Concentrating solar collectors for process heat up to 250°C and small scale CSP – Integrated optical design for improved performance

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Abstract

Concentrating solar collectors like small Parabolic Troughs and Linear Fresnel Collectors are particularly well suited to generate process heat at temperatures between 120 °C and 250 °C in countries with a high potential of direct irradiation. Other applications are combined solar generation of solar heat, industrial cold and electricity, especially in regions with instable power supply and within island grids. The economic viability of such systems and applications has been shown in a study carried out by Fraunhofer ISE (MEDIFRES). With our integrated design approach we are supporting industrial partners in the development of small scale collectors by systematically investigating the effects of reflector material, geometrical configuration, manufacturing and site specific conditions. We characterize relevant components in the laboratory and use the detailed results in our design studies. Combination of sophisticated optical modeling via ray tracing, experimental testing and site conditions results in optimal matching of collector geometry and materials ass well as optimized performance and more precise yield calculations. The detailed optical modeling provides the basis for an overall cost-optimized collector design.

Exemplary results of a design study for a small parabolic trough using aluminum reflectors are shown, focusing on the influence of optical errors and collector geometry on performance.

1. Concentrating solar collectors for generation of process heat

Concentrating solar collectors are very well suited for generation of process heat and electricity in climatic zones of the earth with a high potential of direct solar irradiation. The so-called sun belts are situated around the equator and include Southern Europe, Northern Africa and all major desert areas of our planet. Large scale concentrated solar thermal power plants require a direct normal irradiation (DNI) of at least 1800 kWh/m²a, whereas small scale concentrating solar systems for process heat applications are already feasible at a lower irradiation potential of about 1600 kWh/m²a DNI. Figure 1 shows an overview on concentrating solar collectors and applicable temperature ranges. Small scale CSP is especially suitable for combined generation of process heat, electricity and solar cooling on islands and in countries with instable grid properties [1]. An example for the huge potential of small scale CSP is the Indian market, where 12% of the electricity is generated by systems below 1 MW_{el}. The capacity of industrial in-house power plants is about 12˙322 MW_{el}, which equals 30% of the overall installed capacity [2]. In Europe around 27 % of the total energy demand is used for process heat generation. Process heat in the range of 100°C-400°C accounts for roughly 30% of the total demand for thermal energy [3].

Fig. 1. Overview on concentrating solar collectors. Point focusing collectors are able to generate process heat with temperatures above 450°C. Large Parabolic Troughs and Linear Fresnel Systems are used mainly for large scale electricity generation and use heat transfer fluid temperatures between 250°C and 450°C. Small scale parabolic troughs and Linear Fresnel Systems generate process heat in the range of 150°C-250°C. Low concentrating systems like the new Reflec collector concept are able to generate process heat up to 150°C [4]. Temperature ranges are indicative only.

Medium temperature process heat is mainly used in the production of food and textiles but also in chemical processes and in the metal and paper industry.

2. Collector design and optimization methodology

Due to the large potential of small scale CSP described in the section above, collector performance and cost performance relationships of small concentrating solar collectors is an important topic today. The approach described in this paper is focusing on line focusing collectors. Whereas Linear Fresnel Collectors (LFC) obviously have many parameters for optimization, at the first glance Parabolic Trough Collector (PTC) design seems to be comparatively simple. But as soon as real, new and innovative component properties, local production capabilities, component availability and cost performance relationships are considered, it becomes a much more complex issue. The following topics are to be considered:

- Cost for collector components have to be rather low.
- Low cost reflectors often relate to lower performance in terms of reflectivity and shape accuracy.
- Often, specifically tailored or low performance absorber tubes are used instead of highly selective coated evacuated tubes. Accordingly, heat losses are even more significant in spite of comparatively low working temperatures.
- Robustness of components as well as country specific conditions are highly relevant.

This is why we propose a design approach, where testing of components and cost-performance relationships are integrated into the design process as early as possible.

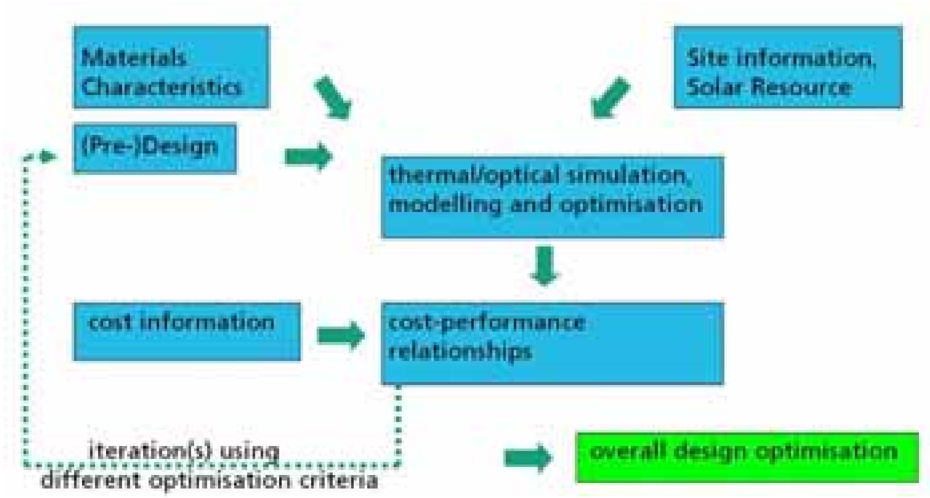

Fig. 2. Optimization and design of concentrating solar collectors, taking component properties, site and solar resources as well as cost information into consideration

2.1. Optical model – ray tracing

At Fraunhofer ISE, we apply ray tracing to model the various design options. Geometrical dimensions, detailed component properties and imaging errors are integrated into the models. The result of the optical simulation is the angle-dependent optical efficiency, which can then be used to calculate annual yields for specific locations and geometrical configurations of the collector array. For determination of the optical efficiency and loss analysis of concentrating solar collectors two different ray tracing tools are used. The Fraunhofer ISE simulation suite Raytrace3D and optionally the commercial ray tracing tool OptiCAD™ [5].

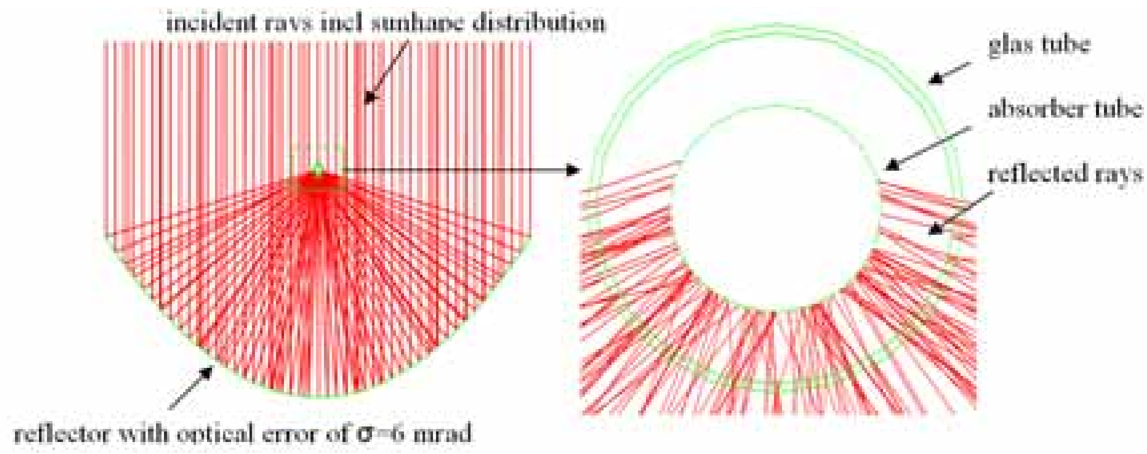

Fig. 3. Ray tracing example parabolic trough

A specialty of the tool Raytrace3D is its strict modularity in terms of program structure and geometry. The program code itself consists of several separate modules for calculation (collector tracking, aiming strategies, detailed component modeling), Monte-Carlo ray tracing of the scenery, analysis of the output data, and optimization procedures. Furthermore, the tool can be integrated into existing tools to forecast annual yields, heat costs and levelized electricity costs (LEC) of proposed systems. Tracking algorithms for Parabolic Trough Collectors, Linear Fresnel Collectors and Power Tower heliostat fields are available.

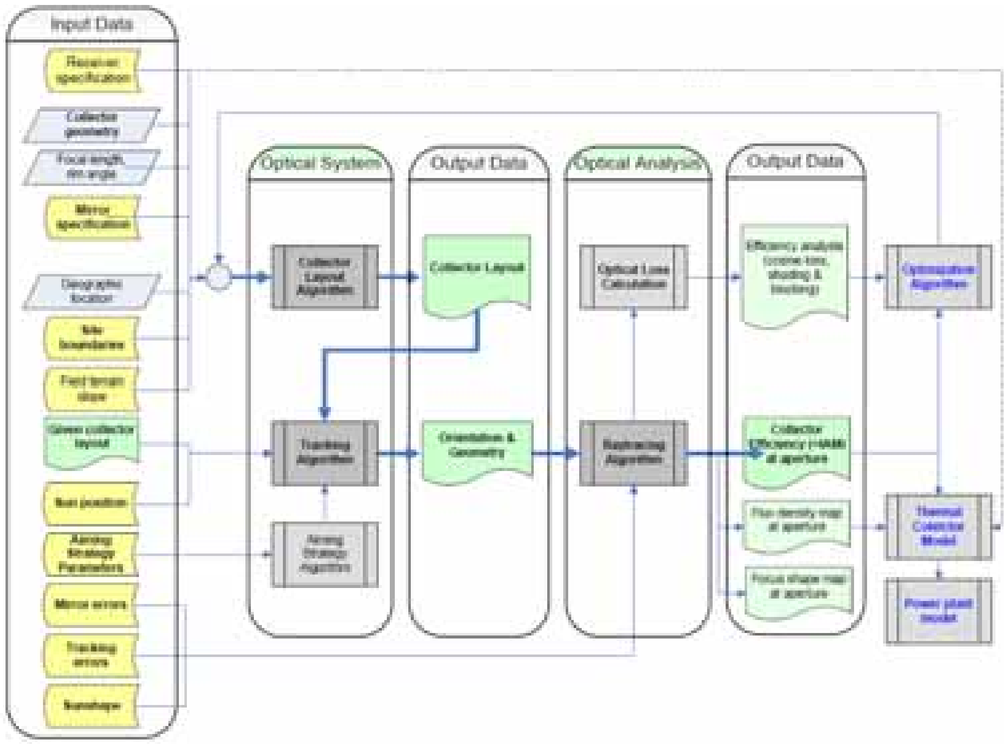

Fig. 3. Visualization of the Raytrace3D concentrating solar collector modeling approach. Modular concepts allows simulation and optimization of Parabolic Troughs, Linear Fresnel Collectors and Power Towers

The integrated algorithms of the geometrical modeling considers all relevant optical loss mechanisms, such as angular distribution of solar beam radiation (sun shape), reflector surface errors, tracking errors, atmospheric attenuation of radiation intensity, shading and blocking due to structure and tracked mirrors or spillage due to aiming strategy.

2.2. Annual collector performance – thermal model

The collector performance changes with the receiver temperature and the angle of incidence on the aperture. The thermal collector model consists of an optical term that gives the angle dependent optical efficiency and a thermal term that includes a heat loss model. The optical performance term results from the optical simulation described in section 2.1. It is described in form of an optical efficiency for normal incidence $\eta_{opt,0}$ and an angle dependent term, the incidence angle modifier IAM .

$$\eta = \underbrace{\eta_{opt,0} \cdot IAM(\Theta)}_{optical\,efficiency} \underbrace{- a_0 \frac{\Delta T}{I_{DNI}} - a_1 \frac{\Delta T^2}{I_{DNI}}}_{thermal\,efficiency}$$

The heat loss coefficients a_0 and a_1, as collector specific values, can best be derived from experiments. A common approach is to depict them with a quadratic function. Thermal losses reduce the absorbed energy, dependent on the temperature level (ΔT is the fluid temperature minus ambient temperature) and on the amount of direct solar irradiance I_{DNI} .

Since heat losses strongly depend on the size and area of the absorber tube, they should be included into the optical design process. For small concentrating collectors there is not yet a cost effective standard receiver available. Often companies seek individual solutions, which have to be considered in the design process.

3. Characterization of materials and components

Collector development and optimization aims at finding cost-optimized collector concepts, taking into consideration individual boundary conditions of the collector, available materials and components. For new concepts and materials relevant data are mostly not yet available, this is why individual components and their materials must be characterized in order to predict the performance with the greatest possible accuracy. Relevant specific optical properties we characterize include:

- Hemispherical, diffuse and direct reflectance
- Angle dependent spectral reflectance
- Beam divergence and scattering caused by the reflector surface
- Exact form of the parabolic mirrors
- Angle dependent transmission of enveloping glass tubes or plates
- Angle dependent absorption of coated tube
- Specific heat loss coefficients

Knowledge of these properties allows us to model the collector as realistically as possible.

For quality assessment of absorber, glass and mirror coatings, spectrometers with modified integrating spheres are used [6]. Surface scattering and beam divergence due to reflector materials are characterized with a goniophotometric set-up [7]. For analyzing of the concentrators surface slope the fringe reflection method [8] is used.

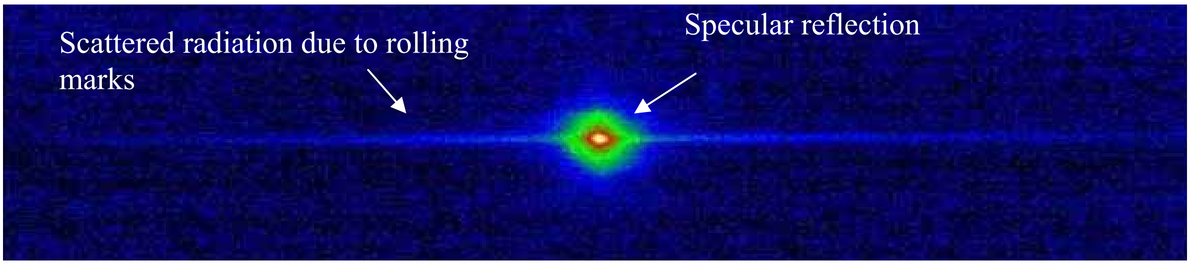

Fig. 5. Aluminum reflectors that are produced by a rolling process have an anisotropic scattering characteristic perpendicular to the roll transport direction. If the scattering profile is taken into account correctly during the design process, more radiation can be reflected onto the absorber.

The resulting values are then integrated into the optical model described in section 2.

4. Example: Design of medium temperature parabolic trough collector

For the design of a concentrating solar collector there are always innumerable variations possible, but the aim is to find the geometry which allows the most cost effective generation of process heat and/or electricity. As an example, the following section shows some results for design variations of a small parabolic trough collector.

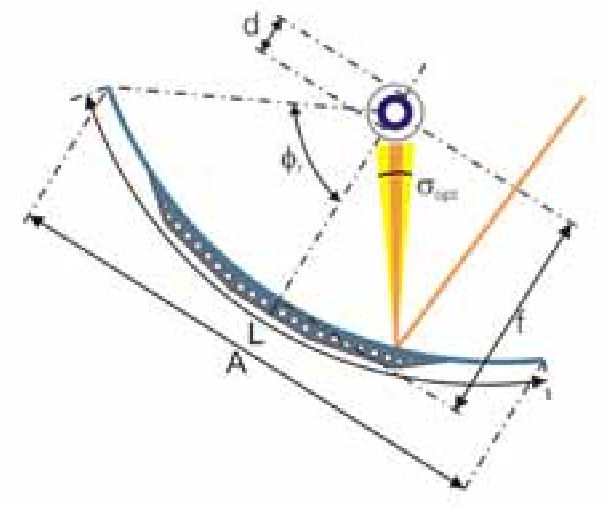

Fig. 6. Design of a small parabolic trough for process heat applications. The direct solar radiation is reflected onto the absorber pipe by a parabolic reflector. Innumerable combinations of the aperture width (A) , focal length (f), boundary angle (φr) and absorber diameter (d) are possible. A cost optimization finally provides the basis for deciding on the most favorable design.

The aim of this exemplary design study was a cost optimized concept for a parabolic trough using aluminum reflectors. Boundary conditions were steam generation at 250°C, DNI >1600 kWh/m^2a and latitudes <43°. A systematic, theoretical study was conducted, analyzing the influence of collector geometry and reflector accuracy on the optical yield for a small parabolic trough collector using specific components. Regarding optical measurements the work included full optical characterization of the reflector sheet, including spectral reflectance over solar spectral range, reflectance as a function of incidence angle, specular solar reflectance, beam spread profile and scattering (compare section 3).

The aim of the optical simulations was to identify an optimal trough design by ray tracing and annual yield calculations.

Exemplary results for systematic design variations show the influence of optical error on absorbed energy. Also the influence of geometry (rim angles and aperture) and of material used (arc length of reflector) can be seen from the results.

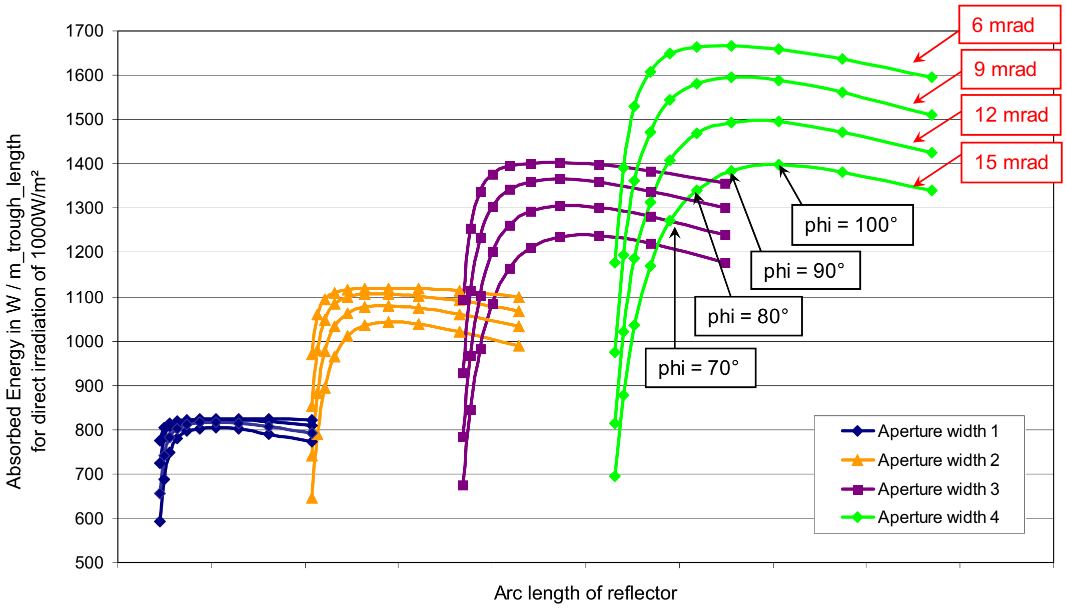

Fig. 7. Influence of aperture width, rim angle phi and optical error of reflected rays (given in mrad half angle) on absorbed power per meter trough (assuming a direct irradiation of 1000 W/m² and normal incidence), plotted against material usage (arc length) of reflector sheet. Colored lines indicate increasing aperture width, from blue to green.

5. Conclusion

Combining optical modeling, experimental characterization of materials and consideration of local resources result in:

• Optimized collector performance due to well-configured collector geometry parameters and matching components.

• Improved yield and performance prediction.

Additionally, the proposed approach allows the development of collector concepts specifically tailored to applications and local resources in emerging markets.

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