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Thermodynamic Modelling and Ray-trace Modelling of Luminescent Solar Concentrators: a Comparison of the two Approaches

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LUMINESCENT SOLAR CONCENTRATORS: A COMPARISON OF THERMODYNAMIC MODELLING AND RAY-TRACE MODELLING PREDICTIONS

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ABSTRACT: The electrical and spectral output from luminescent solar concentrator (LSC) devices is predicted using thermodynamic modelling and ray-trace modelling techniques. Predicted output from four LSCs of varying dimensions, containing different luminescent dyes, are found to be in good agreement with measured output taken from fabricated LSCs. Despite the many different processes involved in the two modelling approach, predicted short circuit current densities from both approaches are found to be in excellent agreement.

Keywords: Luminescent concentrators, ray-tracing, thermodynamic modelling.

1 INTRODUCTION

Luminescent solar concentrators (LSCs) are static, non-imaging concentrators which do not require expensive solar tracking and concentrate both direct and diffuse light. An LSC [1,2] consists of a flat transparent polymer plate doped with a luminescent dye or, which has more recently been researched, with quantum dots [3]. As incident insolation passes through the LSC device matrix, it is absorbed by the luminescent species. Red-shifted light is subsequently emitted isotropically. As the refractive index of the plate is larger than that of the surrounding air, a large fraction of emitted light is guided by total internal reflection (TIR) to the plate edges, where PV cells are attached (Fig. 1). Mirrors can be placed adjacent and parallel to the rear surface to reflect light that may be outside the angular range for TIR. By modelling LSCs, loss mechanisms in the device can be analysed and optimised devices, in terms of both performance and cost [4], can then be designed. In this paper, two different approaches to modelling LSCs are outlined and the spectral and electrical output from each model compared. The model predictions are also compared against measurements taken from fabricated LSCs of varying dimensions, containing different luminescent dyes.
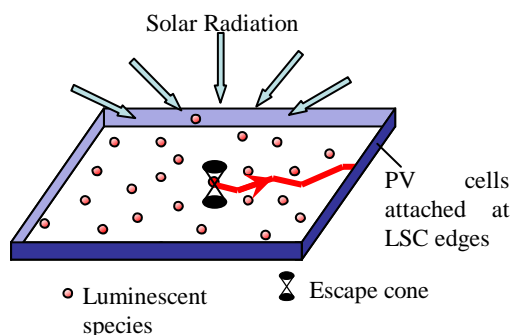

Fig.1 A luminescent solar concentrator consisting of a flat transparent polymer plate doped with a luminescent species. Light emitted by the luminescent species, outside the escape cone, is guided to plate edges where PV cells are attached.

2 ANALYSIS

2.1 Ray-trace model

One approach to determine the optical efficiency of LSCs is Monte-Carlo ray-trace modelling [5,6,7,8,9]. A large number of rays, of a given initial angle and wavelength are traced through the LSC until the ray is lost from the system or escapes through one of the LSC surfaces. As a ray travels between two surfaces inside the LSC, the probability of an absorption event is calculated using the luminescent species absorption spectrum and the Beer-Lambert law. Assuming absorption occurs, the probability of an emission event is given by the quantum yield of the luminescent species. In each case, randomly generated numbers are tested against the calculated probabilities to determine whether the event occurs or not. A measured photoluminescence spectrum is required as model input, which is obtained from a sample of very low doping concentration in order to minimise any effects of re-absorption. The wavelength of a ray, following an emission event, is assigned at random from a weighted distribution corresponding to the measured photoluminescence spectrum. When an emitted ray intersects a surface boundary, the probability of reflection or transmission is determined from the Fresnel equations. A random number is again generated to determine whether reflection or transmission ensues.

2.2 Thermodynamic model

The thermodynamic approach [10, 11] applies a detailed balance argument to relate the absorbed light to the spontaneous emission using self-consistent three-dimensional (3D) fluxes. The 3D flux models for the LSC are derived by applying the method of Schwarzschild and Milne[12], in which the angular dependence of the radiative intensity described by Chandrasekhar's general three dimensional transfer equation[13] is ignored and the radiation is considered as consisting simply of forward and backward streams. This approach has been extended to streams parallel to the x, y, and z axes of a concentrator and appropriate reflection boundary conditions have been applied to the radiation depending on whether it falls within the escape cone or the solid angle of TIR. The photon chemical

potential is determined, by iteration, as a function of position within the LSC, and then the photon fluxes escaping each surface may be calculated. The thermodynamic approach does not require a measured photoluminescence spectrum as input, however is limited to modelling LSCs containing a single luminescent species, whereas the ray-trace approach can be used to model LSCs with multiple species.

3   RESULTS

Two 2.5mm thick Plexit slabs containing a Bayer Fluorescent Red Coumarin dye were fabricated [11]. The dimensions of each slab are given in Table 1. The quantum yield of the dye is required as input for the models. This is obtained by a best fit to the experimental measurements on the two different slab sizes. Two slabs of different sizes containing Fluorescent yellow Coumarin dye were also fabricated. The quantum yield of both dyes was determined to be 0.95. To take electrical output measurements, the slabs were positioned on a matt black stage with a matt black background to avoid unwanted reflections. They were illuminated at normal incidence by an Oriel fibre-optic lamp. A blue filter was used to cut out the long wavelength contribution from the lamp where the absorption properties of the slabs are unknown. A 2.65x2.65 mm Siemens Si photodetector was utilised to obtain short circuit current values at the edges of each slab.

3.1 Predicted photoluminescence spectra

The normalised observed photoluminescence spectra emerging from the bottom surface of the red and yellow slabs are shown in Figs. 2 and 3, respectively. The luminescence peak predicted by both the ray-trace and thermodynamic models, shown in Figs. 2 and 3 for the red and yellow slabs respectively, are in good agreement with the observed luminescence peak. The predicted spectra are slightly narrower than the observed spectra,

however, particularly at longer wavelengths.

3.2 Predicted distribution of photons

Figs. 4(A) and 4(B) show the predicted outcome of all incident photons using the two modelling approaches for the large red and large yellow slabs, respectively. Both approaches predict similar percentages of incident photons escaping each of the LSC surfaces. The absolute difference in the total photons escaping the short edge of the red slab where the photodetector was attached is only 0.15% - a very close match considering the many differing processes involved in each approach.

3.3 Predicted short-circuit current

The photodetector spectral response and its angle dependent reflectivity are used with the predicted photon count escaping at the short edge to obtain the predicted short-circuit current density (J_{sc}). Table 1 shows the measured and predicted J_{sc} of the four LSC devices. The uncertainty in the measurements is due to alignment errors between repeat measurements and due to current generated by coupling of the incident light into the edges of the photodetector. There is a high level of agreement between the predictions and observed values, as well as between the two models.

4 CONCLUSION

Two approaches for modelling luminescent solar concentrators (LSCs) have been outlined and compared Both the thermodynamic and ray-trace modelling approaches have been shown to accurately predict the spectral and electrical output from four different single dye LSCs. Despite the many differing processes involved in each modelling approach, there is very good agreement between both techniques. The results show that both thermodynamic and ray-trace modelling provide useful tools for optimizing LSC devices and predicting their electrical output.

Slab	Dimensions (cm)	Measured J_{sc} (mA/m^2)	Predicted J_{sc} (mA/m^2) **Ray-trace Model**	Predicted J_{sc} (mA/m^2) **Thermodynamic Model**
Red Large	4.78 x 1.7 x 0.255 cm	53.2 ± 2.0	52.0	51.6
Red Small	1.93 x 0.994 x 0.250 cm	22.5 ± 2.0	24.5	23.9
Yellow Large	4.78 x 1.78 x 0.269 cm	10.4 ± 2.0	9.0	10.2
Yellow Small	2.26 x 1.0 x 0.270 cm	5.2 ± 2.0	5.0	5.0

Table 1. Measured and predicted short circuit current densities (J_{sc}) of the four LSC devices.
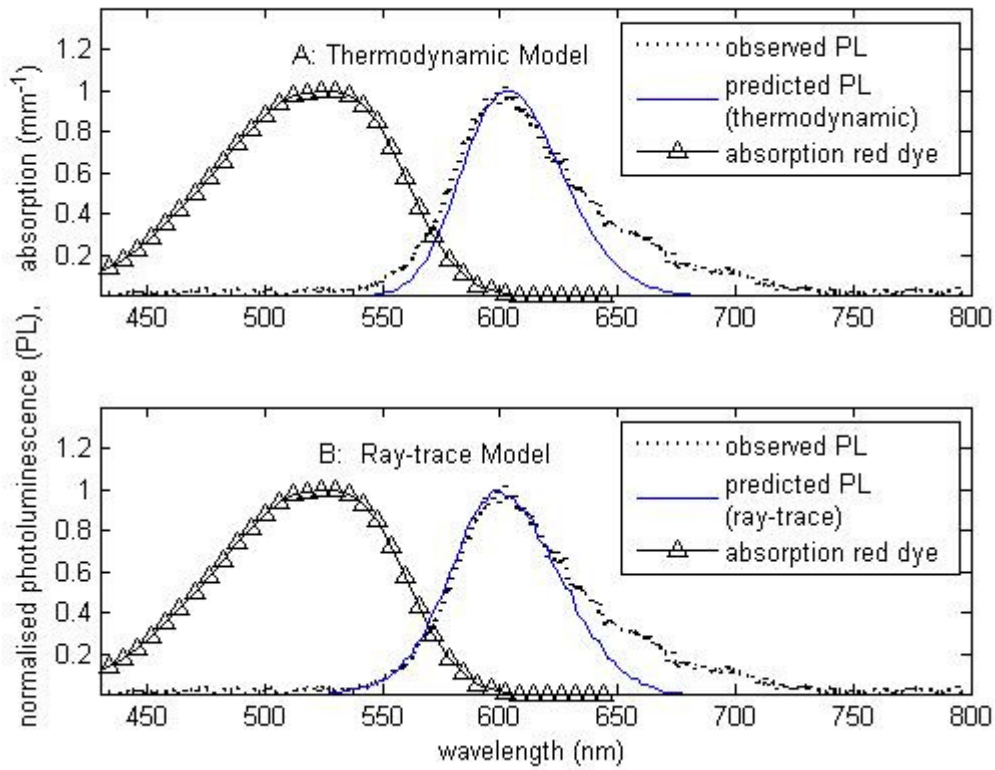
Fig. 2. Measured absorption spectrum of 2.5mm thick Plexit slab with Fluorescent Red dye. Observed and predicted photoluminescence (PL) spectra using (A) thermodynamic and (B) ray-trace models.
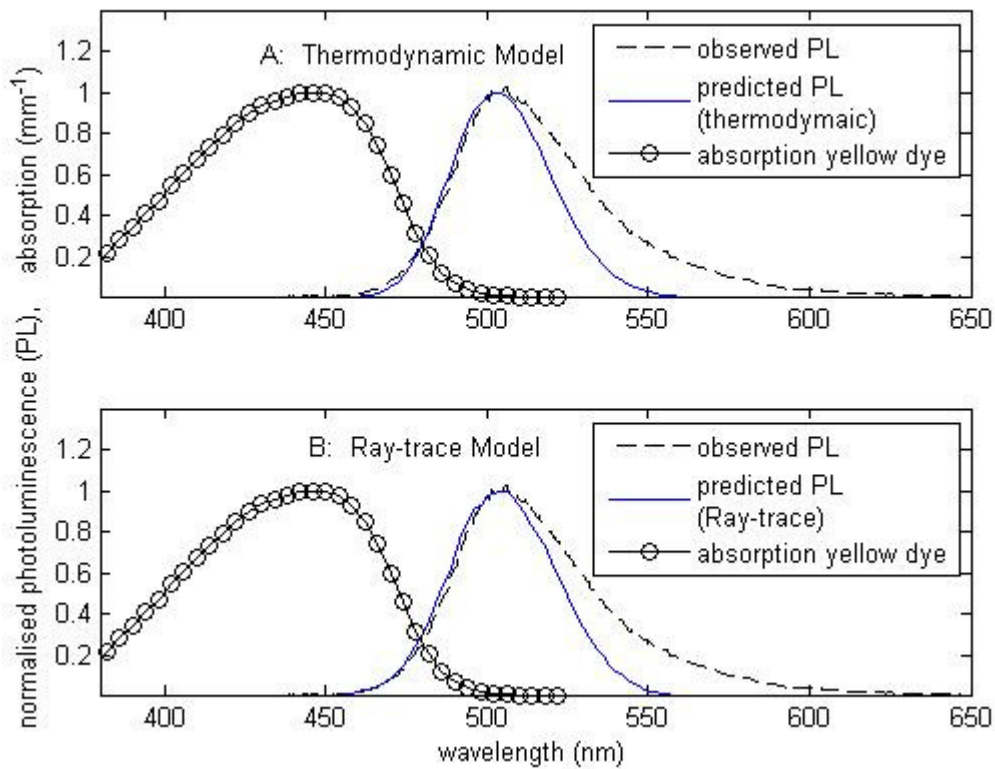

Fig. 3. Measured absorption spectrum of 2.5mm thick Plexit slab with Fluorescent Yellow dye. Observed and predicted photoluminescence (PL) spectra using (A) thermodynamic and (B) ray-trace models.
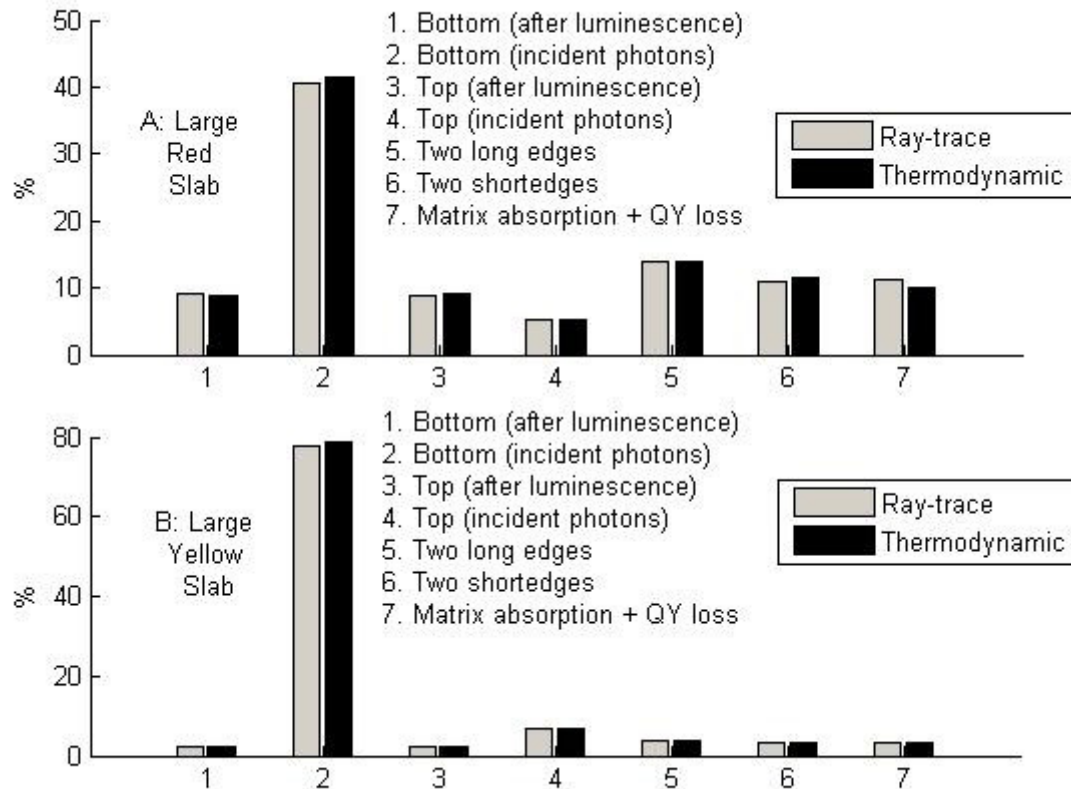
Fig. 4. Bar graphs showing predicted percentage of photons escaping each LSC surface using the ray-trace model (light grey bars) and thermodynamic model (black bars) for A) the large red slab and B) the large yellow slab.

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