

Theoretical and experimental investigation of polymeric solar-thermal flat-plate collectors

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Abstract

In this paper, a novel approach for manufacturing cost effective polymeric solar-thermal collectors is described. The approach known as Twin-Sheet-Thermoforming (TST) is suitable for mass-production and enables a significant cost saving potential compared to conventional, metal-based collectors. Based on an absorber made of acrylonitrile butadiene styrene (ABS), a collector prototype was set-up and tested according to EN ISO 9806:2013. The results were compared to data available both from literature and market available polymeric collectors. The tested prototype shows a higher solar-thermal efficiency compared to market available polymeric collectors and a similar efficiency compared to laboratory prototypes recently described in literature. Against this background, the production and manufacturing costs of polymeric solar-thermal collectors become increasingly important, as these costs directly affect the Levelized Cost of Heat (LCOH) of a solar-thermal system equipped with such collectors.

Keywords: Solar-thermal flat-plate collector, Collector Efficiency, Polymeric Materials, Experiment

1. Introduction

Currently, solar-thermal systems are facing two challenges: On the one hand, the low commodity prices for oil and gas on the world market cause longer payback periods for solar-thermal systems. On the other hand, heating with other renewable energy sources (e.g. heat pumps in combination with photovoltaic systems) becomes economically more attractive. In order to remain competitive compared to other heat generation systems, prices for solar-thermal systems must be significantly decreased. According to Ivancic et al. (2014), current heat generation costs of solar-thermal systems have to be halved to become cost competitive with heat generated by fossil fuels (*fossil fuel parity*). To achieve this goal, different approaches are currently pursued, e.g. increasing the collector efficiency or decreasing the installation costs with so-called *plug-and-function* systems. Further cost reduction can be realized by utilizing cost-effective, polymeric materials on both collector and system level. In this study, the efficiency of a solar-thermal collector based on a polymeric absorber is investigated.

2. State of science and technology

2.1. Polymeric collectors described in scientific literature

The application of polymeric materials for solar-thermal collectors and systems has been subject of various scientific publications. Next to economic key figures like investment and operating costs, the thermal efficiency of polymeric collectors is of major importance for cost effective solar-thermal systems. However, the thermal efficiency of polymeric solar-thermal flat-plate collectors is limited by the physical properties of polymeric materials such as low temperature and pressure resistance.

Martinopoulos et al. (2010) determined the efficiency¹ of a polymeric collector (absorber area: 1.25 m²) both experimentally and with a numerical flow simulation (CFD). A 10 mm thick honeycomb plate made of polycarbonate (PC) was the basis for the absorber. Two acrylic, rectangular, 8 mm wide pipes were used as header channels and connected with the absorber. The same 10 mm thick honeycomb PC plate was used for the backside insulation of the collector. To minimize the thermal losses to ambient, a special nanogel was used, enabling the overall heat transfer coefficient of the insulation to be lowered to 0.018 W m⁻¹K⁻¹. The authors used a 3 mm thick transparent PC plate as a front cover. A circumferential, 30 mm thick insulation made of extruded

$$^1 \eta = \frac{Q_{out}}{Q_{in}} = \frac{\dot{m} \cdot c_p \cdot (T_{out} - T_{in})}{A \cdot I}$$

polyurethane (PUR) minimized the thermal losses towards ambient. Black colored water was used as the heat transfer fluid (HTF). The efficiency of this collector is shown in Fig. 4 (blue curve). The authors point out the importance of a well-designed inlet of the absorber. In case of a poorly designed inlet, the HTF may not be equally distributed across the whole area of the absorber. As a result, the remaining air inside the collector will deteriorate the heat transfer from the absorber to the HTF, resulting in a decrease of the collector efficiency.

Based on the work of Martinopoulos et al. (2010), Missirlis et al. (2014) investigated different manifold configurations in order to determine the optimal position of both the in- and outlet. The highest efficiency could be obtained with a setup where both the in- and outlet pipe are aligned with the orientation of the honeycombed absorber sheet. The efficiency curve of this setup is shown in Fig. 4 (red curve).

Sandnes and Rekstad (2002) carried out experimental investigations on a combined photovoltaic and solar-thermal (PV/T) collector (absorber area = 0.48 m²). The twin-wall shaped polymeric absorber made from polyphenylene ether (PPE) was filled with a ceramic granulate to increase the heat transfer between absorber and the HTF. A 4 mm thick sheet of glass was used ($\tau \approx 0.9$) as a front cover. The HTF was pumped to the upper manifold of the collector, from where it trickled down through the granulate-filled absorber due to the gravity. The efficiency curve of this collector is shown in Fig. 4 (grey curve).

Ariyawiriyanan et al. (2013) tested five different (unglazed) polymeric collectors to determine both the influence of the material and the aperture area on the thermal efficiency. Three absorbers had the same aperture area (1.30 m²) but were made from different polymeric materials. The remaining two absorbers were made from polyvinyl chloride carbon black (PVC-CB) and had an aperture area of 1.8 and 2.0 m², respectively. According to the results from an outdoor-measurement, the authors suggest to choose an absorber material with a high thermal conductivity. In addition, a correlation between increasing aperture area and collector efficiency was found. The efficiency of the 2.0 m² absorber made from PVC-CB is shown in Fig. 4 (yellow curve).

Chen et al. (2015) also adopted the principle of extruded twin-wall sheets as the basis for a polymeric absorber. The absorber (aperture area: 1.16 m²) consisted of an 8 mm thick twin-wall sheet. An additional 4 mm thick twin-wall sheet was used as a front cover, a 20 mm thick foam material was used as the backside insulation. Both the absorber and the glazing twin-wall sheet were made of transparent PC. In their study, the authors mention one general disadvantage of connecting extruded twin-wall sheets with header channels made from different materials: Due to different coefficients of thermal expansion, leakage may occur at higher operating temperatures. To absorb the incoming irradiation, a black coating was applied to the transparent absorber. The authors were able to demonstrate that the position of the coating (either top or bottom surface of the twin-wall plate) hardly affects the thermal efficiency. The efficiency of the absorber is shown in Fig. 4 (black curve).

2.2 Market available polymeric collectors

The approaches described above resulted in some market available polymeric solar-thermal flat-plate collectors. A honeycomb structure is used as an absorber (gross collector area: 0.95 m²) in case of the *One Sun One World* solar collector. The structure is surrounded by a frame made from multiple polymeric parts which are welded together (Buchinger and Berek, 2015). In between the polymeric absorber and the transparent, polymeric glazing, a honeycomb matrix is inserted to mechanically support the glazing and to prevent large deflections of the glazing (e.g. in case of snow load). In addition to the support function of the matrix, the convective losses can be reduced by using such a honeycomb matrix (Hollands, 1965). An identical honeycomb matrix is used between the backside of the absorber and the backside cover of the collector. In this context, the encapsulated air inside the single cells of the honeycomb matrix acts like an insulator to minimize the backside losses to ambient. The efficiency curve of the *One Sun One World* collector was determined according to EN ISO 9806:2013 (One Sun One World GmbH, 2015) and is shown in Fig. 5 (blue curve).

The collector *Eco Flare 3M*, patented by the Israeli manufacturer *Magen Eco Energy*, is composed of a large number of individual plastic pipes (Sessler et al., 2011). The individual risers connect the two manifolds of rectangular cross-section. The efficiency curve of the collector (gross collector area: 2.25 m²) was determined according to DIN EN 12975-2:2006 (Magen eco energy, 2011) and is shown in Fig. 5 (red curve).

The Norwegian company *Aventa AS* utilizes an extruded twin-wall plate of polyphenylene sulfide (PPS) as a basis for an polymeric absorber (Rekstad, 2012). A special feature of this collector (gross collector area:

2.65m²) is the arrangement of the two manifolds. Both of them are located below the absorber to ensure a proper self-draining when integrating the collector into a drain back system (DBS). The front-side glazing is made of a PC plate. The glazing, absorber and the backside insulation (mineral wool) are held together by a frame made of aluminum profiles. The efficiency curve of the collector was determined according to DIN EN 12975-2:2006 (Aventa AS, 2014) and is shown in Fig. 5 (grey curve).

In conclusion, the application of polymeric materials in solar-thermal collectors has been investigated in depth in scientific literature. Some of these concepts have been adopted by manufacturers of polymeric collectors and further developed. It is worth mentioning that all concepts presented in scientific literature as well as all market available polymeric collectors utilize pre-fabricated, semi-finished products (e.g. twin-wall-plates, pipes, etc.) as the basis for a polymeric absorber. The main advantages of this approach relates to the fact that these semi-finished products are widely used across several different industries (e.g. automotive or aerospace technology), yielding relatively low component costs. However, this approach also lead to some disadvantages. Firstly, the assembly of different parts yields higher production costs, either due to higher personnel or machine costs. Secondly, leakage problems may occur in case of insufficient sealing (e.g. welding) between the connection of single components or due to different coefficients of thermal expansion. Due to the lower raw material costs of polymeric materials compared to metals, the replacement of metallic materials (e.g. copper, aluminum, etc.) yields a cost saving potential. However, the manufacturing of polymeric absorbers and collectors should be linked with the materials applied to unleash the full potential of polymers. Some of the disadvantages described above can be compensated by utilizing a modern manufacturing technique for polymeric materials such as the Twin-Sheet-Thermoforming (TST) process. The manufacturing of a polymeric absorber based on this approach is described subsequently.

3. Setup of a polymeric absorber by means of the Twin-Sheet-Thermoforming manufacturing process

Deviating from common approaches described in scientific publications, a highly automated manufacturing process was chosen for mass production of polymeric absorbers. By comparing the respective advantages and disadvantages of several different polymeric manufacturing processes, the Twin-Sheet-Thermoforming (TST) manufacturing process was found to be the most suitable approach for manufacturing polymeric solar-thermal absorbers. The major advantages of the TST process compared to other processes such as injection molding, extrusion, blow molding or single-sheet-thermoforming are the low unit costs and the high reliability of the process (Ehrenwirth et al., 2016). The necessary process steps for manufacturing a polymeric absorber with the TST process are shown in Fig. 1. The major requirement for the TST is a molding tool that contains two halves. Starting from an initial position with both mold halves open (c.f. Fig. 1-a), two polymeric plates (e.g. made of PP, PC, etc.) are inserted and clamped by a mount (c.f. Fig. 1-b). In the next step, both the upper and lower plate are heated up by means of radiators (c.f. Fig. 1-c). The necessary temperature depends on the type of material used and the level of local deformation. Therefore, the temperature across the plate may vary. Prior to further processing, the radiators have to be removed out of the processing zone (c.f. Fig. 1-d). Subsequently, a vacuum is applied to both polymeric sheets (c.f. Fig. 1-e). The combination of the vacuum applied and the viscous material yields the plates to adopt the form of the mold halves (c.f. Fig. 1-f). Afterwards, the mold halves are closed, sealing together the upper and lower part of the absorber (c.f. Fig. 1-g). As soon as the final shape cooled down, the mold halves re-open (c.f. Fig. 1-h). Cutting away manufacturing remnants leads to the final polymeric absorber (c.f. Fig. 1-i). Applying both appropriate glazing to the front side and an insulation to the backside of the absorber finalizes the process (c.f. Fig. 1-j).

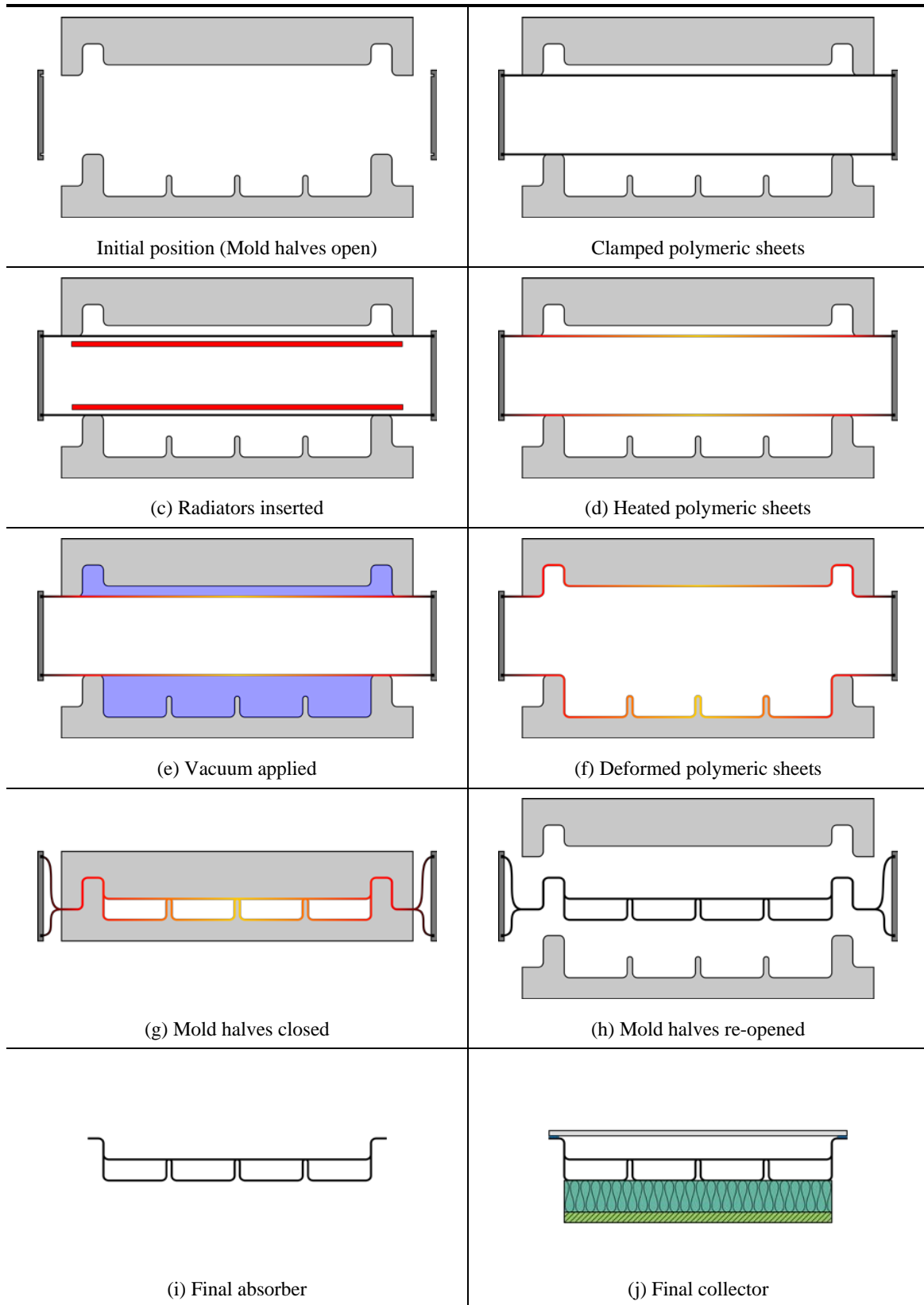


Fig. 1: Necessary process steps for manufacturing a polymeric absorber.

Based on the procedure described above, a prototype was set-up. A 4 mm thick front cover made of glass was glued onto the absorber (c.f. Fig. 2, grey part). A 30 mm thick insulation made from PUR minimizes the heat losses towards the backside (c.f. Fig. 2, crosshatched part). Special profiles made from aluminum were utilized to build a frame, encapsulating the glazing, absorber and the insulation (c.f. Fig. 2, dark blue parts). For both the back and side walls, 4 mm thick transparent walls made from poly(methyl methacrylate) (PMMA) were used. Temperature sensors were applied on the backside of the absorber (T_{Absorber}), the insulation ($T_{\text{Insulation}}$), the back wall (T_{Backside}), the outer side of the glazing (T_{Glazing}) as well as the side wall (T_{Side}) to monitor the temperature of these components during testing. Thermocouples (type T) were used, positioned in the center of each component and fixed with adhesive aluminum tape.

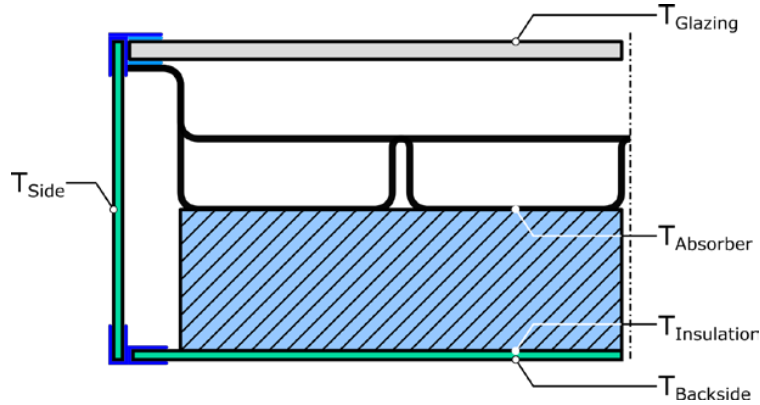


Fig. 2: Cross sectional view of the collector prototype.

The properties of this prototype are summarized in Tab. 1 (last column) and compared with information available from other studies. Comparing the different parts such as absorber, insulation and glazing reveals that the mounted prototype is similar to approaches described in recent studies.

Tab. 1: Properties of polymeric collectors described in previously cited studies vs. tested prototype (last column). Empty cells indicate that no information is available regarding the specific property. Crossed-out cells (—) indicate that the corresponding collector does not include the specific property.

		Martinopoulos et al. (2010), Missirlis et al. (2014)	Sandnes and Rekstad (2002)	Ariyawiriyanan et al. (2013)	Chen et al. (2015)	Tested prototype investigated in this study
Absorber	Area	1.30 m ²	1.30 - 2.00 m ²	0.50 m ²	1.20 m ²	1.32 m ²
	Thickness	10 mm			8 mm	8 mm
	Material	PC	PPO	PVC-B, PB, PP-R, PVC-CB	PC	ABS
	Type	Honeycomb	Twin-wall	Twin-wall	Twin-wall	Twin-Sheet- Thermoforming
Insulation	Thickness (back)	10 mm	50 mm		20 mm	30 mm
	Material (back)	PC + nanogel	Mineral wool		Polyfoam	PUR
	Thickness (side)	30 mm	—		—	—
	Material (side)	PUR	—		—	—
Glazing	Thickness	3 mm	4 mm	—	4 mm	4 mm
	Material	PC	Glass	—	PC	Glass
	Type	Plate	Plate	—	Twin-wall	Plate

The efficiency of the tested prototype was determined according to EN ISO 9806:201 using the university's solar simulator. Fig. 3-a shows the setup of the test rig. The HTF is pumped through the tested prototype (2) by means of a pump (1). An array of special lamps (not shown in the sketch) provides an irradiation with a spectrum similar to the sunlight towards the collector. The energy absorbed by the collector is removed w of a heat exchanger (3) to provide constant inlet temperatures. The volume flow rate is monitored with a magnetic-inductive flow sensor (4). Deviating from EN ISO 9806:201, an additional reservoir (9) was included to the system. As this reservoir is open to the atmosphere, the operating pressure inside the system is a function of the difference in height between collector and reservoir (Pascal's principle). This setup was chosen to prevent damages to the prototype in case of over-pressure. During the test, the inlet (5) and the outlet temperature (6) as well as the ambient temperature (7) were monitored with temperature sensors. Furthermore, the in-plane irradiation is recorded by means of a pyranometer (8). A photo of the prototype during testing can be seen in Figure 5-b.

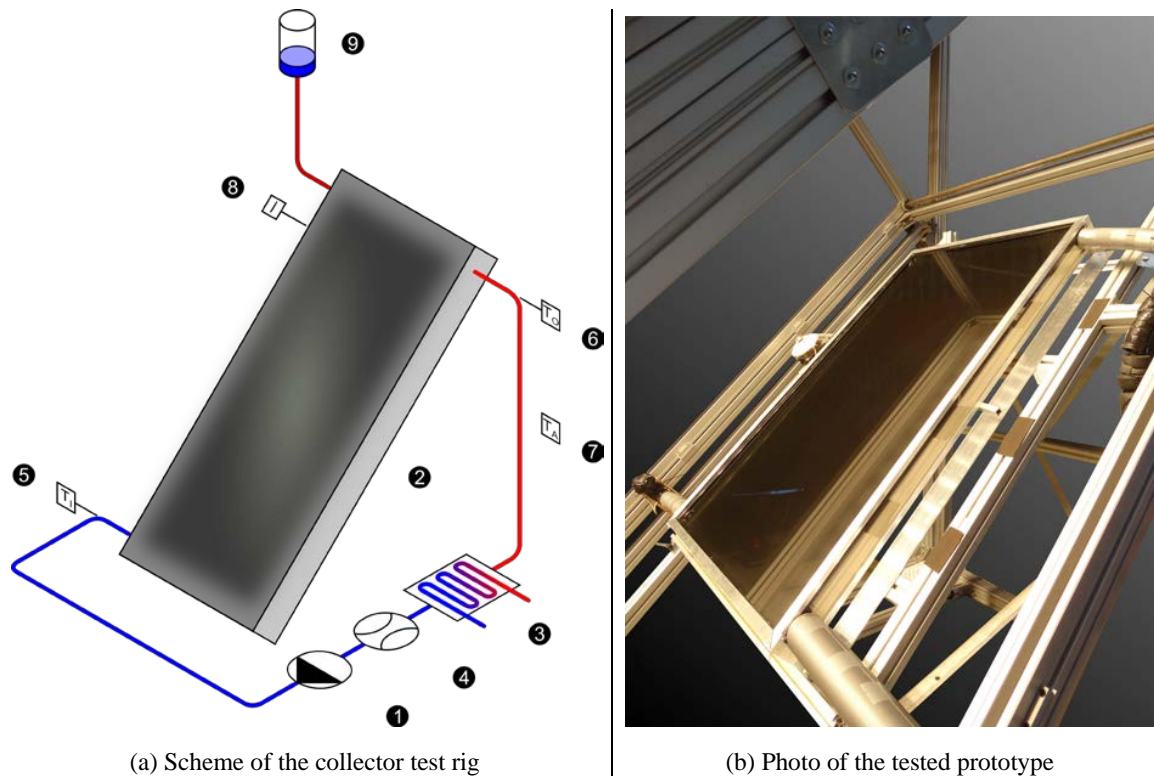


Fig. 3: Determination of the solar-thermal efficiency according to EN ISO 9806:2013.

4. Results and discussion

The efficiency curve of the tested prototype in relation to data available from literature is presented in Fig. 4 (green curve). The measured efficiency curve is well comparable with the results reported by Martinopoulos et al. (2010). Following the advices given by Missirlis et al. (2014), the efficiency of the prototypes could be improved by means of an arrangement of the in- and outlet pipe into and out of the manifolds. A comparison of the tested prototype with market available collectors reveals the highest solar-thermal efficiency of all polymeric collectors analyzed for temperatures $(T_{\text{mean}} - T_{\text{amb}}) / I < 0.07 \text{ m}^2\text{KW}^{-1}$ (c.f. Fig. 5). During measurement of the solar-thermal efficiency of the prototype, the temperatures of each component of the collector were recorded. Tab. 2 (first four rows) shows the steady-state temperatures for different inlet temperatures. Except for the lowest inlet temperature (24.2 °C), the absorber always reaches the highest temperature measured, followed by the glazing and the insulation. Between the insulation and the backside wall, only a small difference in temperature is observed (0.2 °C – 1.4 °C). The temperatures of the side walls are ranging at similar levels as the backside wall.

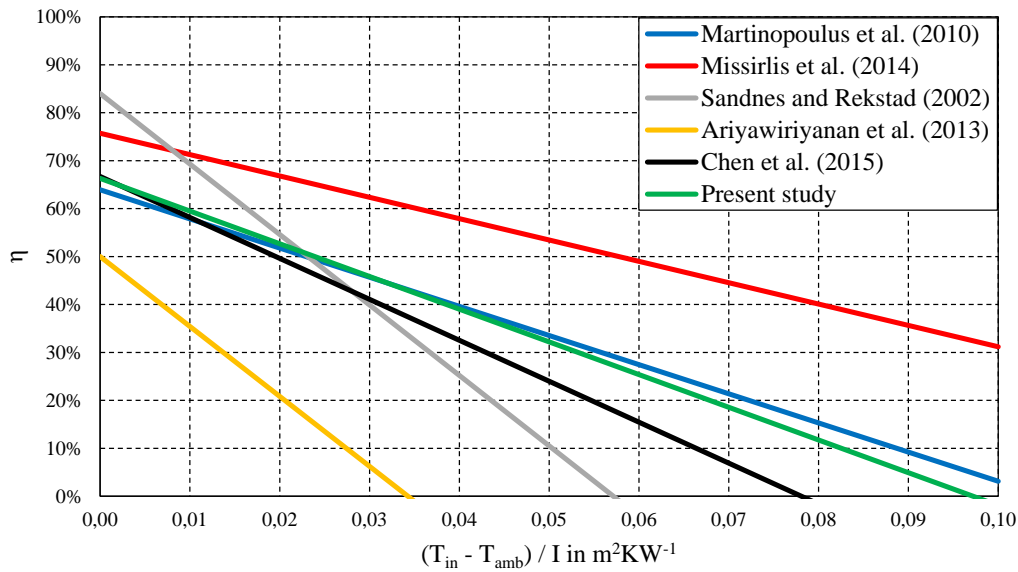


Fig. 4: Efficiency curve of the tested prototype (green curve) contrasted with data available from literature.

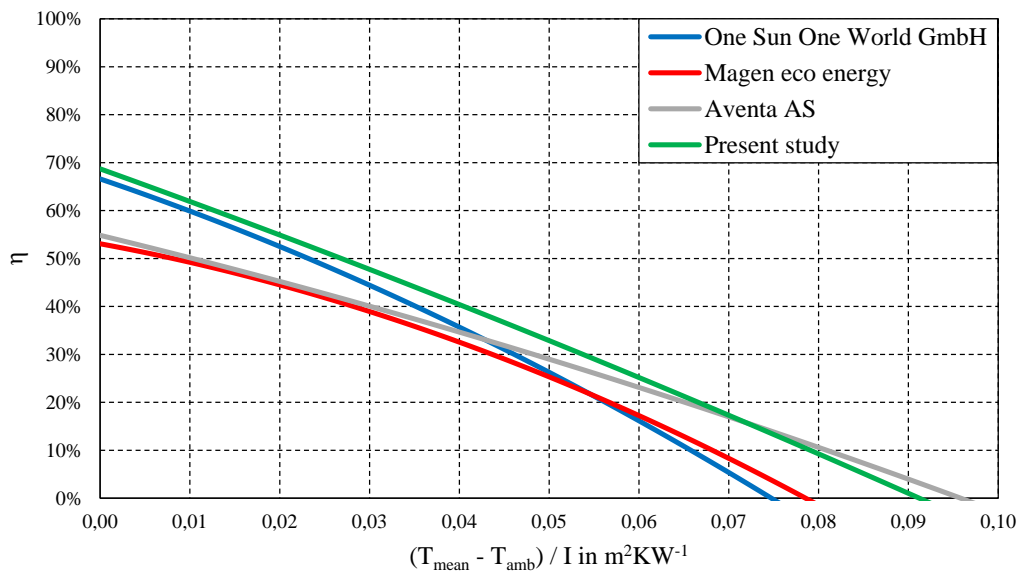


Fig. 5: Efficiency curve of the tested prototype (green curve) compared with market available polymeric collectors (data source: One Sun One World GmbH (2015), Magen eco energy (2011) and Aventa AS (2014)). The efficiency of *One Sun One World* solar collector was determined according to EN ISO 9806:2013, the efficiency of the collectors from *Magen Eco Energy* and *Aventa AS* according to DIN EN 12975-2:2006. For a comparability of the efficiency determined according to different standards, the ratios η_0 , a_1 and a_2 were multiplied by the ratio of the aperture surface area to the gross collector area in the case of *Magen Eco Energy* and *Aventa AS*.

In addition to the case of HTF flowing through the absorber, the component temperatures were evaluated in case of dry stagnation for two different values of irradiation (c.f. Tab. 2, last two rows). Special attention is attributed to the maximum absorber temperature (93.6 °C), as this temperature is of crucial importance for the polymeric material used. In case of ABS, the maximum permissible temperature for permanent operation ranges between 95 °C and 105 °C (Bonten, 2014, p. 199).

Tab. 2: Measured component temperatures for different inlet temperatures in case of a filled absorber and for different values of irradiation in case of an empty absorber (dry stagnation).

T _{Inlet} in °C	T _{Outlet} in °C	T _{Ambient} in °C	T _{Glazing} in °C	T _{Absorber} in °C	T _{Insulation} in °C	T _{Wall (back)} in °C	T _{Wall (left)} in °C	T _{Wall (right)} in °C	I in W/m ²
24.2	30.7	26.5	35.5	30.1	28.5	28.1	29.6	27.5	852.5
35.9	41.5	26.4	38.3	40.4	28.9	28.1	29.9	28.0	853.4
50.5	55.1	27.1	43.2	53.7	31.5	30.3	31.6	29.8	852.1
65.1	68.4	26.6	47.3	67.3	32.2	30.8	32.0	29.9	851.9
Dry stagnation		26.6	64.3	93.6	33.7	31.9	32.9	31.3	879.3
Dry stagnation		27.5	54.7	88.7	33.5	31.6	31.6	29.9	635.0

5. Summary and Outlook

Within this paper, a polymeric solar-thermal absorber made of ABS was produced by means of the Twin-Sheet-Thermoforming manufacturing process. Based on a literature research, characteristic properties of both polymeric absorbers and other main components of polymeric solar-thermal collectors were identified and taken into account when setting up an appropriate prototype. The evaluation of the solar-thermal efficiency according to EN ISO 9806:2013 indicates competitive results compared to different concepts of polymeric collectors both described in scientific literature and market available collectors. Against this background, the production and manufacturing costs of polymeric solar-thermal collectors become increasingly important, as these costs directly affect the Levelized Cost of Heat (LCOH) of a solar-thermal system equipped with such collectors. As a technology capable of mass-production, the utilization of the highly automated TST for manufacturing polymeric solar-thermal collectors enables a significant cost-reduction. However, due to material limitations (such as low pressure and temperature resistance), polymeric solar-thermal collectors must always be considered as part of an entire solar-thermal system. Extending the application of polymeric materials to other parts of a solar-thermal system (e.g. pipes, heat storage, etc.) can therefore lead to further cost reductions. The determination of the LCOH of such a polymeric solar-thermal system is therefore subject of further research.

6. References

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