Solar Heat for Industrial Processes: RefleC-Collector Development and System Design

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Abstract

Since August 2007, Wagner & Co. Solartechnik together with Fraunhofer ISE has developed a stationary concentrating, double-covered (glass and polymer foil) flat-plate collector with external reflectors for the generation of process heat between 80 °C and 150 °C. The prototype has a one-sided CPC reflector on the lower side, approximated by three flat reflector segments. Its acceptance half-angle is 35° with a geometric concentration ratio of 1.26. The reflectors have a measured reflectivity of 86 % and were subjected to a hail-impact test according to EN 12975-2: 2006 (method two with ice balls), where the material did not show any damage.

The reflector construction supports the row in front and makes the distance between the rows, which is necessary anyway, useful for radiation collection. No shading of aperture area occurs. Simulations of the collectors annual energy gain were carried out for Würzburg, Germany with constant inlet temperatures. At 80 °C inlet temperature, the RefleC-collector offers a 64 % higher, at 120 °C a 149 % higher annual energy gain compared to a double-covered flat-plate (all temperature lifts counted, measured efficiency and IAM curves; gains are compared directly, not per aperture area). The errors of calculating with isotropic diffuse irradiation instead of anisotropic sky irradiation are discussed.

A demonstration plant with the newly developed collectors was built in July 2010 at a laundry in Marburg, Germany. The installed aperture area is 57 m^2, the primary storage volume is 1 m^3 and the secondary storage volume 2 m^3. The collector field works at temperatures up to 130 °C. The solar system supports the partly open steam network of the laundry by pre-heating of demineralised make-up water and by pre-heating the feed water of the steam boiler (feed water up to max. 120 °C). Also water for the washing machines is heated. The plant is monitored by Fraunhofer ISE, and collector-optimized control mechanisms will be applied.

1. Background and Aims of the RefleC Project

Even though in some countries like India, China and Austria the share of solar thermal systems generating heat for industrial process is significant and growing [1], the worldwide discrepancy between the very high potential and the number of systems installed is still obvious.
It is estimated that within EU 25, 3.8 % of the enormous industrial heat demand could be provided by state-of-the-art solar thermal installations, corresponding to 100 to 124 GW_{th} installed capacity [2]. This would quadruple the overall installed collector capacity of the European Union (28.5 GW_{th} installed at the end of 2008 [1]). On the other hand, the number of plants installed worldwide is still

negligible: Approximately 200 solar process heat plants with a total capacity of ca. 42 MW_{th} (ca. 60,000 m^2) are currently in operation [3]. This is still only 0.02 % of the capacity installed worldwide (estimated to 189 GW_{th} or 270 mill. m^2 by the end of 2009 [1]).
The reasons for this situation are very diverse. For industrial decision makers often energy consumption is still not a major issue, especially in sectors where it only accounts for a small share of the production costs. Partly there are also uncertainties about the effects of the discontinuous solar heat supply to both process control or product quality. Planners of solar thermal systems on the other hand lack experience with industrial processes. The planning effort is high because the industrial plant has to be analyzed with respect to process optimisation and waste heat recovery before a solar thermal plant should be designed (cf. [4, 5]). Usually also the economical requirements are higher than for residential buildings, so that solar systems with state-of-the-art technology can often not be realized.

Working on decreasing these barriers, the main objective of the RefleC project is to develop a collector with significantly higher annual energy gains than standard flat-plate collectors at working temperatures above 80 °C. At the same time, the heat generation costs up to working temperatures of 150 °C are aimed to be lower than for vacuum tube installations. The collector also offers the possibility to adapt its design to certain locations, temperature levels and seasonal load profiles. Technical progress in supplying high temperature heat is expected by designing and monitoring a demonstration plant equipped with the newly developed collector.

2. Collector Development

The collector design was optimized by carrying out raytracing-simulations, heat loss and energy gain calculations and measurements of test samples in an iterative way. The fundamentals of the early collector concept with a truncated CPC (Compound Parabolic Concentrator, reflectors on the upper and lower side of a flat-plate collector row) are described in [6]. The final collector configuration which resulted from improving the initial concept is shown in the right picture of Fig. 1 and in Fig. 6.

Fig. 1: RefleC test samples during outdoor characterization at the TestLab Solar Thermal of Fraunhofer ISE (efficiency curve position; from left to right: RefleC_1, Oct. 2007; RefleC_2, June 2008; RefleC_3, Aug. 2009)

2.1. Optical and Thermal Characterisation

After determining the optical properties of the applied materials from the literature or by own measurements, the effective reflectance-transmittance-absorptance-product $(\rho\tau\alpha)_{eff}$ of promising collector variants was calculated for perpendicular and angular irradiance by raytracing with parallel rays. From these values incidence angle modifier (IAM) curves were calculated (cf. Fig. 3).

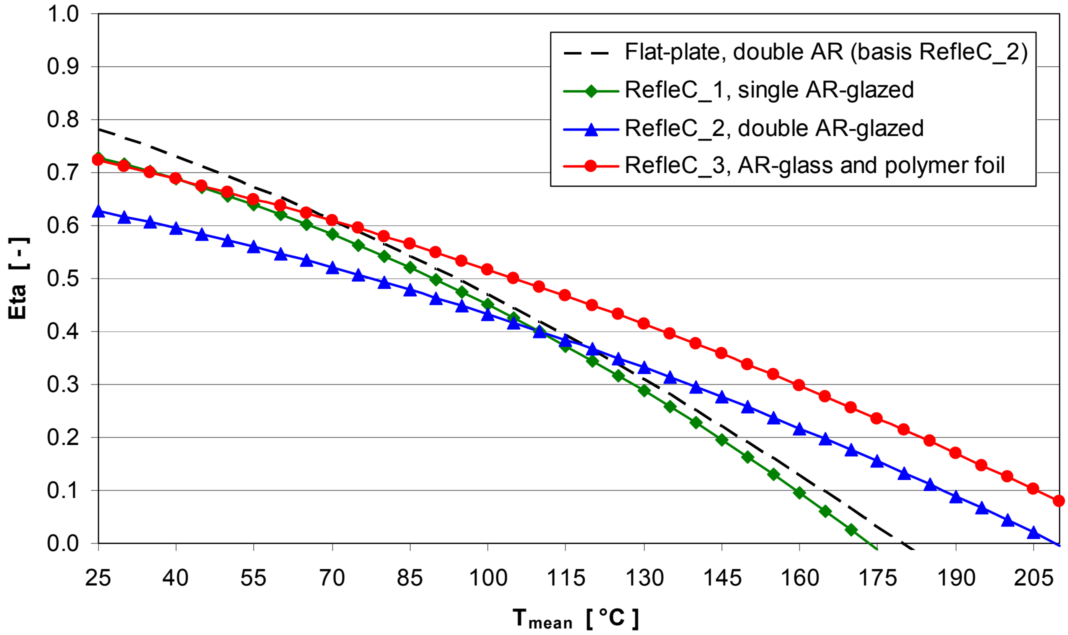

Fig. 2: Stationary measured thermal efficiency curves

The efficiency curves of the test samples were measured including fluid temperatures T_{mean} as high as possible (e.g. RefleC_2 was measured up to T_{mean} = 188 °C). The three test samples had different basis collectors, of which only the very good, double AR-glazed basis collector of RefleC_2 is shown. RefleC_1 was constructed to proof the concept and to investigate thermal and optical losses. Compared to its single AR-glazed basis collector a significant reduction of the thermal losses (related to aperture area) was achieved. The raytracing simulations were validated by IAM measurements on RefleC_1 [7]. The efficiency curve of RefleC_1 was below a very good double AR-glazed flat-plate.

Tab. 1: Parameters of the three RefleC test samples built

Test sample	θ_c [°]	C_{geo} [-]	Aperture width basis collector [mm]	ρ_{hem} reflec-tors [-]	Arc length reflectors [mm]	Arc length gap [mm]	Cover basis collector
RefleC1	35°	1.435	1618	0.838	1145 **(two-sided)**	150	**single** AR glazing
RefleC2	20°	1.625	2080	0.838	1435 **(two-sided)**	190	**double** AR glazing
RefleC3	35°	1.257	1858	0.886	2700 **(cp. Fig. 1 and 6)**	400	**double**, AR glazing and foil

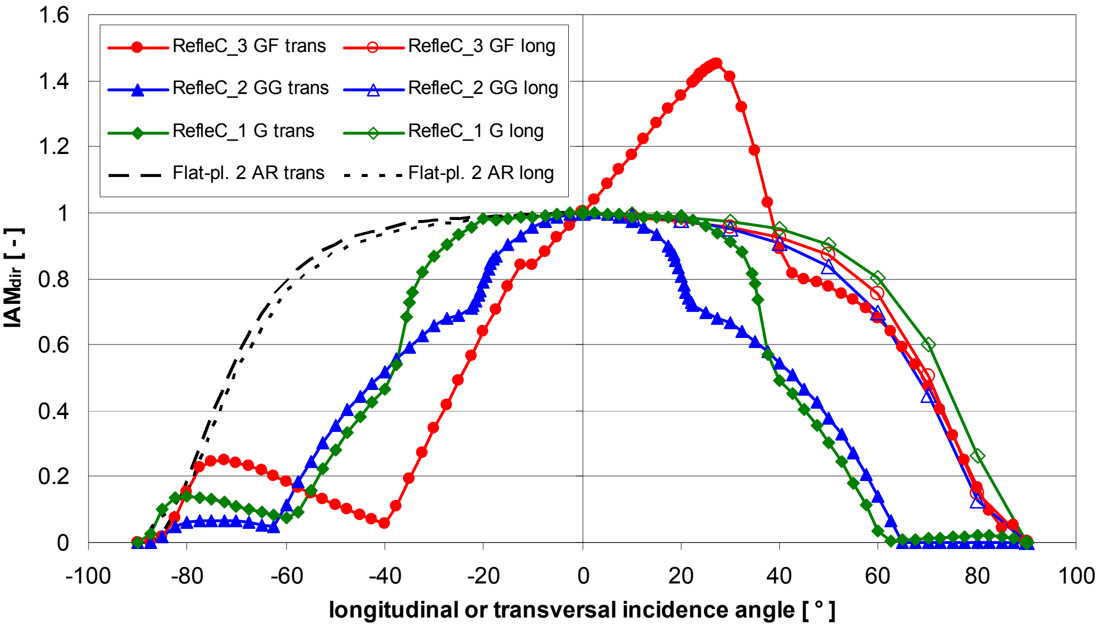

Fig. 3: Raytraced IAM-curves of the three test samples and the double AR-glazed basis collector. The longitudinal curves are symmetric and valid without end losses (only plotted in one direction).

When a measured conversion factor η_o is divided by the effective reflection-transmission-absorption product $(\rho\tau\alpha)_{eff,\perp}$ derived from perpendicular raytracing (cf. Tab. 2), the result is the collector efficiency factor F´. For the double AR-glazed flat-plate this value results to 0.93. For RefleC_1 a significantly lower value of 0.87 results, which in spite of uncertainties because of the influence of the different basis collectors leads to the conclusion that local radiation concentrations can significantly reduce the factor F´ and thus the collector's heat conversion efficiency.

RefleC_2 was constructed with the aim of further reducing the heat losses, which was achieved by double-covering the basis collector and due to a higher concentration ratio. As a drawback of the higher concentration a smaller acceptance half-angle had to be chosen [6]. Thus, the collector was not optimised for a maximum annual energy gain, but for a maximum seasonal gain. The low conversion factor η_o of RefleC_2 can be explained by two fundamental effects:

A comparison of the raytracing results of RefleC_2 single glazed and RefleC_2 double glazed shows that the $(\rho\tau\alpha)_{eff,\perp}$ of the variant with double AR cover is 5.5 % lower due to increased optical losses because of the flat incidence angles of the reflected rays on the cover of the basis collector (not indicated in Tab. 2). Furthermore, a calculation of F´ results in a very poor value of 0.83, which is 10 percentage points below the one of the basis collector. It can be concluded that the high concentration ratio of 1.625 combined with the bundling of rays by the parabolic shape (cf. Fig. 1, center picture) increased the heat removal problems already identified for the first test sample.

RefleC_3 was constructed for an optimized collector field integration and a high acceptance of diffuse irradiation (cf. Tab. 2 and Fig. 6). The local radiation concentration on the absorber was substantially reduced by approximating the remaining lower CPC reflector by three flat segments. This resulted in a calculated F´ of 0.92, which is nearly as high as for the flat-plate. Additionally the thermal losses were in the same range as for RefleC_2, despite of the significantly lower geometrical concentration ratio C_{geo}. Unfortunately the uncertainties of the heat losses of RefleC_3 are higher, since up to now the collector was only measured up to T_{mean} = 93 °C.

2.2. Comparison of collector designs by annual energy gain

For the simulation configuration outlined in the abstract the double-covered flat-plate shows a ca. 22 % higher annual energy gain than a standard flat-plate – at 120 °C the additional gain rises up to ca. 68 %, but at this constantly high inlet temperature the absolute gains are low. The additional gains resulting from the reflector at the optimized slope of 55° are mentioned in the abstract, specific values can be found in Tab. 2. For the RefleC-collectors, the aperture area is always orientated parallel to the absorber and is defined as the area from which perpendicular direct irradiation is directed to the absorber. From Tab. 2 it is clearly visible that RefleC_3 shows significantly higher gains than RefleC_1 and RefleC_2 (which do not show potential to compete with RefleC_3, even if they were double covered and optimized for maximum annual energy gain).

The discontinuous IAM curves (cf. Fig. 3) express a radiation acceptance very sensitive to the incidence angle, which also affects the collector's acceptance of diffuse irradiation. Values for the diffuse IAM $K_{\tau\alpha, diff}$, calculated for isotropic diffuse irradiation are given in Tab. 2. It was an important step in the RefleC project to develop a methodology for simulating the $K_{\tau\alpha, diff}$ for anisotropic diffuse irradiation dynamically for every time step using the Brunger distribution [7]. Energy gain simulations showed that it is crucial for the assessment of the collector's acceptance of diffuse irradiation to model the diffuse irradiation in this more realistic way.
At the current state of our work a fixed, isotropic calculated value for $K_{\tau\alpha, diff}$ would underestimate the annual energy gain of the double-covered flat plate by 8 % at 80 °C (11,3 % at 120 °C). For RefleC_2 the gain would be 12,7 % (16 %) lower and for RefleC_3 even 14,8 % (17,3 %).

For a similar but not double covered collector configuration an additional energy gain of 55 % at 70 °C was simulated for Swedish climate [8]. The reflector length was twice the height of the flat-plate and its reflectance was 0.8. A commercially available flat-plate with internal CPC-reflectors is discussed in [9]. An overview of other commercially available processes heat collectors is given in [10].

Tab. 2: Parameters and simulation results of the RefleC test samples. Simulations are based on the values given in Tab. 1 and 2 and Fig. 2 and 3. At constant collector inlet temperatures every positive energy gain was counted. The IAM for diffuse irradiation was calculated dynamically with anisotropic Brunger distribution [7].

Test sample	A_{Ap} [m^2]	$(\rho\tau\alpha)_{eff,\perp}$ [-]	$K_{\tau\alpha, diff}$ (isotropic, long trough)	β_{opt} [°]	Yield absolute at T_{in} = 80 °C [kWh/year]	Yield absolute at T_{in} = 120 °C [kWh/year]	Yield specific at T_{in} = 120°C [kWh/(m^2 year)]
FP 2 AR	2.022	0.842	0.82	40	639.9	265.1	131.1
RefleC1	4.380	0.838	0.62	40	1229.9	472.9	108.0
RefleC2	3.867	0.755	0.55	40	916.8	464.7	120.2
RefleC3	2.542	0.794	0.67	55	1051.6	667.5	262.6

3. Pilot plant at the laundry Laguna

Since a detailed analysis and optimization of the industrial plant was not covered by the collector development project, only the components of the plant promising for solar thermal heat integration were equipped with measuring devices. A rough system flow diagram and general information on the boundary conditions of the affected technical devices provided the basic information necessary to assess where, at which temperature levels and to which extent solar heat could be integrated.

3.1. Initial situation and possibilities for heat integration

Laguna is a medium-sized laundry situated at a commercial area in Marburg, Germany. The statics of the flat roof were proved to be sufficient for the loads of the collector field. Two gas-fired steam boilers (300 kW each) generate steam which is distributed to the different processes by a steam network. A significant share of the steam is consumed directly. The condensate from the steam which is not directly used returns to the feed water tank. Working time is from 7:30 to 15:30, the plant is not operated at weekends and usually there are no holidays. Four possibilities to integrate solar heat were identified and are shown in Fig. 4.

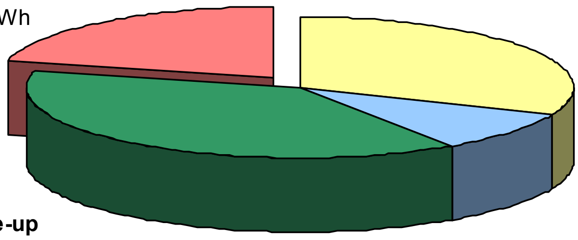

Fig. 4: Thermal load of the four investigated processes for a **typical working day**. The maximum temperatures are all restricted by the supported processes. Solar heated feed-water is further heated by an economizer.

Solar heat integration into the heat distribution network (Fig. 4, left hand side) and into specific processes (Fig. 4, right hand side) was investigated in detail. Boiler feed-water is required constantly during the working hours. Since the feed-water tank has a fill-level control, the additional, decalcified make-up water is usually filled into the tank six times per day for approx. 30 min. at a very constant volume flow of 1 m^3/h. The hot water for the three washing machines is provided by a hot water pipeline. The machines are usually filled once per hour within 30 seconds, while the big machine requires 125 l and the two small machines require 62.5 l each. The temperature levels required vary with the washing programmes. Inside the machines cold water is added to reach the working temperatures between 25 and 75 °C. Via a thermostat the water is heated up by steam in case the temperature is not high enough. The automatic washing plant requires 5 m^3/day at 70 °C with very high instantaneous mass flows of 300 l/min. Here the integration of solar thermal was not realized, also because of the existing internal heat recovery.

Feed-water pre-heating is a very suitable process to be supplied by the high temperature heat from the RefleC-collectors. The other low-temperature processes have a sufficient load with a utilizable temperature of 20 °C and both are open processes, which makes solar pre-heating very economic.

3.2. Solar system design

In Fig. 5 the system concept of the solar system is shown. The size of the system was not primarily determined by the thermal loads but rather by economic reasons, since the prototypes of the RefleC-collectors had to be fabricated with high manual effort.

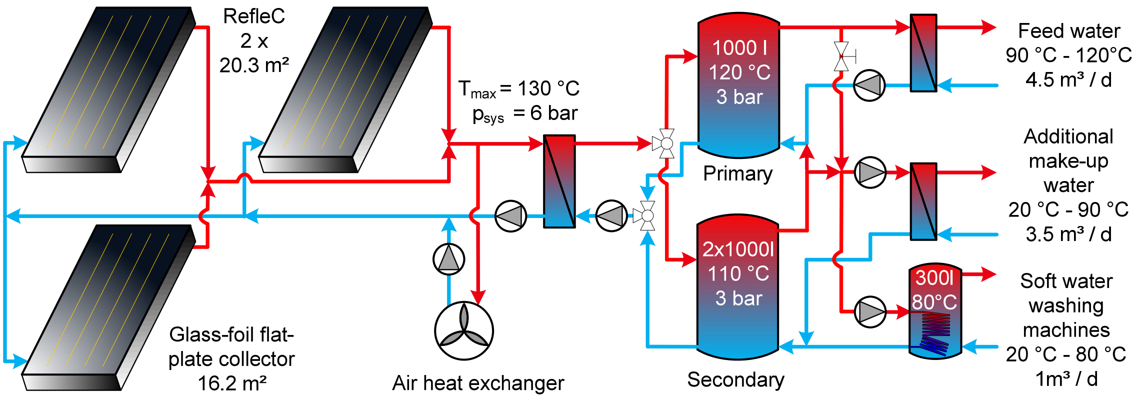

Fig. 5: System design scheme of the solar plant (simplified)

The collector field consists of parallel collectors with three parallel sub-fields. The double-covered flat-plates are mounted in front of the RefleC-collector row (cf. Fig. 6). Either the primary storage or the parallel secondary storages are loaded. The primary storage support the feed-water effectively can due to its low volume; the secondary storages support the low-temperature processes. In winter, the bypass of the feed-water heat exchanger (cf. Fig. 5) is manually opened, so that only the low-temperature processes are supported by all three storages. For feed-water and make-up water fresh water stations transfer the heat. Because of the high instantaneous mass flows, the water for the washing machines is provided from a 300 l storage tank. An air heat exchanger should help to prevent the collector field from stagnation during installation and optimization of the control strategy.

Fig. 6: RefleC-collector field at laundry “Laguna” in Marburg, Germany under construction. Due to the risk of glare and radiation concentration in the ambient, the ends of the trough were equipped with vertical metal sheets.

4. Conclusion and outlook

The simulation results for the newly developed RefleC-collector are very promising. The collector shows at 120 °C ca. 75 % of the energy gain of a very good vacuum tube collector (related to aperture area), so that the new concept could become an economically interesting alternative.
The monitoring equipment installed in this first system built will increase knowledge both on the collector behaviour and on solar thermal integration into process heat systems. Appropriate control mechanisms have to be developed to remove the generated heat from the field effectively, because the thermal capacity of the RefleC-collector is very low.

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