Micro-Mirror Concentrator System

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Abstract

As part of the research project SCoSCo an innovative collector concept was developed by the consortium of the ScoSco project, namely University Patras, Solar-Institut Jülich, Calpak S.A., Hilger GmbH and Heliokon GmbH. The objective of the project is to develop a concentrating collector that could be easily integrated in buildings; therefore, a concentrating solar collector with fixed mirror was found to be an interesting approach.

The state-of-the-art methods for the generation of solar process heat use different concepts like tracking Fresnel mirrors or parabolic troughs. The proposed concept is innovative and presents advantages in cost- and life-cycle assessments. It can also be integrated in buildings very easily. The scientific findings answer for example the question of the geometric configuration of the concentrator and the optimal receiver type.

Keywords: Solar Process Heat, Concentrating Collector, Raytracing, Mirror Array

1. Introduction

In the past decades, several approaches of solar process heat collectors were developed (Weiss, 2008). Most approaches use single tracking axis linear concentrators (parabolic trough or Fresnel). The moving primary aperture area of tracking trough collectors prohibit an easy integration into buildings. On the contrary, linear Fresnel collectors can be easily installed on flat roofs. In order to achieve high performance, precise tracking is necessary. Typically, evacuated receiver tubes must be used to reach high conversion efficiency at medium operating temperatures (150 - 200 °C). Due to the costly components, solar process heat at these temperatures is still relatively expensive.

2. The mirror-array approach

As part of the Germano-Hellenic bilateral research project SCoSCo an innovative collector concept was developed with the objective to design and test a concentrating collector that could be easily integrated in buildings; therefore, a concentrating solar collector with fixed mirror was found to be an interesting approach. Within the scope of the project in order to reduce costs, a concentrating collector with a simple flat-plate receiver is proposed. The optical concentrator consists of an array of mirror facets placed in a box that protects the mirrors from wind loads and dirt. The innovative micro mirror box system has a built-in tracking mechanism, but the whole system is fixed. The solar concentrator consists of an array of mirror facets preconfigured to form a focal point at approximately 1.5 m. During tracking all mirrors move simultaneously in a coupled double - axis mode, in order to maintain the system in focus along the sun path. The mirrors and the corresponding mechanical system are housed inside a glass-covered casing like that of a flat-plate collector, as seen in Fig 1. The mirror module is installed at a fixed position. Therefore, this concept can be considered as fixed-mirror solar concentrator (FMSC) or Fresnel dish concentrator.

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Fig. 1: Mirror-Box Concentrator with Receiver

The receiver can be a relatively small flat-plate collector, optimized for high-intensity solar irradiance and higher temperatures (e.g. using AR-coated iron-free glass cover, thicker absorber sheet, closer fluid channels, high-temperature resisting materials and insulation).

This concept presents the following advantages:

- The point-focusing feature allows high concentration values of ~50 even with relatively large optical and tracking errors of about ± 10 mrad.
- Instead of expensive receiver tubes, a small non-evacuated flat-plate receiver can be used.
- A patent of micro-mirror systems was filed by SIJ/DLR in 2006 (Sauerborn, 2008). A prototype developed for CSP applications was already designed (see Fig. 1).
- It is an innovative concept that has not yet been analysed and tested and no research results regarding its performance were found in the literature.

3. Optical performance analysis

Raytracing models were created with the COMSOL (Fig.2) and Tonatiuh software tools. These calculations allow the specification of the number of mirrors, their dimensions, and their gap width. All (rectangular and flat) mirror facets are arranged so that their centres are positioned on a regular grid on a flat plane. The size and position of the receiver can be modified. It always faces the centre of the mirror array. Its position can only be modified in form of a rotation around the mirror array y-axis.

The alignment of the mirrors is defined by the method “create_FMA” in which all mirror facets are adjusted to reflect incoming light from each mirror facet centre to the receiver centre if the incidence angle is normal to the array plane. The adjustment angles are different for each mirror facet. This 2-axis rotation is carried out in two steps, first a rotation around the y axis pivoted at the facet centre, second a rotation around the x axis pivoted at the facet centre. The order matters in two aspects: firstly, the angular adjustments have to be calculated differently if the order of rotations is reversed, secondly, it affects the facet orientation (in the sense of its rotation around its facet normal).

Similar considerations have to be done with respect to the tracking angles. They are directly related to the arrangement of the cardanic bearings of the mirror facets, which consist of an outer (fixed) bearing and an inner one fixed to the rotating outer one. The COMSOL model assumes an inner bearing that allows rotation around the y axis and an outer (fixed) bearing with x-axis rotation (see appendix B for the code of this alignment). The tracking angles are the same for each mirror facet.

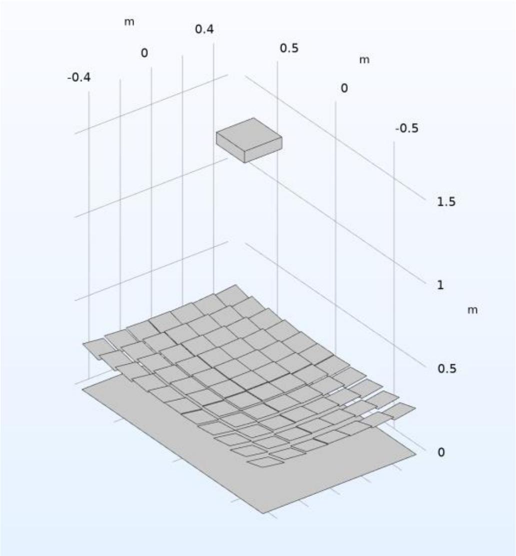

Fig. 2: View of the raytracing elements of the micro-mirror system 7x11

The optical errors of tracking, alignment and mirror surface quality are combined in one parameter “opticalError” which is used to create a random cone of reflected rays with normal distribution. The sigma value of this distribution is set to “opticalError”. The angular ray distribution of the sun disk is also implemented on the mirror surfaces and combined with the optical error calculation. In order to implement this, the equations of the surface reflection at the element “wall_1” had to be modified accordingly. The principle of raytracing model and the reflected rays are shown in Fig. 3.

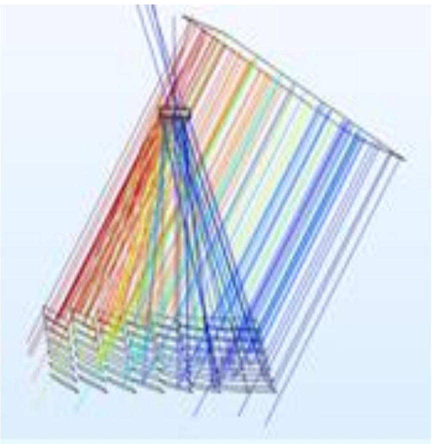

Fig. 3: Raytracing simulation of mirror-array system

Raytracing simulation allows the calculation of the intensity distribution on the receiver (see Fig.4).

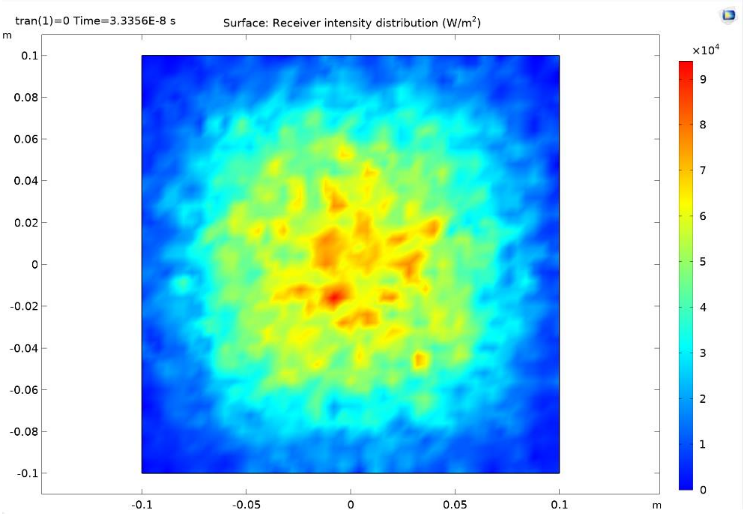

Fig. 4: Resulting intensity distribution on the receiver due to focusing with the mirror box

As a key result, the optical intercept factor γ was determined as a function of the angles of incidence (Table 3).

**Table 1: Intercept data from COMSOL simulations of Table 3,
left: transversal, right longitudinal variation of incidence angle (100,000 rays).**

θ_{trans}	γ		θ_{long}	γ
0	0.883		0	0.883
15	0.887		15	0.898
30	0.886		30	0.926
45	0.795		45	0.916
60	0.653		60	0.836
75	0.482		75	0.698

The relatively low intercept factor γ of 88.3 % at 0° (normal) incidence is due to the gap between the mirror facets and the relatively large optical error of ± 7 mrad. If the error is increased to ± 10 mrad the intercept at normal incidence decreases to 0.833.

For the optimization of the collector parameters the thermal efficiency of the whole system was supposed to be > 50 % at the design point (normal incidence, 250 °C collector temperature). This goal can be achieved with the following parameters:

Table 2: Collector parameters allowing a thermal efficiency > 50 % at the design point

Mirror reflectivity	ρ_m	0.9
Mirror glass cover transmittance	τ_m	0.92
Absorber absorptance	α_a	0.92
Receiver window transmittance	τ_w	0.95
Collector efficiency factor	F'_c	0.97

The optical efficiency η_o can be calculated from these parameters as

$\eta_o = F'_c \cdot \gamma \cdot \rho_m \cdot (\tau_m)^2 \cdot \alpha_a \cdot \tau_w$.

The overall collector efficiency is calculated as

$$\eta = \eta_o - F_c' \cdot U_L \frac{(T_m - T_U)}{G_{DNI}}$$

with T_m the average collector fluid temperature, T_U the ambient temperature, G_{DNI} the direct beam radiation intensity, and $U_L = a_1 + a_2 \cdot (T_m - T_U)$ the overall thermal loss coefficient.

Table 3: Ray tracing parameters allowing a concentration ratio of c=38

mirrorWidthX	0.14	M	Width of the mirror in the x-direction
mirrorWidthY	0.14	M	Width of the mirror in y-direction
gapX	0.0015	M	gap between mirrors in x-direction
gapY	0.0015	M	gap between mirrors in y-direction
focalLength	1.4	M	Focal length of the mirror array and distance of receiver from array centre
numMirX	7		number of mirrors in the x-direction
numMirY	11		number of mirrors in the y-direction
ref	1		mirror reflectivity
opticalError	7×10^{-3}		optical error normal random distribution
sundisk	4.65×10^{-3}		sun disk uniform random distribution
rec_width	0.2	M	receiver width
rec_length	0.2	M	receiver length

The overall optimization of parameters is also limited by the practical limitations of the size of the cover glass, which should not exceed a width of about 1 m.

In order to cross-check our calculations, the Tonatiuh software was used. Tonatiuh is an open source Monte Carlo ray-tracing software developed specifically for solar power plants. A model with the dimensions in and optical characteristics described in Table 3 was used as input. The intercept factor was calculated as a function of the incidence angle and similar results with COMSOL were obtained. The intensity distribution on the absorber surface patterns were also similar for both software.

4. Thermal Performance Analysis

Figure 5 shows the complete model of the solar collector system for the calculation of annual energy yield with Matlab Simulink Carnot toolbox. The Carnot program combines the easy-to-use graphical environment of Simulink with the powerful algorithms and differential equation solvers of MATLAB for the application of solar thermal system simulation (Wemhöner et. al 2000). The thermal loss parameters of the receiver were assumed to be $a_1 = 6.28$ W/m²/K and $a_2 = 0.005$ W/m²/K.

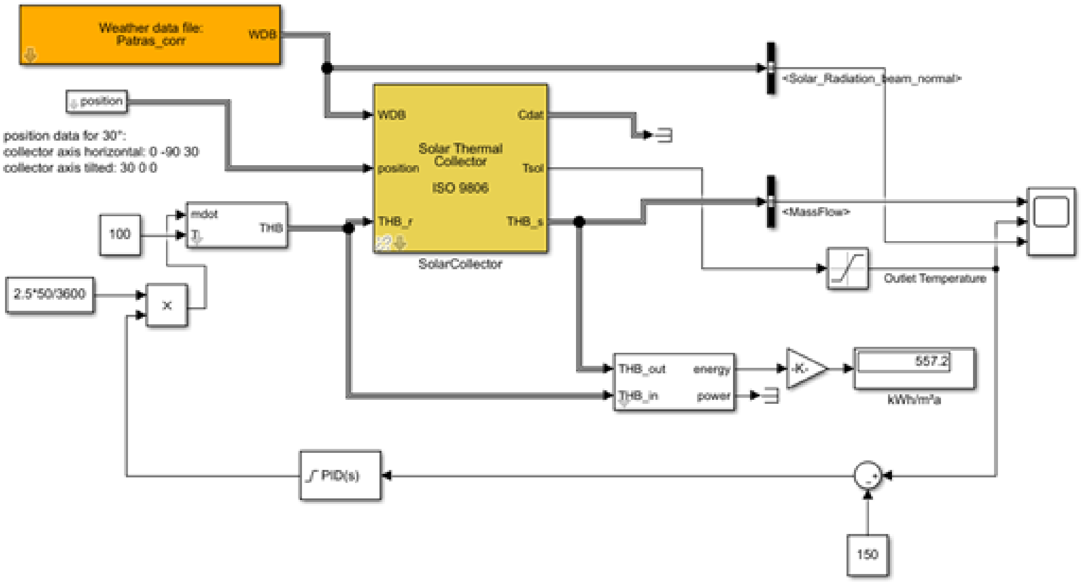

Fig. 5: Annual Energy Yield Simulation (Carnot Toolbox (CARNOT, 2019)

A sensor is connected to the solar collector to measure the mass flow of the heat transfer fluid and the output temperature. The sum block calculates the temperature difference between the set point value (150°C) and the actual value of the outlet temperature of the solar collector measured by the sensor. Since there are fluctuations in solar radiation throughout the day, the temperature difference is fed into the PID Controller to control the mass flow of the heat transfer fluid inside of the collector and keeping the outlet temperature of the solar collector at 150 °C with a constant inlet temperature of 100 °C.

The input and output of the THB of the solar collector is connected to a block called Energy Meter. The Energy Meter block calculates the annual solar yield of the system by measuring the temperature of the inlet and outlet of the solar collector and the volumetric flow rate of the heat transfer medium. The function of the gain block is to convert the energy in J to $\frac{kWh}{m^2a}$.

The annual energy yield for this concept is 793 kWh/m²a at Patras (weather data 2016) for the case with ± 7 mrad error and 750 kWh/m²a for the case with ± 10 mrad error, respectively.

5. Modification of the Incidence Angle to simplify the box construction

In addition, a series of simulations were performed using MATLAB/Simulink/Carnot (2019) to calculate the performance with different IAM functions, in which the IAM was set to zero above angles of incidence varying between 20° and 45° (transversal) and between 40° and 70° (longitudinal). Thus, the effect of restricting the angular range can be explored. For very large angles of incidence the energy of the reflected rays does not have a big influence on the annual energy yield; therefore, the construction of the mirror box, especially the movement of the mirrors, can be simplified. Through the limited angle, the mounting pins can be constructed shorter and because of that the height and the width of the box is even smaller. Nevertheless, it is very important that the Energy Yield is bigger than 700 kWh/m²a, and in the following steps the incidence angle was varied to find out the optimum.

The simulation results illustrated in Fig. 6 show that it is possible to “cut-off” the incidence angle. With the full range of rays in the longitudinal direction and the variation in the transversal direction it appears that it is possible only to consider the rays with an incidence angle ± 40°; this leads to an annual energy yield of 741.8 kWh/m²a. For the longitudinal direction with the full range of transversal rays, it is possible to stop the simulation at ± 60° with the annual energy yield of 716.6 kWh/m²a. The combination of both gives as a simplification optimum at the transversal ±45° and at the longitudinal ±60°. In this case the annual energy yield is 709.8 kWh/m²a.

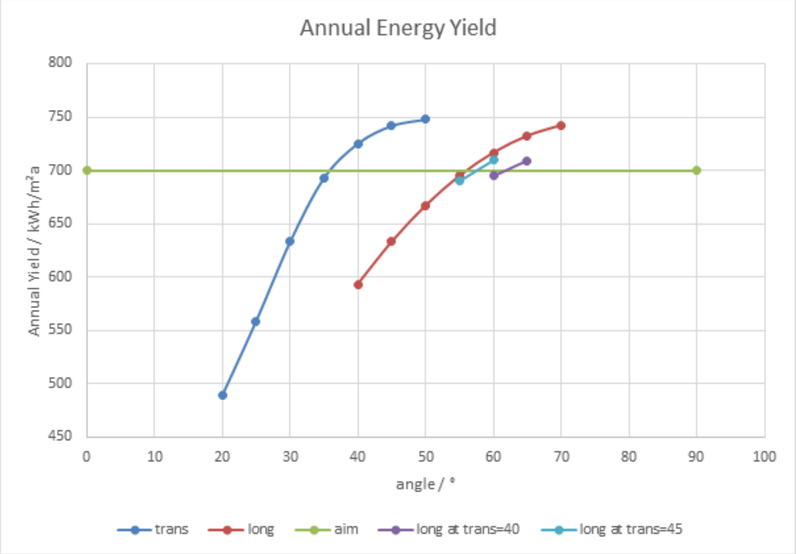

Fig. 6: Annual Energy Yield with variation of incidence angle (longitudinal and transversal) at which the IAM is set to zero (±10 mrad case)

The result of that simulation showed that the mirrors only have to move by ± 22.5° in the transversal and ± 30° in the longitudinal direction.

From these limits, the pin length L and the distance D from the point of rotation to the box edge can be derived as shown in Figure 7 and Figure 8:

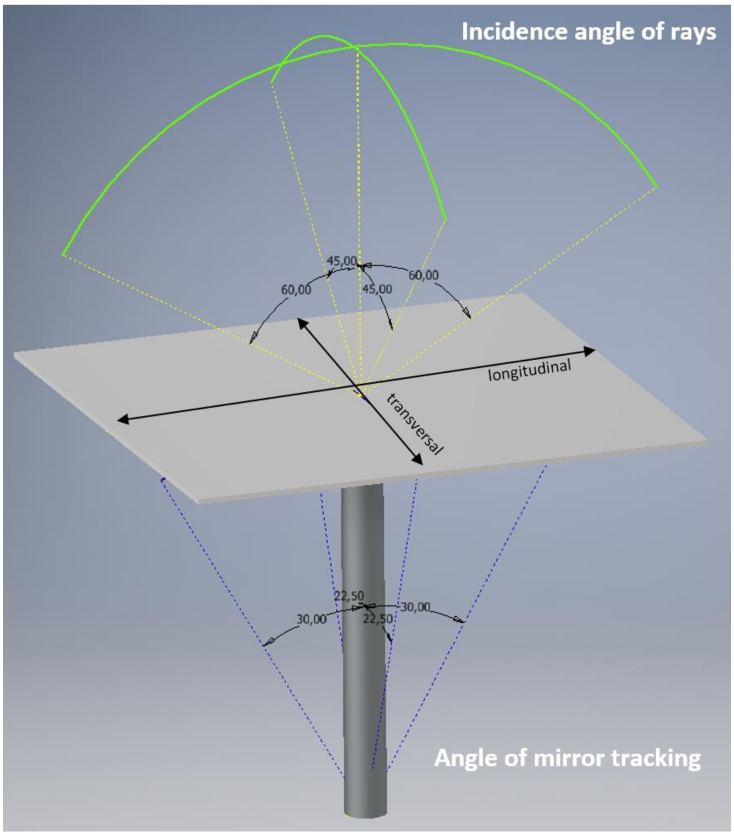

Fig. 7: Sketch of mirror tracking path (yellow: angles of incidence, blue: pin/mirror movement)

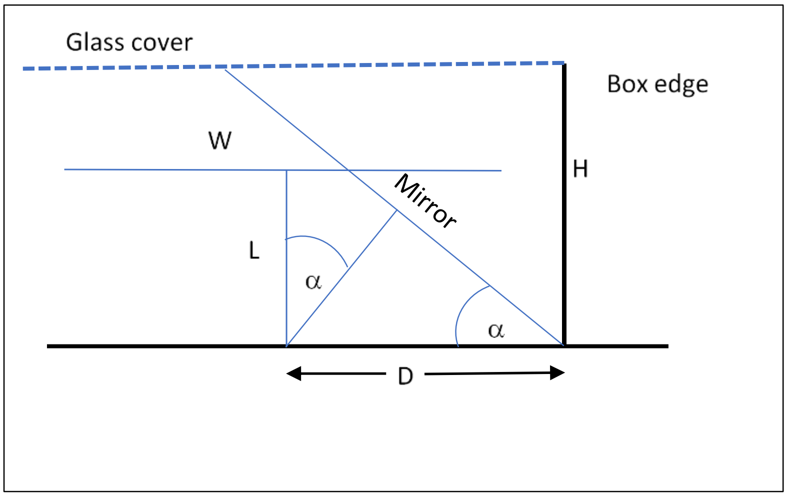

Fig. 8: Sketch of the calculation of Length and angles for pin movement

With the given angular restrictions and the mirror width W = 14 cm, the following dimensions can be realized:

L = 5 cm, D = 10 cm, and H = 8 cm.

6. Conclusion

A concentrating collector with a simple flat-plate receiver is proposed. The proposed concept is innovative and presents advantages in cost and life-cycle assessments. Optical simulations were performed using COMSOL and Tonatiuh software, yielding similar and satisfactory results. The expected energy yield can be up to about 800 kWh/m²a under the weather conditions of Patras, Greece using standard optical components. Further improvements are possible by using AR glazing for the glass cover of the mirror array, higher absorber, or mirror quality. A cost-benefit analysis of these material properties will have to be carried out. The new collector design can also be integrated in buildings very easily. On our next steps, two identical prototypes will be assembled and tested experimentally in Jülich, Germany and Patras, Greece, in order to study the proposed system’s behaviour under outdoor conditions for both climate zones. Technical details of the tracking system, as well as operating problems and impacts on the overall system cost is confidential at this point but will be published as soon as the experimental testing is complete.

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8. References

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