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Spectroscopy, photostability and optical efficiency of luminescent solar concentrator

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Abstract. The spectroscopic properties of 1,4,170 and 750 oxazine dyes doped in polymethyl methacrylate (PMMA) were measured and studied. The photostability of these samples were outdoor tested during the four seasons. The optical efficiency of luminescent solar concentrator (LSC) of 750 oxazine dye was measured and calculated hourly for one year (1995–1996) considering day 21 as a reference day for each month. The performance of LSC has been tested at three different positions using X-Y tracker.

Keywords. Luminescent solar concentrator; spectroscopy; fluorescence spectra; oxazine dye; Stokes shift; optical efficiency.

1. Introduction

The performance of luminescent solar concentrator (LSC) is determined by the spectroscopic properties of the dyes doped in polymethyl methacrylate (PMMA). Since there are a number of factors that are desirable for performance of a LSC, such as the high extinction coefficient of the molecules of the dye used, strong fluorescent properties, and high photostability, we have made a characterization of the dyes used.

A number of theoretical and experimental papers on the performance features of luminescent solar concentrator have been published [1–3]. The operation of an LSC is based on absorption of solar radiation in a collector containing a fluorescent species in which the emission bands have little or no overlap with absorption bands [4]. The fluorescence emission is trapped by total internal reflection and concentrated at the edges of the collector which is usually a thin glass or PMMA plate. LSC has the following advantages over conventional solar concentrators: they collect both direct and diffuse light and there is good heat dissipation of non-utilized energy by the large area of the collector plate in contact with air so that essentially "cold light" reaches the PV cells. Therefore tracking the sun is unnecessary, and the luminescent species can be chosen to allow matching of the concentrated light to the maximum sensitivity of the PV cells. The main advantage is that the large area to be covered by the solar cell is reduced to the area of the edges [5].

The theory of LSC, which is based on internal reflection of fluorescent light which is subsequently concentrated at the edges, has been discussed in detail for organic dyes incorporated in bulk polymers [6,7].

In this paper, we measured the spectroscopic properties of oxazine dyes doped in PMMA, the outdoor tests of photostability and the performance of 750 oxazine dye LSC over a period of one year (1995–1996).

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2. Experimental

Oxazine dyes were obtained from Radiant Dye Lasers Accessories GmbH, and polymethyl methacrylate was supplied from Merck. Absorption spectra were recorded on a Perkin Elmer Lambda 4B spectrophotometer within the wavelength range (200–900 nm), and the fluorescence spectra on a Shimadzu RF 540 spectrofluorimeter. All measurements were carried out at room temperature.

The samples for photodegradation measurements and single dye LSC have been prepared by dissolving PMMA and the dye in benzene and the resultant mixture was mixed using magnetic stirrer. The mixture was cast in a glass tank and left for one week at room temperature. After curing, the plate was removed and put into a furnace at 70°C for two days. The edges were cut and polished.

The optical efficiency of the LSC plate have been estimated under outdoor illumination. Scientech 372 power and energy meter have been used for measuring the power of solar cell attached to the edge of an LSC plate $15{\cdot}2 \times 7{\cdot}4 \times 0{\cdot}3\,\mathrm{cm}^3$ with the aid of silicon oil for optical matching.

3. Results and discussion

3.1 *Spectroscopic properties*

The performance of LSC is determined by spectroscopic properties of the dye molecules chosen for the experiment. We measured the visible absorption spectra, which extends from $520 \Rightarrow 680\,\mathrm{nm}$ for 1, 4, 170 and 750 oxazine dyes doped in PMMA and presented in figure 1. Analyzing the absorption spectra of 1, 4 and 170 oxazine dyes show that an intense vibration band corresponding to the allowed origin is associated with a $1 \Leftarrow 0$ transition and a weak shoulder corresponding to the $2 \Leftarrow 0$ transition. The absorption spectrum of 750 oxazine dye in composed of 2 peaks, one at 612 nm and the other at a shorter wavelength of 585 nm.

The emission spectra of 4, 170 and 750 oxazine dyes are measured from the surface of the sample. There is difficulty in measuring the emission spectra of oxazine 1 due to its low fluorescence intensity.

The Stokes shift ($\Delta\upsilon$) (defined as the difference between the absorption and fluorescence maxima) were evaluated and are given in table 1. The Stokes shift of the 4 and 750 oxazine dyes were found to be larger than that of the 170 oxazine dye thereby indicating a lower self-absorption of the emitted radiation. Poor efficiency of the collectors is the result of high self-absorption if the bands largely overlap[8].

3.2 *Photostability*

The instability of the organic dyes is one important problem for the realization of the luminescent solar concentrator. The degradation can be significantly diminished by incorporating the dye into a polymeric matrix where the diffusion of the molecules to the surface is hindered. This leads to long-term stability of the absorption and emission maxima and very slow change of emission intensity.

For measuring the photostability of single dye LSC, the $1 \times 3 \times 0{\cdot}3\,\mathrm{cm}^3$ plate of 1, 4, 170 and 750 oxazine dyes doped in PMMA are prepared as referred to earlier. The samples were put in a glass box to absorb most of the UV spectra and placed horizontally

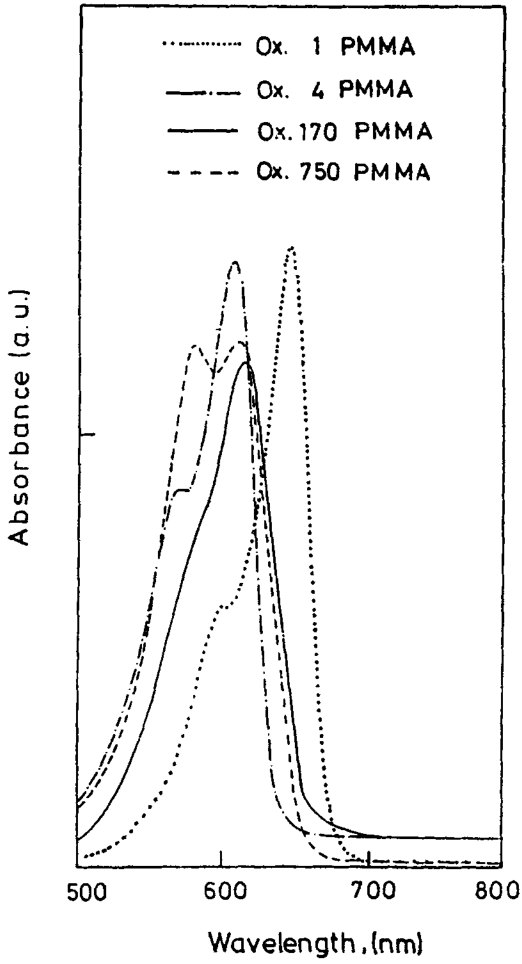

Figure 1. Absorption spectra of oxazine dyes doped in PMMA.

Table 1. Spectroscopic properties of oxazine dyes doped in PMMA.

Dye	λ_{abs} nm	λ_{em} nm	Stokes shift nm
Oxazine 1	648	—	—
Oxazine 4	611	641	30
Oxazine 170	619	636	17
Oxazine 750	612	633	21

on the roof of our Faculty Building to receive full solar radiation. The optical density was measured every two days. The photodegradation was calculated by dividing the absorbance after exposure to solar radiation by that before exposure and is presented in figure 2. The photodegradation shows good exponential fitting as in figure 3.

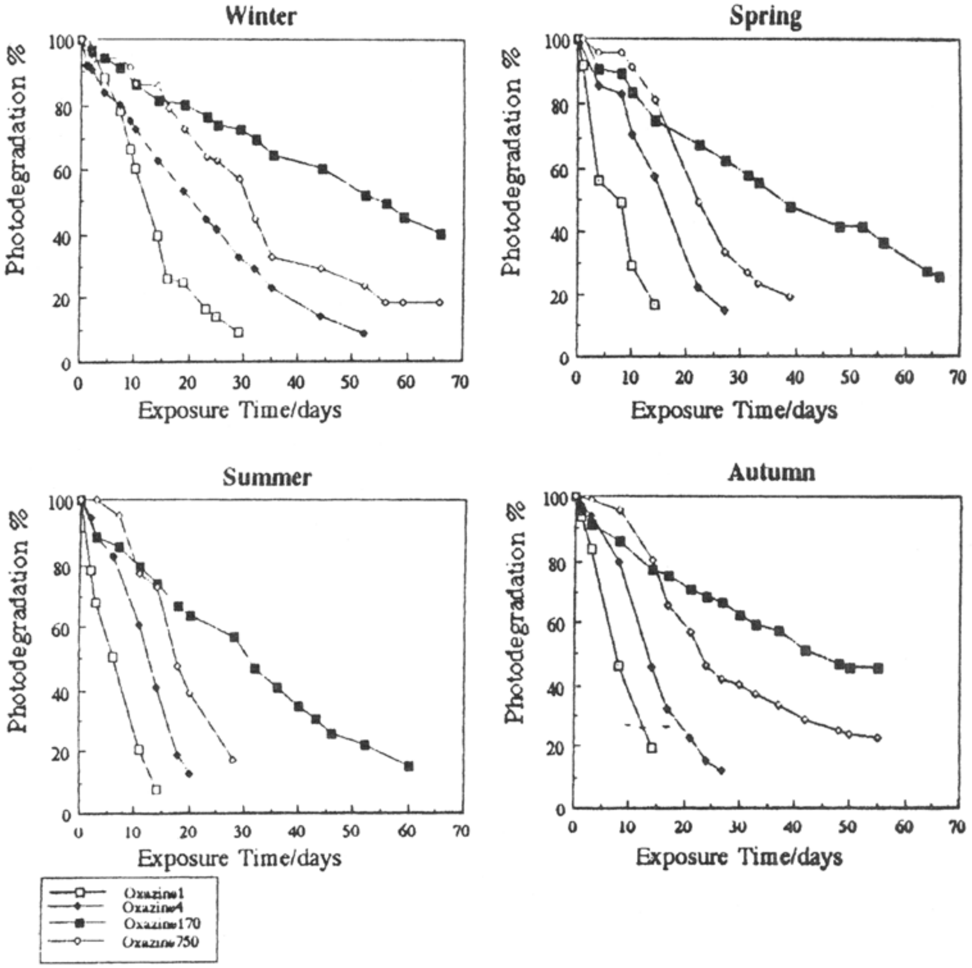

Figure 2. Seasonal photodegradation of oxazine dyes doped in PMMA.

From the measured values and figures, the photodegradation of dyes are faster in summer than in other seasons and this is attributed to the high temperature in summer. Poor photostability limits the ultimate usefulness of the 1 and 4 oxazine dyes.

3.3 *Performance of LSC*

The performance of 750 oxazine dye LSC under solar illumination was measured in the following way: the plate, of dimensions previously described, was placed on X-Y tracker as shown in figure 4, simulating the hourly solar radiation on the roof of our Faculty of Science Building, Zagazig University, Egypt for a full day chosen through each month (day 21 of each month) during the year 1995–1996. Another identical solar cell was used as a reference with its plane horizontal.

Three different positions were considered, horizontal, optimum tilt and tracking. It is valuable to denote that the tilt considered is the tilt of the plate and not of

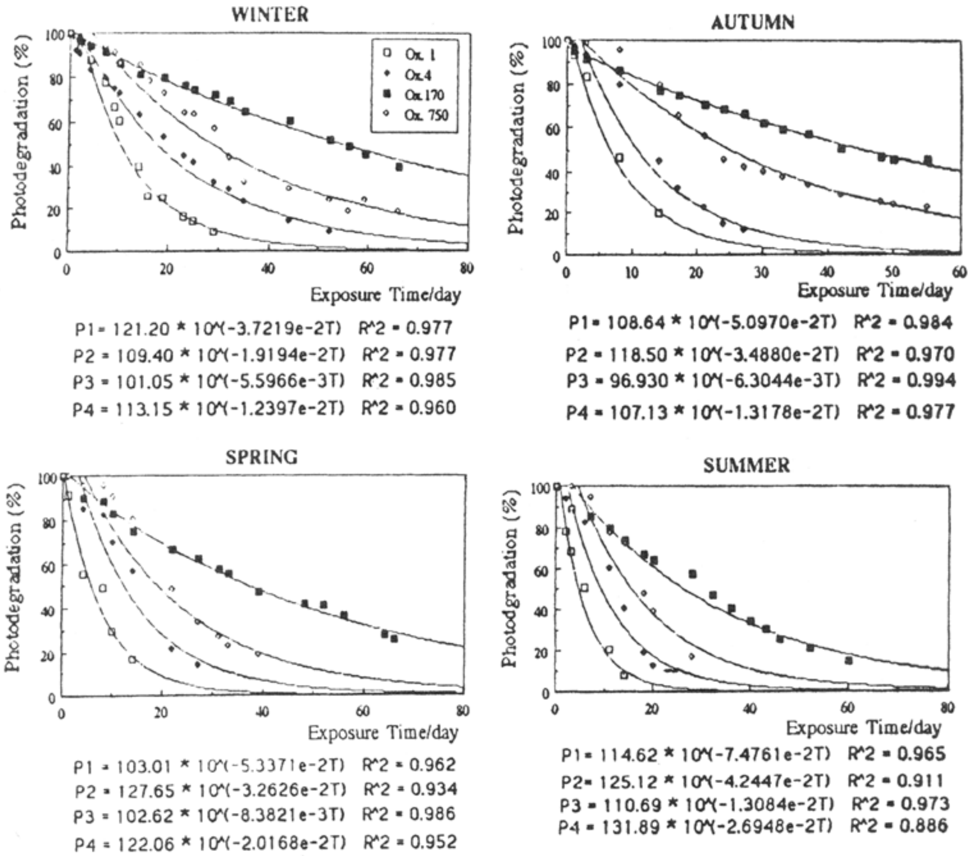

Figure 3. The fitting of the photodegradation for oxazine dyes doped in PMMA.

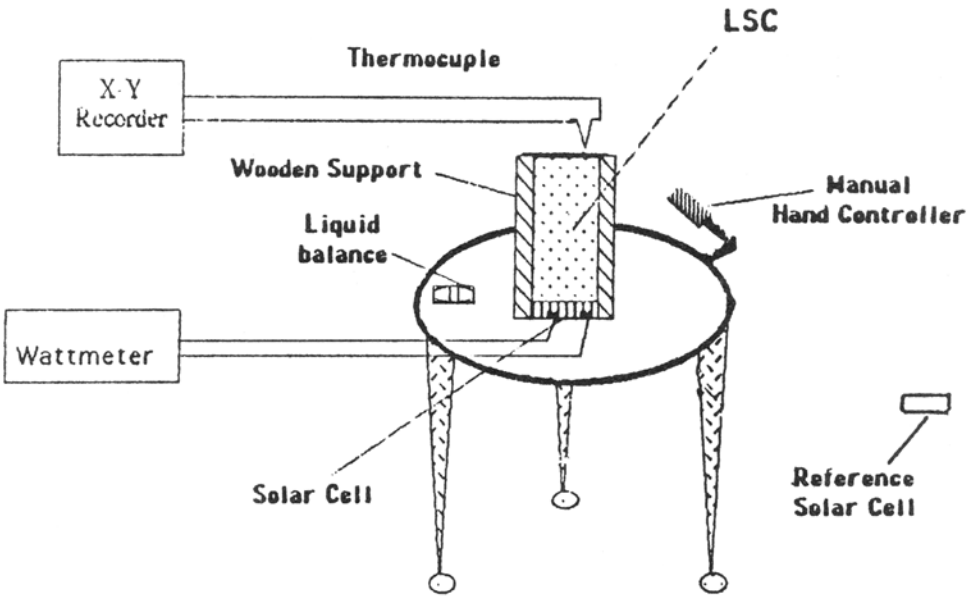

Figure 4. X-Y tracker.

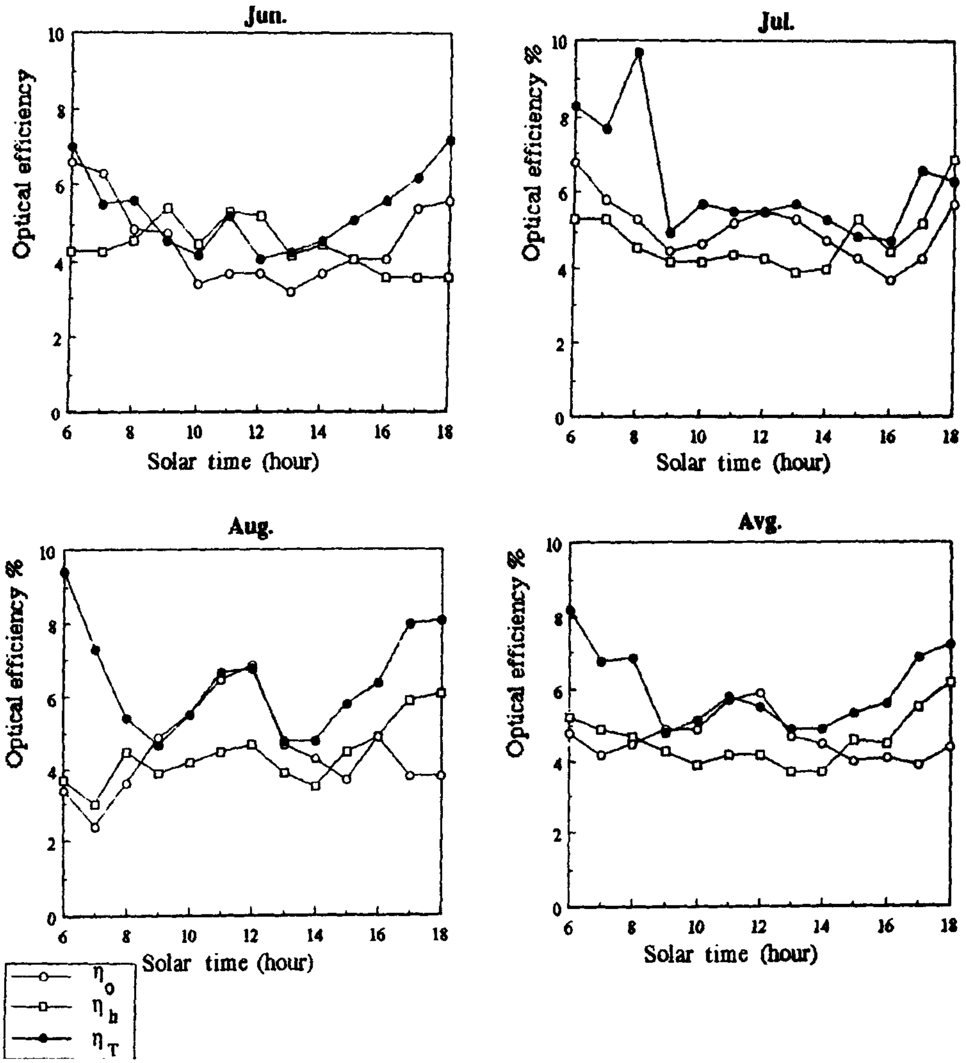

Figure 5. Hourly distribution of optical efficiency during the summer season.

the solar cell since the plate directly simulates the solar radiation while the cell indirectly receives the output spectrum from the edge of the plate after several internal reflections.

The optical efficiency (η_{opt}) is calculated using the following equation,

$$\eta_{\mathrm{opt}} = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} = \frac{S_{\mathrm{edge}}}{S_{\mathrm{ref}}} \frac{1}{G},$$

where S_{edge} and S_{ref} are the output power density of the solar cell attached to the edge of the collector and the reference solar cell, respectively. G is the geometric gain defined as the ratio of the top surface area to the edge area of the collector and was found to be 8·3.

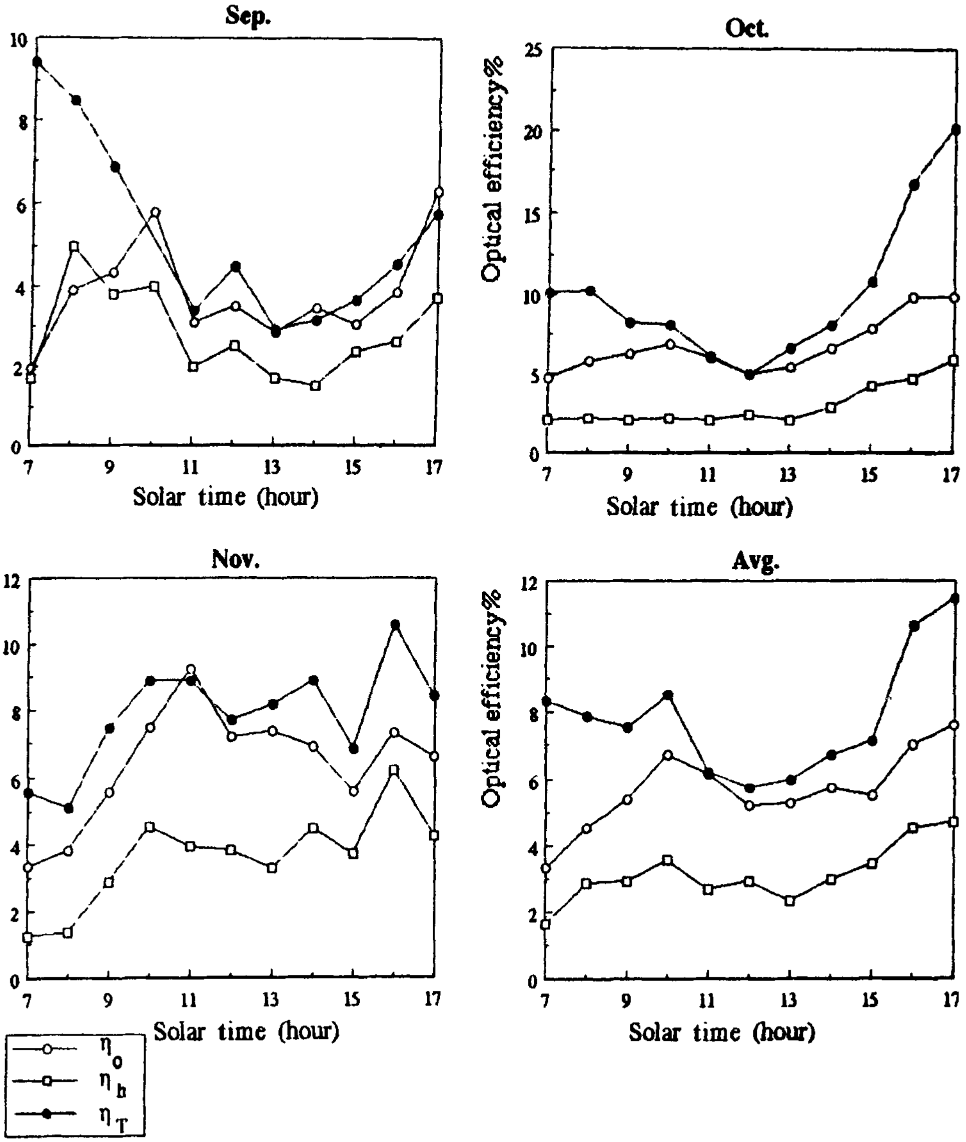

Figure 6. Hourly distribution of optical efficiency during the autumn season.

The results of operating the LSC system during daylight (from 6 AM to 6 PM) in the four seasons in 1995–1996 are given in figures 5, 6, 7, 8 and are valuable results for the tracking, specially in the range near sunrise and sunset. The tracking effect is weak around midday and this is due to the coincidence of the optimum tilt and tracking.

From the calculated values and figures, it is noted that the optical efficiency increased near sunset and sunrise and decreased around midday. From the practical point of view it is advantageous, since better utilization of the LSC is achieved and its efficiency increases when the input power density of solar radiation decreases.

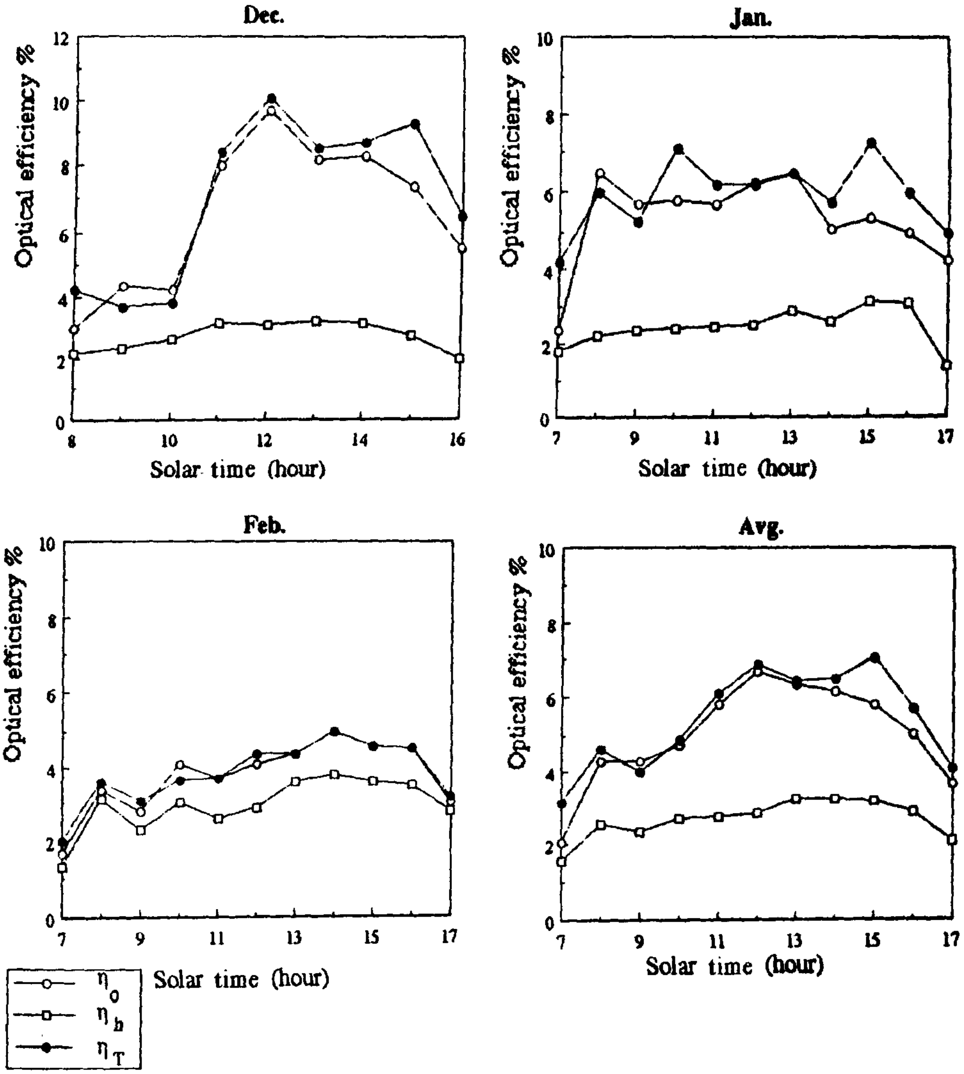

Figure 7. Hourly distribution of optical efficiency during the winter season.

Due to heavy cloud in winter, the optical efficiency increased around midday as shown in figure 7.

4. Conclusions

Our results show that the tracking increased the optical efficiency, by about 40%, specially in autumn and spring. There is satisfactory agreement of the optical efficiency values between tracking and optimum tilt in summer and winter. From this point of view and for practical purposes, we suggest the horizontal position for the LSC, due to the high cost of the tracking technique. Seasonal average value of hourly optical efficiency at three positions are presented in table 2.

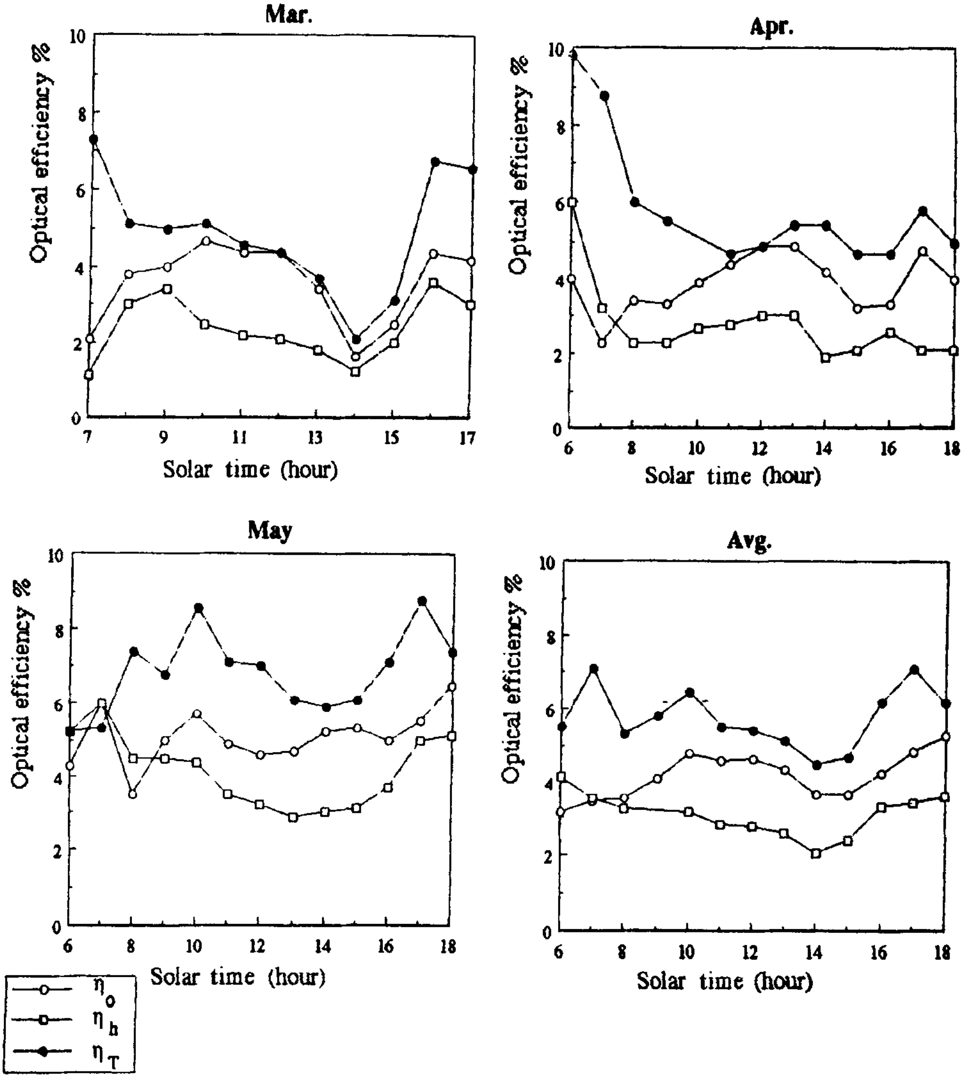

Figure 8. Hourly distribution of optical efficiency during the spring season.

Table 2. Seasonal average value of hourly optical efficiency (η_{opt} %) of LSC during the year 1995–1996.

Season	Horizontal	Optimum	Tracking
Summer	4·6	4·7	6·0
Autumn	3·5	5·68	8·05
Winter	3·0	4·98	5·4
Spring	3·5	4·1	5·9

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