THE NON-FLUORESCENT FLAT PLATE SOLAR CONCENTRATOR

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ABSTRACT: Apart from costs, one of the keys to the market introduction of the fluorescent solar concentrator (FSC) is its outdoor lifetime, which up to now, is limited a few years by the lifetime of the fluorescent dye or quantum dot. This study shows that omitting the dye or quantum dot still can give power conversion efficiencies (PCE), which are comparable to, or even larger than that of the FSC. This can be done by using a special type of bottom mirror. It is shown that a PCE of 4.5% can be achieved.
Keywords: Cost reduction, Flat plate concentrators, Modelling,

1 INTRODUCTION

The development of the FSC has recently shown renewed interest. The increasing research effort has resulted in new record power conversion efficiencies ranging from 6.7 to 7.3%, [1-3] depending on the concentrator configuration, using multiple GaAs solar cells along the side. Based on these numbers, people have already started the discussion on market development of the FSC. However, substantial power conversion efficiency is an important, but not the only important requirement for market introduction. Lifetime and cost are two other aspects that can make or break the fluorescent solar concentrator. Previously, we have studied the cost aspect in detail.[4] It was shown that the fluorescent solar concentrator can be an interesting approach for photovoltaics. The lifetime of the FSC is less well studied. There are a few reports in literature, mentioning outdoor lifetimes of more than one year[5] and five years,[6] for FSCs based on fluorescent dyes. Although the lifetimes are increasing, they are far too short for outdoor power generation applications, for which a minmum lifetime of 20 years is required.

The FSC typically consists of a flat polymer plate, containing fluorescent dyes or particles, with one or more solar cells connected along the sides, see Fig. 1. The dyes absorb the incoming sunlight and emit light at a slightly longer wavelength. This emission is largely isotropic. Part of the emitted light is trapped inside the polymer plate, the plate thus functioning as a waveguide, and is guided to the solar cells at the side. The main components of such an FSC are the polymer plate, the fluorescent particles or dyes and the attached solar cell.

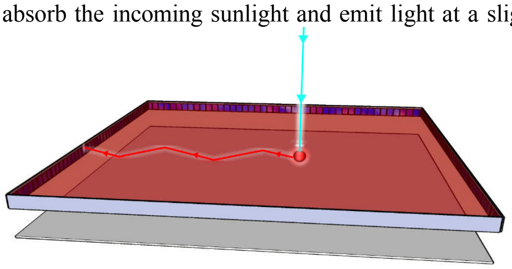

Figure 1: schematic view of an FSC with 4 PV cells connected to the sides. Incoming sunlight is absorbed by the dye (red dot) which subsequently emits light of a slightly longer wavelength. This emitted light is guided to the PV cell by total internal reflection.

The limiting component with respect to the lifetime is the fluorescent dye. It is well known that the organic dyes that are used in the FSC are not stable in air, as photo-oxidation reactions can take place. Besides that, also reactions with monomer residues and additives of the polymer matrix can occur, resulting in reduction of photo-active dye in the FSC. From other applications, e.g. when used as roofing material, it is known that polymer plates or sheets can have outdoor lifetimes of more than 10 years.[7] The attached solar cell can in principle be any type of solar cell that is able to convert the emitted light efficiently into electricity, but most often a Si solar cell is used. This type of solar cells has a claimed outdoor lifetime of more than 30 years. So if the fluorescent dye could be omitted from the concentrator, the lifetime would be increased from a few years to more than 10 years. Recently we have studied the possibility of what we have called the non-fluorescent solar concentrator or flat plate solar concentrator (FPSC), i.e. a flat plate concentrator without fluorescent particles or dyes. In this paper we will discuss ray-tracing simulations of such an FPSC and compare the results with that of a standard FSC. Furthermore, we will show that this FPSC can be cost effective with respect to silicon based photovoltaics.

2 RAY-TRACING MODELING

We simulate the behavior of the FSC and the FPSC with an in-house built computer program.[8] This program is a ray-trace program based on Monte Carlo techniques. Random numbers are drawn to simulate the fate of the photon. Based on Beer's law (exponential) weighted distribution, a random number is used to determine the traversal length of a photon. Furthermore, random numbers are used to determine the type of absorption (dye or polymer), the emission/no-emission event by the dye (based on the quantum efficiency), the direction of isotropically emitted light (independently of the direction of incident light), the wavelength of emitted light as well as the transmission/reflection choice at the interfaces of the plate (based on reflection coefficients). The polymer-PV reflection coefficients are determined by converting the air-PV reflection coefficients with the help of the Fresnel equations. Power conversion efficiency (PCE) was calculated using the EQE spectrum as determined from raytracing simulation, and the AM1.5G spectrum, where an open circuit voltage of 0.6V and a fill factor of 0.76 was assumed for the Si PV cell.

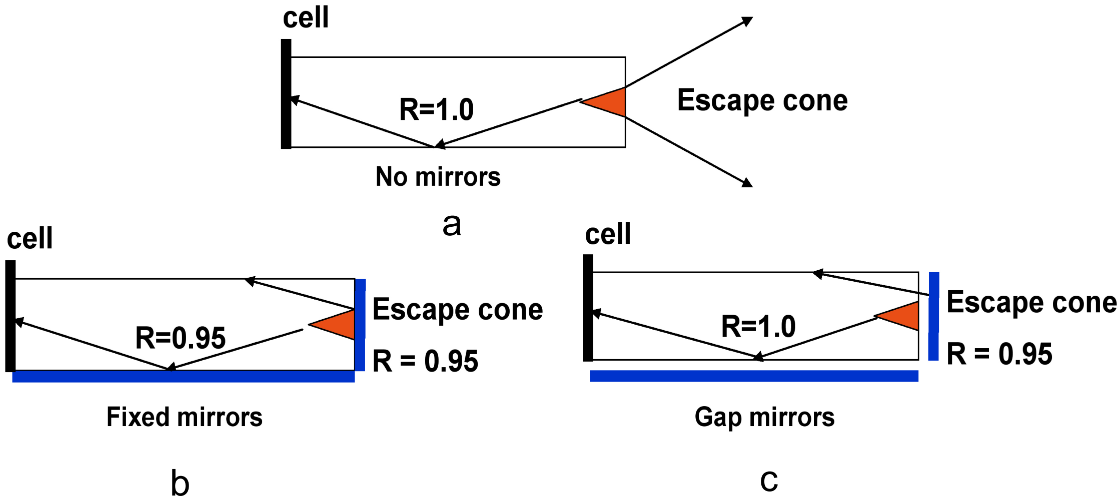

Figure 2: Schematic explanation of the effect of the air-gap mirror versus a direct mirror. A) no mirrors attached, b) all direct specular mirrors with R = 85%, and c) all air-gap specular mirrors with R = 85%.

Calculations were performed for 5x5x0.5 cm3 plates of Polymethylmethacrylate (PMMA), containing two dyes were used, 0.01 wt.% Lumogen F Red 305 (Red305) from BASF (a Perylene) and 0.003 wt.%. Fluorescence Yellow CRS 040 (CRS040) from Radiant Color (a Coumarine).

3 RESULTS

As mentioned in the introduction, the FSC consists of a polymer plate containing a fluorescent dye. The dye absorbs the incoming sunlight and emits light at a longer wavelength. This emission is largely isotropic. When the emitted light reaches an edge of the polymer plate, it is either reflected, or transmitted. According to Snell's law, there exists a critical angle for light at the interface, which is determined by the refractive index difference between the polymer plate and the surrounding air. In three dimensions this results in the escape cone. If light is emitted outside the escape cone, the light is reflected with a reflection coefficient of 100%, i.e. total internal reflection (TIR). The polymer plate is thus acting as a waveguide, and transports the light to the edges where a solar cell is attached, see Fig. 2a. However, a large part of the light is emitted within the escape cone resulting in escape losses. The most obvious solution to reduce these losses is to place a mirror at the edges of the plate where no solar cell is connected, to reflect the transmitted light back into the plate as in Fig. 2b. Unfortunately this also affects the TIR, as the light now faces an interface between the polymer and the material of the mirror. The resulting reflection. coefficient will always be less than 100%. The emitted light bounces back and forth several times between the mirrors before it reaches the solar cell. The cumulative reflection losses will therefore reduce the performance of the device. The solution to this problem is to leave an air gap between the polymer plate and the mirror as in Fig. 2c. In that way TIR still takes place, but light that leaves the polymer plate will be reflected by the mirror. In the remainder of this paper we will call this type of mirror an air-gap mirror.

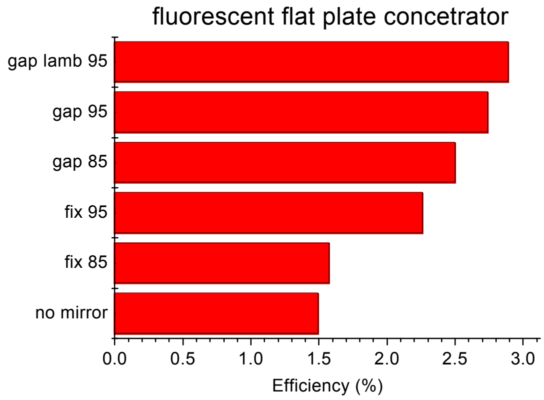

Figure 3: Power conversion efficiency as calculated using ray-tracing simulations for an FSC with different mirror configurations. For abbreviations, see text.

With the ray-tracing model that we have developed, the power conversion efficiency (PCE) was calculated for different mirror onfigurations of the FSC. Figure 3 shows the results. The effect of the applied mirrors depends on the reflectivity (R) of the mirror and if an air gap is used or not. If mirrors with R = 95% are used, then applying the mirror directly to the polymer plate (fix 95) results in an increase in the power conversion efficiency from 1.5-2.3%. The same mirror gives an increase in performance from 1.5% to 2.8% when an air-gap between the polymer plate and the mirror is present (gap 95). A further increase can be obtained a Lambertian type of mirror (gap lamb 95) is used, leading to a calculated PCE of 2.9%. Note that these calculations are performed for a 5x5x0.5 cm3 concentrator with one mc-Si PV cell connected to the side. Based on these results, an air-gap mirror was used in all FSC experiments and modeling. In the first experiments, metallic air-gap mirrors were used, but white, diffuse mirrors offer a higher reflection coefficient over a larger wavelength range than metallic mirrors. For this reason a white diffuse Lambertian type air-gap mirror was used for the later experiments. The experimental results were in agreement with the ray-trace simulations where this type of mirror was also implemented.[9,10]

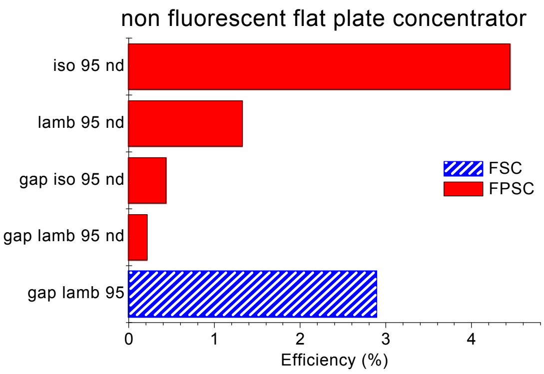

Figure 4: Power conversion efficiency as calculated using ray-tracing simulations for an PFSC with different mirror.

As mentioned in the introduction, the lifetime of the FSC is limited by the lifetime of the organic dye. In Fig. 4 the result of a ray-tracing calculation is shown for an FSC without the fluorescent dye (gap lamb 95 nd) and with the mirror configuration as for the standard FSC, i.e. with specular air-gap side mirrors and a Lambertian air-gap mirror at the bottom. For comparison, also the PCE of the standard FSC is given. Clearly the omission of the fluorescent dye reduces the PCE substantially from 2.9% to only 0.22%. However this mirror configuration is optimal for the FSC where the dye is used to redirect the incoming sunlight towards the PV cell. Without the dye, another mechanism has to be found to redirect the incoming light. As a first step the Lambertian airgap mirror was replaced by an isotropic diffuse mirror (gap iso 95 nd, see Fig. 4)), doubling the PCE with respect to the Lambertian air-gap mirror, but still much lower than for the best FSC. The reason why these configurations do not work so well, is because the light that reflects from the back side mirror enters the polymer plate under an angle that falls within the escape cone and it will thus also escape at the front side of the plate. Only a small fraction that reaches the PV cell before reaching the top facet will be converted into electricity. The fact that the isotropic mirror performs better than the Lambertian mirror shows that the former is better in redirecting the light, i.e. in a more horizontal direction (see figure 5), which allows a larger volume to take part in the conversion. The mirrors work much better when the air-gap is omitted. Now light is reflected under all angles within the plate, both inside and outside the escape cone. The results in Fig. 4 show that the effect is huge, especially for the isotropic mirror (iso 95 nd). With this mirror directly applied to the polymer plate, a power conversion efficiency of 4.4% can be achieved without the organic dye being present, which is even higher than for the FSC. This makes this configuration very interesting.

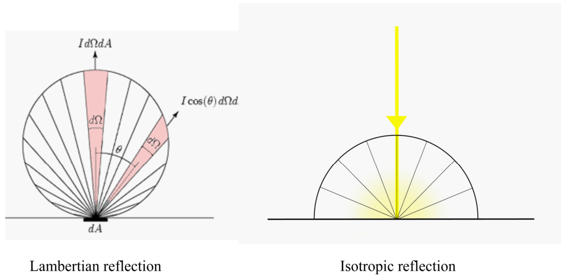

Figure 5: Schematic presentation of the reflection of a Lambertian and isotropic mirror.

4 COST ASPECTS

Previously we have reported on the cost aspects of the FSC. It was shown that a 25x25 cm2 FSC of 1 mm thickness can deliver electricity at about 1/3rd of the €/W price of conventional c-Si technology. In this calculation it was assumed that the price of the FSC plate per m2 was 1/15th of that of a c-Si solar cell, and the Balance of System costs were not taken into account. A similar calculation was performed for the FPSC and the result is given in Fig. 6 together with the result for the FSC. The calculation was done for both the Lambertian bottom mirror and the isotropic mirror. For the FSC the optimal configuration with an air-gap between the mirror and the plate was used and for the FPSC the mirror was directly attached to the plate. As can be seen in Fig. 6, the FSC indeed has a minimum of 0.35 in relative costs per unit of power for a plate size of 25x25 cm2, for both the Lambertian and the isotropic mirror. For the FPSC the minimum is even lower, 0.2, but also the optimal plate size is much lower, roughly 3x3 cm2 and it is only observed for the case of the isotropic bottom mirror. However, a more practical, though sub-optimal, size of 10x10 cm2 if for the FPSC yields a €/W price that is comparable to that of an optimal FSC. When a Lambertian mirror is used, the €/W price is much higher, 0.75, although still lower than that of conventional c-Si technology. This shows that the FPSC can be an interesting option for photovoltaic energy conversion.

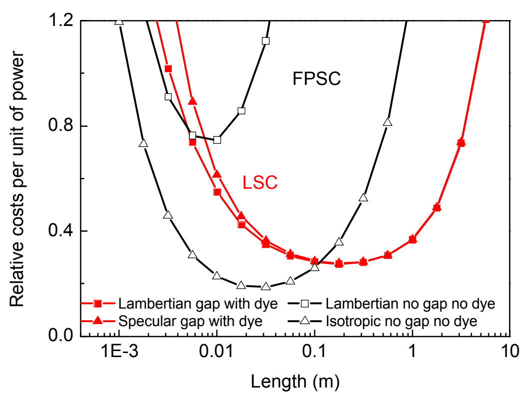

Figure 6: Relative costs per unit of power for bothe the FSC and the FPSC for different mirror configurations.

6 CONCLUSIONS

Although the Fluorescent Solar Concentrator (FSC) is thought to be an interesting approach to reduce the costs of PV, one of the drawbacks is its limited lifetime. The limitation is resulting from degradation of the fluorescent dye. Without the dye, the power conversion efficiency (PCE) strongly reduces, making the concept less interesting for PV applications. However, it is shown that by choosing an alternative backside mirror for a dye-less flat plate concentrator, the calculated PCE becomes 4.4%, which is even higher than for the conventional FSC. Cost calculations show that the dye-less Flat Plate Solar Concentrator (FPSC) can generate electricity at about 1/5th of the generating costs of conventional c-Si technology, where we assumed that the price of the FPSC per m2 is 1/15th of the price per m2 of the c-Si cell. This opens the door to a stable FPSC which can be cost effective with respect to c-Si PV technology.

ACKNOWLEDGEMENTS

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