانتقال ضوء الشمس عبر المنظومة البصرية.

INTRODUCTION

Attempts to integrate optical fibers into solar energy systems began in the mid-seventies [1] and continued with the concise work of Cariou et. al. in the early 80th [2],[3] and others [4],[5], [6],[7],[8]. However, these attempts have not yet been utilized successfully in major energy consuming applications such as the power generation industry. The reasons can be traced to the high cost of fibers, low numerical aperture (low solar energy concentration in the fiber) of the fibers that were considered, and the absence of receiver technology that can fully utilize the geometrical flexibility of optical fibers to improve the system efficiency. These limitations may be alleviated due to recent advances in fiber technology. Driven mostly by the communication market, the fiber industry has grown significantly during the 90's, leading to a significant reduction in fiber cost and improvement in fiber performance. Recent progress in optical fibers for indoor lighting may also be useful for solar energy, since the requirements for solar energy applications are much closer to those for lighting fibers than to communication fibers. The third issue is addressed by recent developments in a high temperature solar receivers [9],[10] opening the way to benefit from the unique geometrical flexibility of optical fibers.

PRINCIPLE OF OPERATION

Schmidt Cassegrainin arrangement is used in the optical solar system design. Optical solar system consists of a tracking parabolic dish as a primary reflector, suggested to concentrate the solar rays on a secondary reflector, a cold mirror, which splits the solar spectrum into visible light which is reflected, directed into a plastic optical fiber cable, and infrared radiation which is transmitted away from the optical system. The solar lighting system uses a roof-mounted solar collector, see Figure (1) to concentrate visible sunlight into a bundle of plastic optical fibers. The optical fibers penetrate the roof and distribute the sunlight to multiple luminaries within the building. The hybrid luminaries blend the natural light with artificial light (of variable intensity) to maintain a constant level of room lighting.

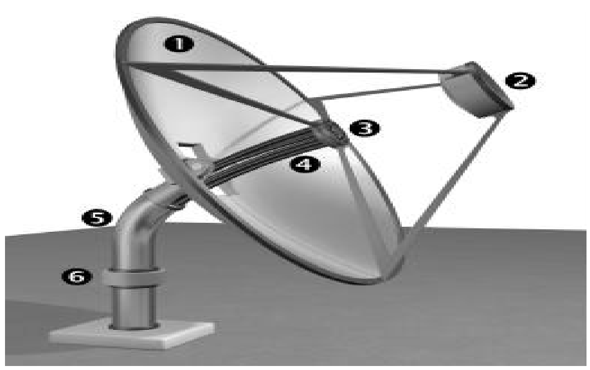


Figure (1) shows solar lighting system, where 1 is primary reflector, 2 is secondary reflector, 3 is fiber mount, 4 is large core optical fiber, 5 is angled stand with altitude tracking mechanism, and 6 is azimuth tracking mechanism [11].

When sunlight is plentiful, the fiber optics in the luminaries provides all or most of the light needed in an area. During times of little or no sunlight, a sensor controls the intensity of the artificial lamps to maintain a desired illumination level. Unlike conventional electric lamps, the natural light produces little to no waste heat, having an efficacy of 200 lumens/Watt and is cool to the touch. This is because the system's solar collector removes the infrared (IR) light from the sunlight— the part of the spectrum that generates much of the heat in conventional bulbs. Because the optical fibers lose light as their length increases, it makes sense right now to use hybrid solar lighting in top-story or single-story spaces [12].

SOLAR LIGHTING SYSTEM KEY COMPONENTS

Designing solar lighting system needs knowing all technical details of all optical elements composing the system [13], which are:

1 – Primary reflector (dish) coated with highly reflective material of given reflectivity (ρ). The geometrical dimensions should also be given, such as: diameter (d), depth (h), focal length (f),radius of the parabola (p), rim angle (ψ_{rim}), and surface area (A_s),
see Figure (2).

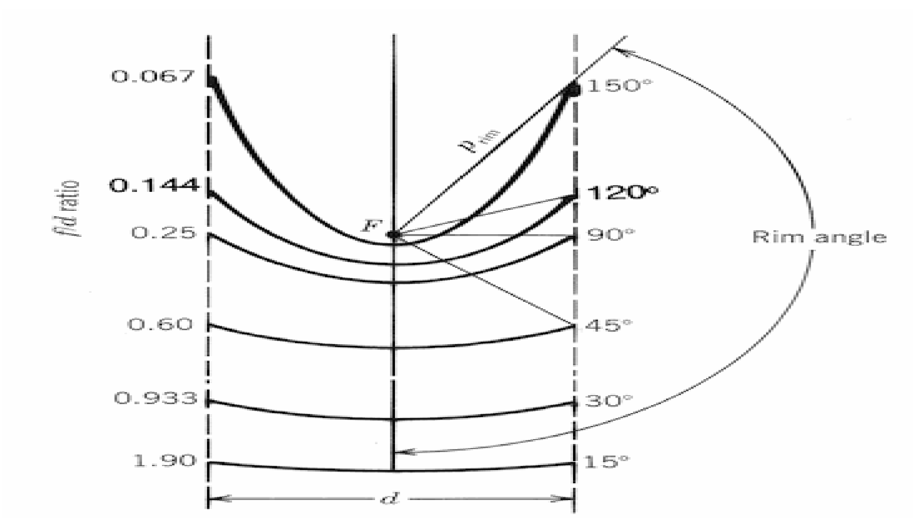


Figure (2) Shows primary reflector (dish) geometrical dimensions [14].

2 – Secondary reflector (cold mirror) is a selective optical element; material of this element is Borosilicate coated glass .Cold mirror is used to separate IR from the solar spectrum. It transmits IR bands (hot band) and reflects visible band (cool light). Transmittance and reflectivity of this element should be given and visible portion percentage should be known.

3 – Plastic optical fiber (POF) is prepared to guide visible light to the interior. POF has large diameter to contain diameter of concentrated sun spot image to maintain high efficiency of this element and also has large numerical aperture, NA. POF has

the type of polymethyl methacrylate, or PMMA. Diameter, length, NA and average attenuation of the POF should be known.

4 – Grooved glass rod is prepared to scatter visible light transmitted from POF. This rod plays the role of a fluorescent tube but without electricity. Grooves on the surface of the glass rod guide the direction of scattered visible light, see Figure (3).

Figure (3) Grooved glass rod for scattering solar visible light [15].

SOLAR DISH TRACKING

Since the concentrator always needs to be perfectly oriented towards the sun, it is mounted on a two-axial tracking system. Therefore a simple movable metal construction holds the solar dish, assisted by two servomotors, for horizontal and vertical orientation towards the sun. The orientation towards the sun is achieved by a sun tracking sensor [16].

Generally, tracking electronics consists of the following:

1. Four photo sensors (The Optical Stage).
2. Amplification Stage.
3. Comparison Stage.
4. Motion Stage.

Optical Stage, it is the sensors, which produce error signals of the tracking sun's path. According to these error signals we can correct the path of the tracking mode and re-center the dish system.

Amplification Stage, it is the next stage, which is responsible for processing the four signals received from the sensors. This process implies to amplify each signal by differential operation amplifier to a level that the next stage can handle it. For this purpose four amplifiers are needed.

Comparison Stage, It is the next stage, which is composed of four comparators, each two of them are responsible for processing the signals received from the up or down direction, while the other two are responsible for processing the signals received from the right or left direction.

Motion Stage, solar dish re-centering is fulfilled through moving (X-Y) dual servomotors. Command signals of (X-Y) servomotors are external which are received from the four sensors.

SYSTEM DESIGN FORMULATION

Reflecting dish, the primary reflector, is constrained by the following parameters which are given in the following equation which specifies the optical efficiency of the reflecting dish, $\boldsymbol{\eta_{Disht}}$ [14]:

$$\eta_{Disht} = \rho_{Dish}\,\Gamma \qquad \dots (1)$$

Where $\boldsymbol{\rho}$ is reflectivity and $\boldsymbol{\Gamma}$ is capture fraction.

Cold mirror, the secondary reflector, optical efficiency $\boldsymbol{\eta_{CM}}$, is given by the following equation [17]:

$$\eta_{CM} = \rho_{CM}\, V_{Spectrum} \qquad \dots(2)$$

where, $\boldsymbol{\rho_{CM}}$ is reflectivity of cold mirror and $\mathbf{V_{Spectrum}}$ is percentage portion of visible light in solar spectrum which is 45 %.

Plastic optical fiber efficiency, $\eta_{POF,}$ is by the following equation [17]:

$$h_{POF} = \left(\frac{A_S}{A_F}\right)\left(10^{-\frac{La_{ù}}{10}}\right) \qquad \dots(3)$$

Where, $\boldsymbol{A_S}$ is sun pot area, $\boldsymbol{A_F}$ is POF aperture area, $\boldsymbol{L}$ is POF length and $\boldsymbol{\alpha_F}$ is POF absorption coefficient.

Scattering Glass Tube optical efficiency, $\boldsymbol{\eta_{SGT,}}$ is given by the following equation [17]:

$$h_{SGT} = \left(\frac{A_S}{A_G}\right)e^{-L_F a_G} \qquad \dots(4)$$

Where, $\boldsymbol{A_G}$ is scattering glass tube aperture area, L_G is length and α_G is absorption coefficient.

Optical efficiency of daylighting illumination system, η_{DIS} is given as:

$$\eta_{DIS} = \eta_{Disht}\,\eta_{CM}\,\eta_{POF}\,\eta_{SGT} \qquad \dots(5)$$

The solar power in unit of Watt emitted from the scattering glass rod is given as [14]:

$$P_{Solar} = I_{Beam}\,Cos(\theta)\,\eta_{DIS}\,A_S \qquad \dots(6)$$

Where $\mathbf{I_{Beam}}$ is solar flux in unit W / m^2, $\boldsymbol{\theta}$ is solar incident angle in unit of radian, $\mathbf{A_S}$ is dish's surface area in unit of m^2.

Equation (6) can be reduced to cancel cosine effect by applying tracking system which makes the concentrator, the dish, always to be perfectly oriented towards the sun as follows:

$$P_{Solar} = I_{Beam}\, \eta_{DIS}\, A_S \qquad ...(7)$$

Since human eye is adapted to see visible spectrum for the interval (380 -780) nm in Lumen unit according to different visibility, V (λ), of each wavelength, λ, [18]:

$$V(\lambda) = 1.019\, e^{-285.4\, (\lambda - 0.559)2} \qquad \ldots (8)$$

Each Watt of 555 nm wavelength corresponds 683 lumen; where this wavelength has the highest visibility by the eye which approaches unity.
For covering the interval (380 -780) nm, namely a luminous term, X_v, of the sunlight, one can integrate the product of the corresponding radiant term, X_λ, by the photopic spectral luminous efficiency, V (λ) as follows:

$$x_n = K_m \int_0^{\infty} X_l V(l)\, d(l) \qquad ...(9)$$

RESULTS AND DISCUSSION

To design a daylighting illumination system which integrates optical fibers into concentrated solar flux, one needs to know the minimum illumination solar components dimensions which achieve an acceptable level of the required photometric human vision in a building; a classroom.

First, one should check the effect of solar dish's rim angle on dish's surface area, focal length, sun's spot diameter, optical fiber core diameter and dish's concentration ratio.

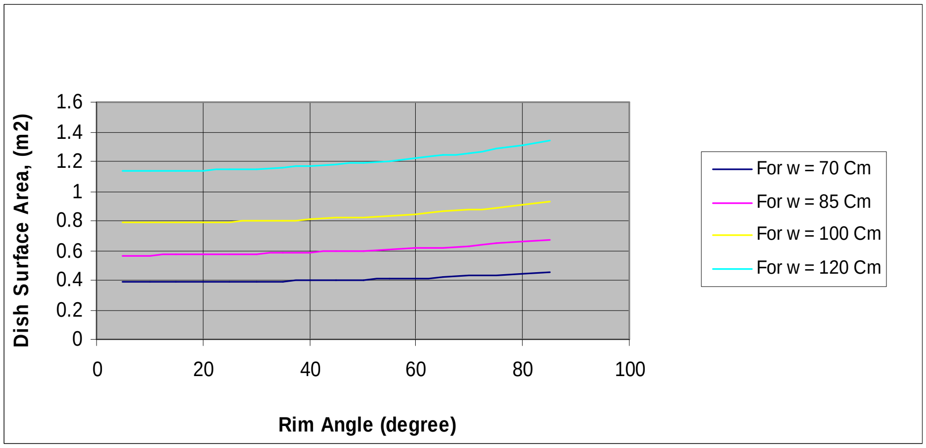


Figure (4) Solar dish's surface areas versus rim angles for different aperture diameters.

It is clear from Figure (4) that as dish's rim angle increases for given aperture diameter, surface area increases too.

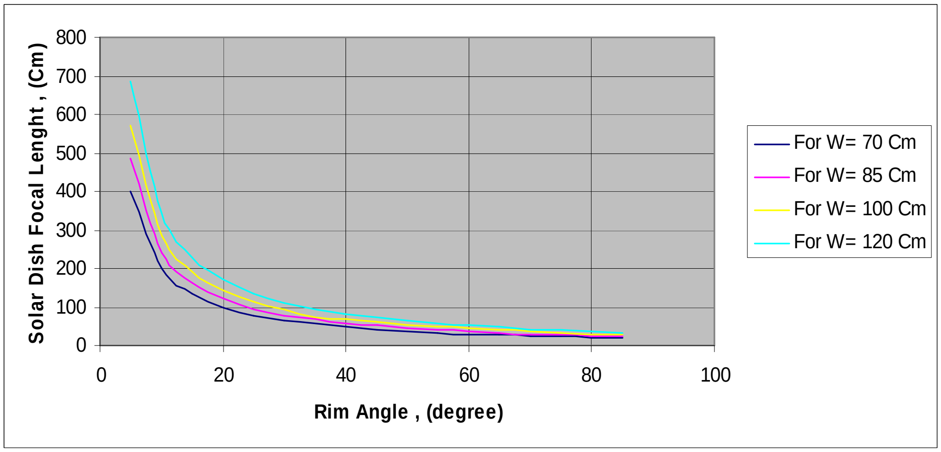


Figure (5) Solar dish's focal lengths versus rim angles for different aperture diameters.

It is clear from Figure (5) that as dish's rim angle increases for given aperture diameter, dish's focal length decreases.

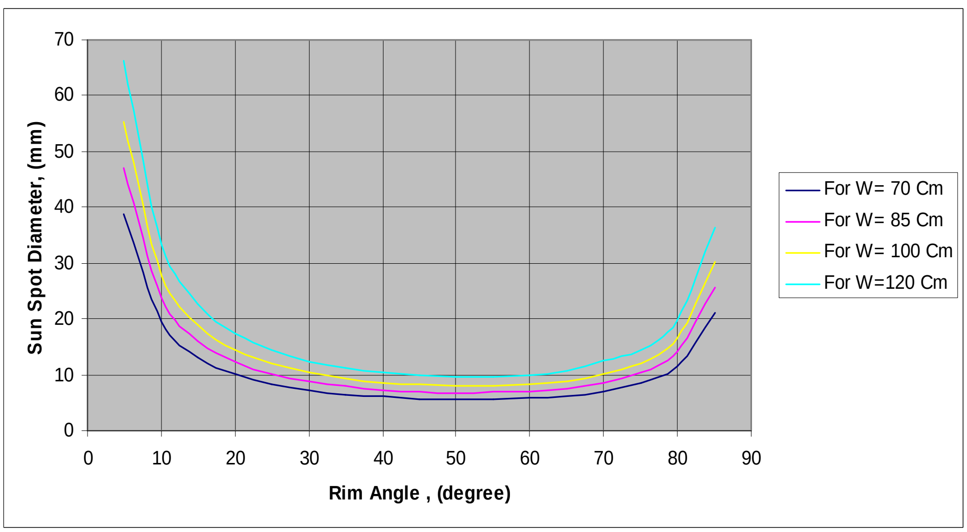


Figure (6) Sun's spot diameter versus rim angles for different aperture diameters.

It is clear from Figure (6) that as dish's rim angle increases for given aperture diameter sun's spot diameter decreases until it reaches rim angle = 55° then sun's spot diameter starting to increase.

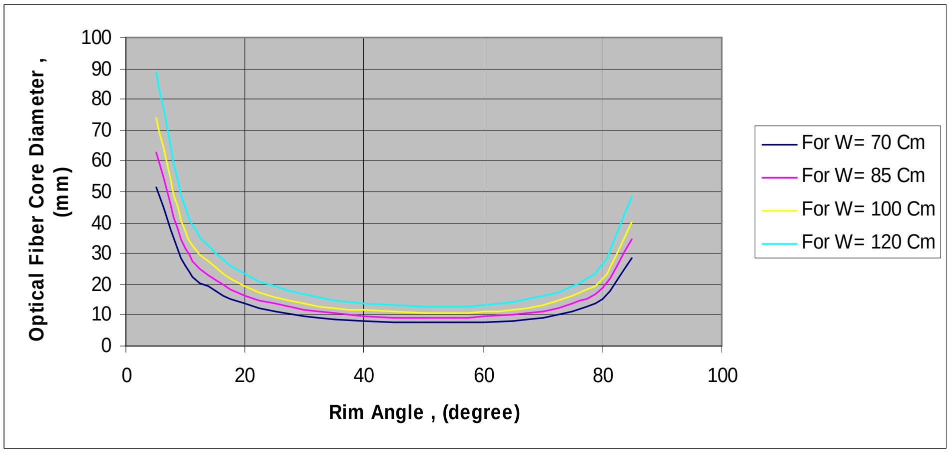


Figure (7) Plastic optical fiber diameter versus rim angles for different aperture diameters.

It is clear from Figure (7) that as dish's rim angle increases for given aperture diameter, required plastic optical fiber diameter decreases until it reaches rim angle = 55° then sun's spot diameter starting to increase.

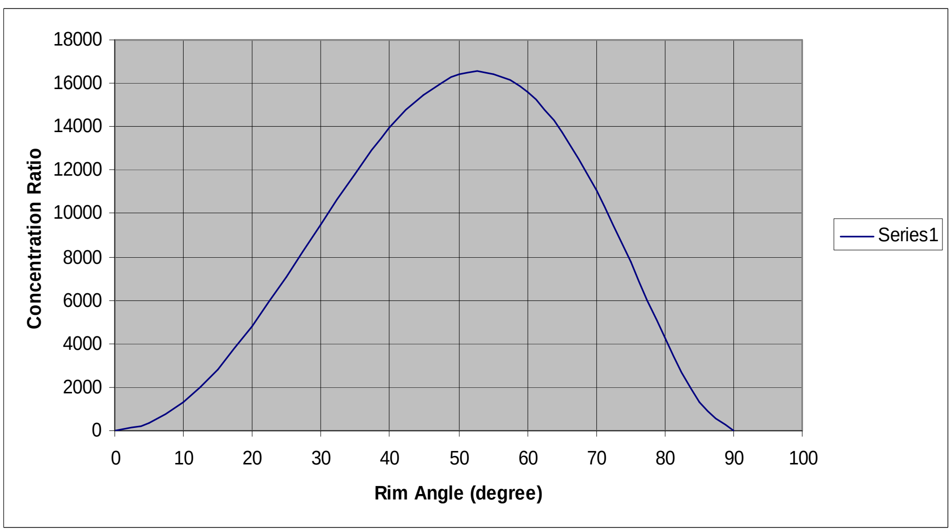


Figure (8) Solar dish's concentration ratio versus rim angles for different aperture diameters.

It is clear from Figure (8) that as dish's rim angle increases, dish's concentration ratio increases until it reaches rim angle = 55° at the peak then sun's spot diameter starting to increase until to reach zero at 90°.

Second, solar dish's surface area coating material should be checked for reflection versus solar spectrum wavelengths.

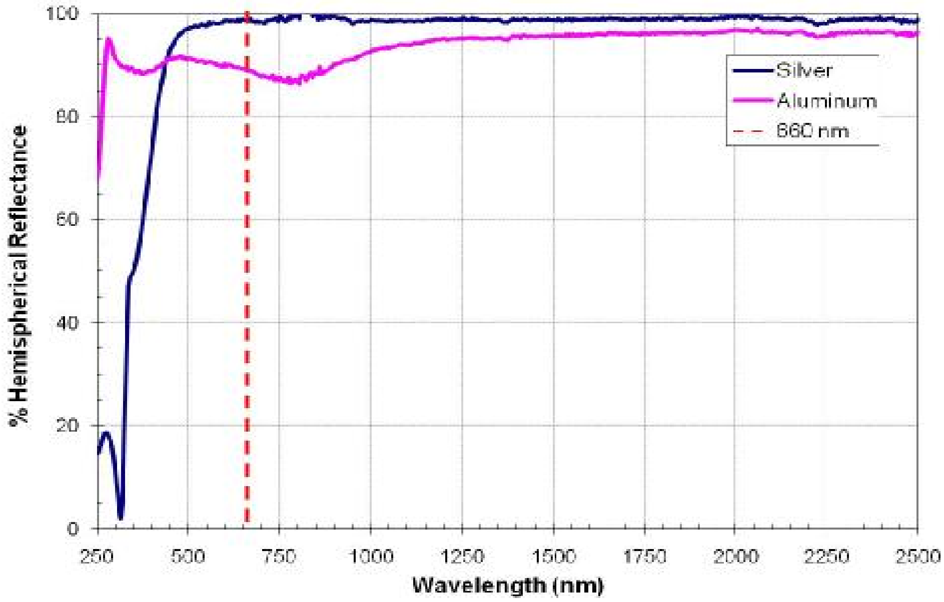


Figure (9) Comparison curve for reflection between solar dish's surface area coating by Silver and Aluminum versus solar spectrum wavelengths.

It is clear that, applying Silver coating to the solar dish's surface area implies to nearly 94 % reflection percentage for visible portion of solar spectrum rather than Aluminum which implies to nearly 86 %.

Third, cold mirror transmission should be known for sunlight spectrum to protect plastic optical fiber from getting melt due to high temperature generation.

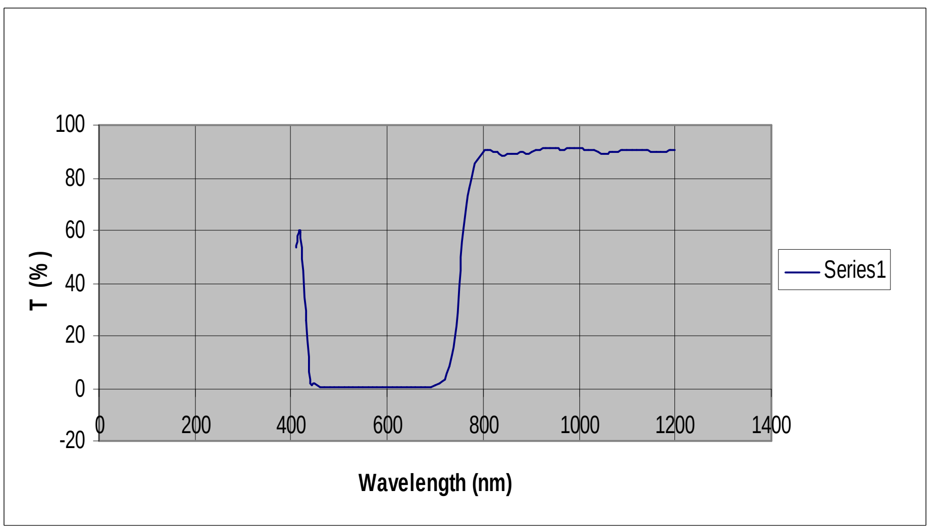


Figure (10) Transmission curve of sunlight versus wavelengths by using cold mirror.

It is clear that visible spectrum of sunlight is not transmitted comparing by infrared spectrum which causes warming effect is transmitted away from the cold mirror.

Fourth, plastic optical fiber transmission should be checked for different lengths.

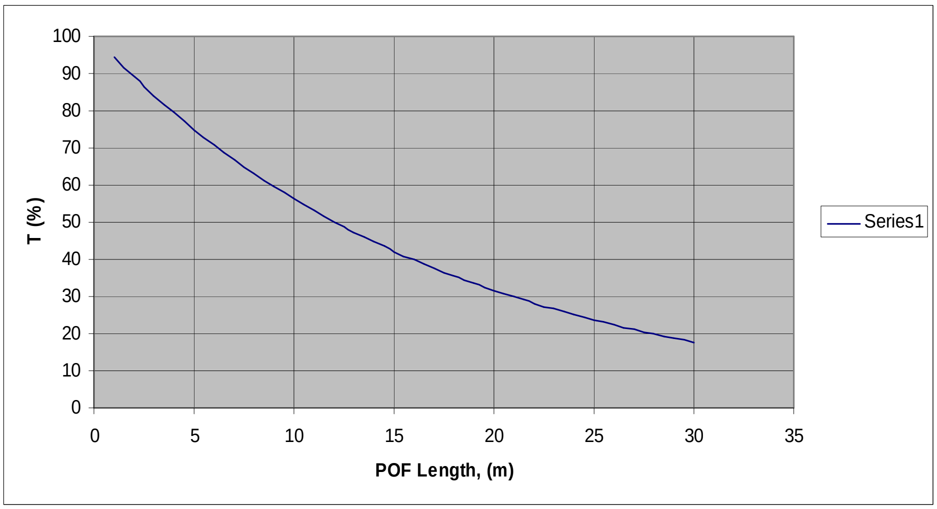


Figure (11) Plastic optical fiber transmission versus its length for visible sunlight spectrum.

It is clear that as plastic optical fiber length increases, its transmission for sunlight decreases severely because of high absorption coefficient value, of the order 0.25 dB.

Fifth, scattering glass tube transmission should be checked for different lengths.

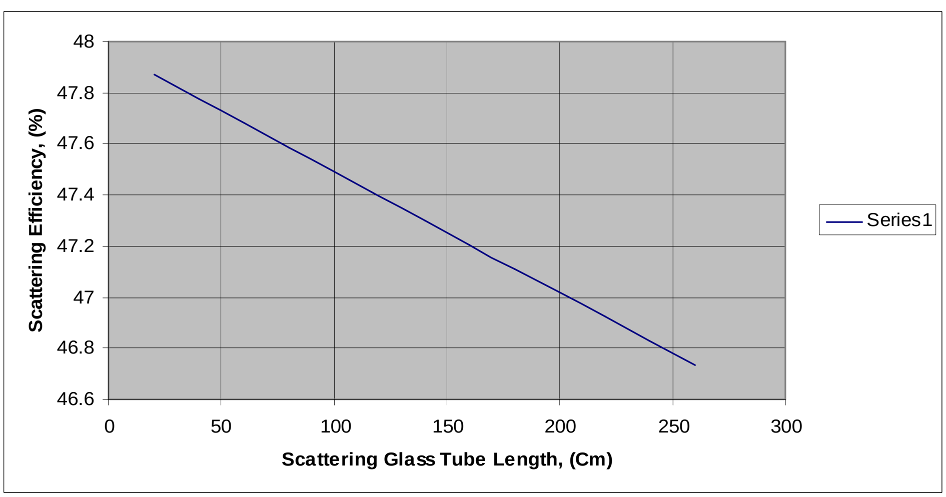


Figure (12) Scattering glass tube efficiency versus its length.

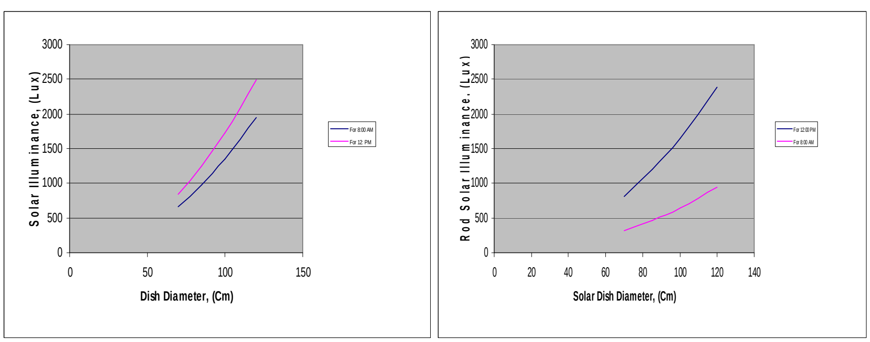
It is clear that as glass tube length increases, its scattering efficiency for sunlight decreases slightly because of low absorption coefficient value, of the order 10^{-5} mm^{-1}.

Choosing proper dish's aperture diameter is constrained by the need of sufficient illumination level for certain need such as: reading, living room… etc.

Table (1) Shows illuminance for human eye level of different cases [19].

Illuminance, (lux)	Example
10^{-4}	Total starlight, overcast sky.
0.002	Moonless clear night with airglow.
0.01	Quarter moon.
0.27	Full moon on a clear night.
1.0	Full moon overhead at tropical latitudes.
3.4	Dark limit of civil twilight under a clear sky.
50	Family living room.
80	Hallway / toilet.
100	Very dark overcast day.
400	Sunrise or sunset on a clear day.
500	Office lighting.
1000	Overcast day, typical TV studio lighting.
10000 - 25000	Full daylight (not direct sun).
32000 - 130000	Direct sunlight.

The following curves are for illumination level versus different dish's aperture diameters at two major days over year in Baghdad city – Iraq [20].



(a) (b)

Figure (12) Shows scattered visible solar illuminance from the glass rod versus dish diameter for (a) 21 June (b) 21 December.

CONCLUSIONS

Integrating plastic optical fiber by solar dish is achieved for illumination purpose. This integration is involved by material of reflecting surface area for the dish which is coated either by Silver or Aluminum, cold mirror to reflect visible spectrum exclusively to protect the plastic optical fiber from getting melt. The plastic optical fiber is coupled by scattering glass tube to spread visible spectrum into the space of a building. Rim angle of the solar dish is chosen to be 55° as optimum angle. Required illumination level is ranging from low to high scale for human need according to the diameter of solar dish and chosen day, hour and location.

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