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Analysis of polymeric solar-thermal collectors in drain back systems by simulation

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Abstract

Polymeric solar-thermal collectors combine positive engineering properties and attractive cost saving potentials. However, volumetric absorbers made from polymers require open, non-pressurised systems in order to resist the typical loads acting on such a setup. The drain back principle is able to meet these requirements but demands higher pump capacities and additional components. This papers analyses the thermal behavior of polymer-based drain back systems in simulation studies based on MATLAB/Simulink and compares it with the performance of conventional metal-based solar-thermal systems. The results indicate a lower maximum collector temperature for the drain back system compared to the conventional setup as well as a slight decrease in the system efficiency.

Keywords: Polymeric collector; solar-thermal system; drain back system; simulation; MATLAB/Simulink; CARNOT

1. Introduction

Over the last years, polymeric materials became increasingly important in various sectors, e.g. automotive, construction or packaging industry. The positive engineering properties of plastics such as low weight, freedom of design and manufacturing techniques have contributed to the success of these materials. Polymer-based solar-thermal collectors provide an attractive cost-saving potential compared to commonly used materials (e.g. copper, aluminium). However, the economic benefit of standard solar-thermal systems equipped with polymeric collectors compared to standard systems is very limited due to the balance between decreased system costs and decreased system efficiency (Reiter 2014b). Furthermore, the thermal and mechanical limitations of polymers turn the application of plastics into a challenge. Consequently, new system setups for the specific properties of polymeric collectors are required. A non-pressurised drain back system avoids stability problems of the absorber and moreover allows an extension of the use of polymers to the parts of the solar circuit for further cost reductions. The analysis and evaluation of so-called drain back systems with polymeric collectors via simulation will be the basic step to overcome the mentioned hurdles for polymeric collectors.

2. Basic Principle of Drain Back Systems

A well-known problem of solar-thermal systems is stagnation. The evaporation of the solar fluid causes a high pressure inside the collector, which is critical for polymeric materials in combination with the high temperatures. These problems can be overcome with the open, unpressurised architecture of a drain back system. During normal operation, a pump (1) circulates the heat carrier through the solar-thermal collectors (2) (Fig. 1, left). Afterwards, the fluid passes the drain back vessel (3) and the heat exchanger unit of the storage tank (4) to transfer the heat to the storage volume. All components of the system — except the collector — are located inside the building.

In contrast to a standard solar-thermal system, a drain back system is usually open and non-pressurised. As soon as the pump switches off, the collectors empty themselves as the solar fluid drains back into the vessel (cf. Fig. 1, right). This approach offers several advantages. As the heat carrier remains inside the frost-

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protected shell of the building, there is no need for an anti-freeze fluid. Compared to conventional systems — which usually use a water-glycol-mixture as a heat-carrier — the use of water is much cheaper and offers better heat transfer properties. The unpressurised system configuration allows the utilization of volumetric absorbers, which enables a high heat transfer capability between absorber and fluid. Cost advantages result from the use of cost-efficient polymeric pipes within the solar circuit. Furthermore, essential safety components (e.g. expansion vessel, bleeder valves, etc.) can be saved due to the non-pressurised setup of the system.

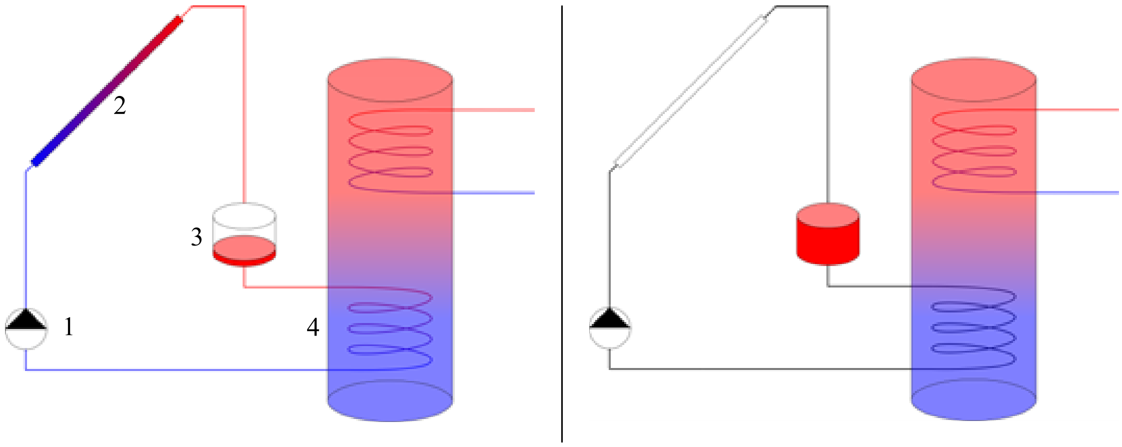

Fig. 1: Schematic build-up of a drain back system (left: operating mode; right: system shut down)

The open architecture requires higher pump capacities at the start of the system operation. The pump has to overcome the height difference from the drain back tank to the highest point of the system until the solar circuit is filled. Another drawback of a drain back system could be an increased effort for installing / mounting the system. Since the water has to be able to drain back as the pump switches off, a strict angle of inclination of the pipes has to be ensured to prevent frost damages caused by remaining water in the collectors and the piping outside the building.

The advantages of the drain back principle represent a great potential for solar-thermal systems with polymeric components to reach a higher economic benefit. The analysis of the system behavior regarding the thermal output is the essential basis to evaluate the competitiveness of new setups. Therefore, the various solar-thermal system setups were investigated in simulation models. Furthermore, the influence on the solar yield depending on the implemented heat source and heat distribution system was analysed to identify the optimal use of polymeric systems.

3. Simulation Model

MATLAB/Simulink (Mathworks n.d.) and the CARNOT Blockset (Hafner et al. 1999) were used to investigate the solar-thermal systems via simulation. In a first step, a detailed analysis of different types of heating systems and solar-thermal collectors was performed. Afterwards, the influence of various climates on the performance of drain back systems was investigated.

Investigation of different heating types for the application of drain back systems

In this set of simulations both an older building with a high energy demand and a standard building with a lower energy demand located in Würzburg (Germany) has been analysed. The parameters of the two building types can be seen in Tab. 1. The older building corresponds to an energy efficiency class F (according to $EnEV_{2014}$), the standard building corresponds to an energy efficiency class B (according to $EnEV_{2014}$) (EnEV 2013). The analysis of different heating systems in those single-family households is the basis for the evaluation of the annual solar yield.

Tab. 1: Description of the simulated heating systems

		Würzburg (Germany)	**Oslo (Norway)**	**Rome (Italy)**
Older building with 150 m^2	Domestic hot water load in kWh/m^{2}a	17	17	17
	Space heating load in kWh/m^{2}a	158	192	71
	Total system load in kW/m^{2}a	**175**	**209**	**88**
Standard building with 150 m^2	Domestic hot water load in kW/m^{2}a	17	17	17
	Space heating load in kW/m^{2}a	54	67	22
	Total system load in kW/m^{2}a	**71**	**84**	**39**

For the two building types located in Würzburg, two scenarios for the system setup were distinguished (cf. Tab. 2) in order to point out the influences on the performance of the solar-thermal system. A 15 kW oil heating boiler and a floor heating are used in scenario A. In scenario B a 15 kW oil heating boiler in combination with radiators is used. The implementation of radiators as heat distribution system will lead to a decreased solar yield because of the higher flow temperatures for the heat supply in the building.

Tab. 2: Scenarios for conventional heat generation and heat distribution in the simulation models

Scenario	Type of heat source	Type of heat distribution system
A	Oil heating boiler (15 kW)	Floor heating (flow temperature: 26–35 °C)
B	Oil heating boiler (15 kW)	Radiator (flow temperature: 31–79 °C)

The scenarios were equipped with various solar-thermal systems (cf. Tab. 3). These systems for domestic hot water preparation and space heating have eight collectors with a total aperture area of 14.6 m^2 and a 900 l storage tank.

Tab. 3: Setups of the solar-thermal systems

System	Type of collector	Type of solar circuit	Fluid
1	State-of-the-art collector	Closed, pressurised	Water-glycol mixture
2	Polymeric collector	Closed, pressurised	Water-glycol mixture
3	Polymeric collector	Closed, pressurised	Water
4	Polymeric collector	Drain back	Water

The combination of the two different scenarios and the four different setups for the solar-thermal systems are shown in Fig. 2. On the left side of the energy flow chart, all energy sources are listed which can contribute heat to the storage tank. Here, the energy supply from the auxiliary heater (in this case an oil heating boiler) and the energy supply from different kinds of collector arrays (according to Tab. 3) are taken into account. On the right side of the chart, two different heat consumers (domestic hot water demand and domestic space heating demand) are listed.

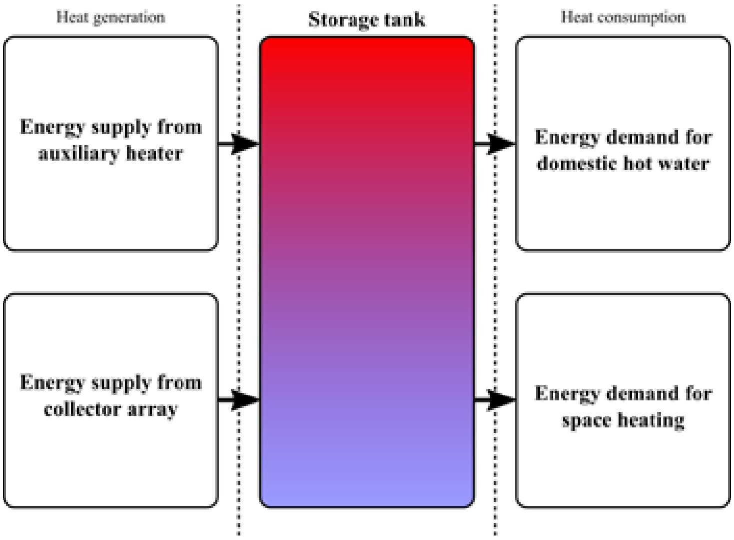

Fig. 2: Energy flow chart of the investigated solar-thermal systems

The collector array is orientated with a slope of 45° directly to the south and the volume flow is 40 $lm^{-2}h^{-1}$. The state-of-the-art collector of system 1 is a commonly used flat-plate collector type with selective absorber coating. The parameters of the state-of-the-art collector and the polymeric collector are shown in Tab. 4.

Tab. 4: Parameters of the two collector types

Collector data	State-of-the-art collector	Polymeric collector	Unit
Zero loss efficiency	0.771	0.811	--
Linear heat loss coefficient	3.68	6.30	$Wm^{-2}K^{-1}$
Quadratic heat loss coefficient	0.0127	0.0215	$Wm^{-2}K^{-2}$
Stagnation temperature	208	128	°C

The polymeric collector with a rigid foam trough and a non-selective (α=ε=0.95), volumetric absorber was implemented in a dynamic two-dimensional collector model being developed for parameter studies in collector design (Reiter et al. 2014a). The collector concept was optimized regarding manufacturing costs and part temperatures being suitable for commodity plastics (Reiter et al. 2014b). Therefore, the selective coating was omitted and the insulation has a reduced thickness in combination with an additional air gap of 20 mm. The identified stagnation temperature according to standard DIN EN 12975-2 (2006) was 128 °C. This enables the use of polypropylene (PP) as material for absorber and trough. The glazing is a conventional single cover made from solar glass. Fig. 3 shows the sectional view of the polymeric collector approach.

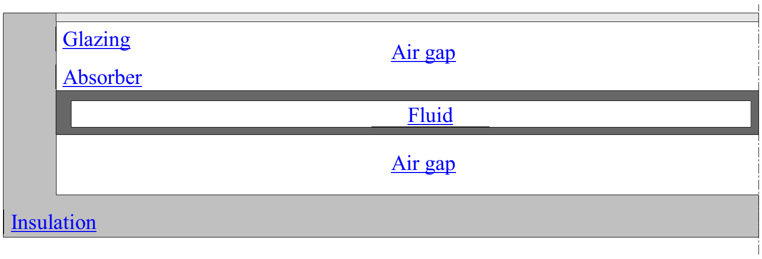

Fig. 3: Cross section of the polymeric collector model

Fig. 4 shows the efficiency curves of both collectors. Due to the missing selective coating the polymeric collector approach has a decreased efficiency in comparison to the state-of-the-art collector.

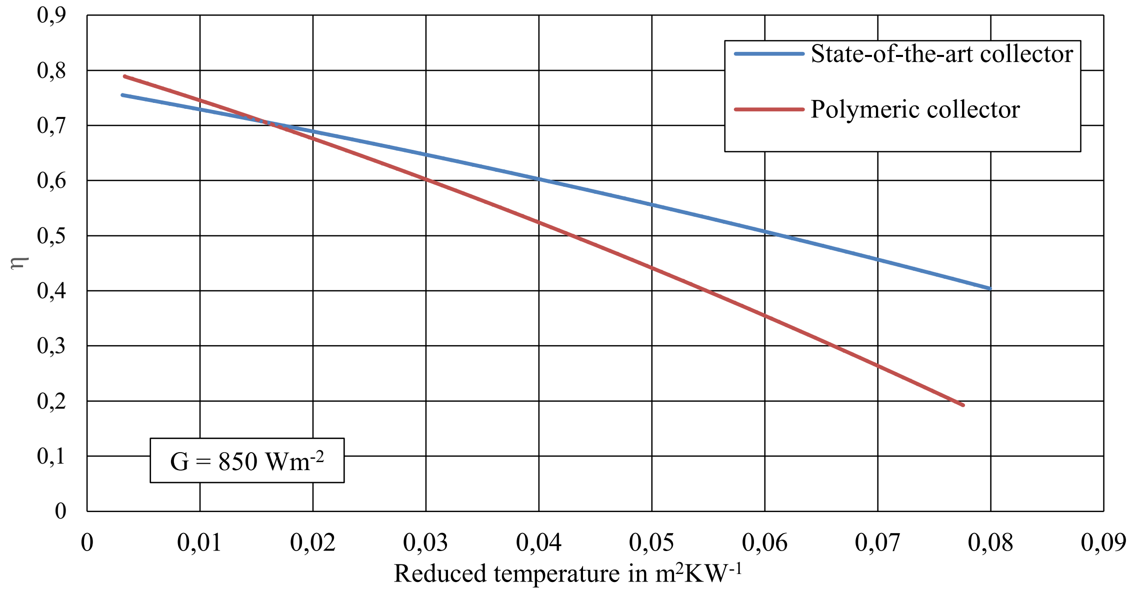

Fig. 4: Collector efficiency

In the drain back system, the fluid content of approx. 40 l is stored in the external drain back tank. The tank has a volume of 80 l and has the same insulation properties like the storage tank.

Investigation of various climatic regions for the application of drain back systems

In order to evaluate the drain back systems under various climates, three different locations were considered in this study. Tab. 5 shows the amount of annual irradiation (direct and diffuse) as well as the annual mean temperature of the locations.

Tab. 5: Annual irradiation and mean temperatures of the three locations for the simulation study

	Würzburg (Germany)	**Rome (Italy)**	**Oslo (Norway)**
Annual direct irradiation in $\frac{\mathrm{kWh}}{\mathrm{m^2a}}$	531	925	407
Annual diffuse irradiation in $\frac{\mathrm{kWh}}{\mathrm{m^2a}}$	564	640	464
Mean annual temperature in °C	9.0	15.6	7.3

All simulation models use an oil heating boiler for heat generation in combination with a floor heating (scenario A). The heat generation is supported by a drain back system with polymeric collectors (System 4). Again, an older building with a high energy demand and a standard building with a lower energy demand were taken into account. The parameters of the two building types are shown in Tab. 1.

4. Simulation Results and Discussion

The efficiency of the solar-thermal system concepts is analysed and evaluated in annual simulations by means of the fractional energy savings f_{sav} according to the standard DIN EN 12977-2 (2012). The fractional energy savings are the relation between the amount of conventional energy being saved by means of the solar-thermal system and the energy consumption of the conventional heating system without solar-thermal installations (cf. eq. 1).

$$f_{sav} = \frac{Q_{Con} - Q_{aux}}{Q_{con}} \times 100\% \qquad \text{(eq. 1)}$$

with:

Q_{Con}: Energy consumption of the heater of the conventional system

Q_{aux}: Energy consumption of the auxiliary heater of the solar-thermal system

Investigation of different heating types for the application of drain back systems

The solar-thermal system with state-of-the-art collectors and closed, pressurised solar circuit (system 1) represents the reference for the evaluation of the systems in the different scenarios. The fractional energy savings of the systems as well with polymeric collectors show the expected reduced solar yield due to the lower collector efficiency (cd. Tab. 6). Thus, the fractional energy saving decreases in scenario A from 28.3 % to 22.8 % (in case of an older building) and from 13.3 % to 10.4 % (in case of a standard building). The influence on the solar yield due to the lower efficiency of the polymeric collectors is approximately -19.7 % (older building) or rather -21.8 % (standard building).

Tab. 6: Fractional energy savings of the simulated systems

Index	Type of heat generation / heat distribution system	Type of solar-thermal system	Standard building		Older building	
			f_{sav} in %	Relative decrease in %	f_{sav} in %	Relative decrease in %
A1	Oil heating boiler / floor heating	State-of-the-art collector (water-glycol mixture)	28.3	---	13.3	---
A2		Polymer-based collector (water glycol mixture)	22.8	approx. -19.7	10.4	approx. -21.8
A3		Polymer-based collector (water)	22.7		10.4	
A4		Drain back system (water)	22.7		10.4	
B1	Oil heating boiler / Radiators	State-of-the-art collector (water-glycol mixture)	15.9	---	7.6	---
B2		Polymer-based collector (water glycol mixture)	11.2	approx. -30.0	5.3	approx. -30.6
B3		Polymer-based collector (water)	11.2		5.3	
B4		Drain back system (water)	11.1		5.2	

Scenario B with oil heating boiler and radiators, however, shows a higher influence on the system performance due to polymeric collectors. The fractional energy savings of the systems with polymeric collectors are about 11.2 % in case of an older building and 5.3 % in case of the standard building, whereas the reference system shows 15.9 % (older building) / 7.6 % (standard building). The required high flow temperatures for the radiators cause a decrease between -30.0 % and -30.6% of the solar yield in the systems with polymeric collectors.

The use of water instead of water-glycol mixture causes almost none influence on the system efficiency. This effect can be observed independent from the type of heat generation and the type of building. The volumetric absorber design enables an optimal heat transfer from absorber surface to fluid. Furthermore, the flow conditions in the absorber are in all cases laminar due to low fluid velocities caused by the large cross section of the part. Thus, the fluid properties have a much smaller influence on the collector performance than in state-of-the-art collectors.

The drain back system setup has also almost none influence on the system performance. The delayed collector operation due to the filling and the emptying of the collector array as well as the additional heat losses of the drain back tank show no considerable effect on the fractional energy savings.

Investigation of different climatic regions for the application of drain back systems

The fractional energy savings of the systems as well as the relative decrease of the solar yield — in relation to the reference system — are listed in Tab. 7. Again, the solar-thermal system with state-of-the-art collectors and closed, pressurised solar circuit (system 1) is the reference for the evaluation of the systems.

Tab. 7: Fractional energy savings of the simulated systems depending on the location

Location	**Type of solar-thermal system**	**Standard building**		**Older building**	
		fsav in %	**Relative decrease in %**	**fsav in %**	**Relative decrease in %**
Würzburg	State-of-the-art collector (water-glycol mixture)	28.3	---	13.3	---
	Drain back system (water)	22.7	-19.8	10.4	-21.9
Oslo	State-of-the-art collector (water-glycol mixture)	19.4	---	8.8	---
	Drain back system (water)	15.1	-22.0	6.6	-24.7
Rome	State-of-the-art collector (water-glycol mixture)	66.7	---	37.2	---
	Drain back system (water)	57.5	-13.8	31.1	-16.6

The high irradiation values (cf. Tab. 5) cause the highest fractional energy savings in Rome. In case of the older building the fractional energy savings are 37.2 and 66.7 % in case of the standard building. However, the investigated system setups focus on locations with higher heating energy demands like in Central or Northern Europe.

The older building located in Würzburg enables fractional energy savings of 13.3 % respectively 28.3 % in case of the standard building. Using a drain back system with polymeric collectors causes relative decreases of -21.9 % (older building) or rather -19.8 % (standard building) in comparison to the reference system (pressurised system with state-of-the-art-collectors).

Due to low irradiation values and cold temperatures in Oslo, fractional energy savings of only 8.8 % (in case of the older building) respectively 19.4 % (in case of the standard building) were reached. Nevertheless, the relative decreases in system efficiency (-24.7 % / -22.0 %) are comparable to the values from Würzburg.

The results indicate a good applicability of drain back systems in southern climate zones — apart from the above mentioned aspect of the system setup for warm climates — because of the low discrepancy of the relative decreases against the reference system. For Central and Northern Europe, the relative decreases of the system efficiency between reference systems and drain back systems are quite similar. Hence, polymeric collectors show almost the same potential for cold and moderate climates despite the reduced collector efficiency.

5. Conclusion

The simulation study proved, that drain back systems with polymeric collectors reduce the solar yield of the solar-thermal systems by approximately a fifth compared to conventional setups of solar-thermal systems in Oslo and Würzburg. In Rome, the relative efficiency decrease between the reference systems and the drain back systems is even lower. However, polymeric solar-thermal systems in buildings with radiators have a limited energetic potential. The influences of the adjustments for polymeric systems are negligible.

The reduction of maximum collector temperature from 208 °C to 128 °C in combination with non-pressurised setup enables a wide use of cost-effective materials for the installed parts. Furthermore, by saving parts like the expansion vessel or safety valves as well as glycol-mixture the simple setup results in a high cost saving potential of polymeric drain back systems. This will lead lower system costs and will balance the reduced system performance.

The results of the simulations serve as a basis for further investigations on system level enabling a comparison of solar-thermal heat costs in terms of cents per kilowatt hour. Therefore, the model has to be extended with regard to the electric power consumption of the pumps. Also the costs for the system setups have to be identified for a detailed cost analysis.

6. References

DIN EN 12975-2 (2006) *Thermal solar systems and components – Solar collectors – Part 2: Test metho*ds; German version EN 12975-2:2006. DIN German Institute for Standardization. Berlin (DE): Beuth Verlag GmbH, pp. 16.

DIN EN 12977-2 (2012) *Thermal solar systems and components – Custom built systems – Part 2: Test methods for solar water heaters and combisystems*; German version EN 12977-2:2012. DIN German Institute for Standardization. Berlin (DE): Beuth Verlag GmbH, pp. 21.

EnEV 2014: Zweite Verordnung zur Änderung der Energieeinsparverordnung, vom 18. November 2013, Bundesministerium für Verkehr, Bau und Stadtentwicklung, Berlin 2013.

HAFNER, B. et al. (1999) Carnot Blockset Version 1.0 - Conventional and renewable energy systems optimization blockset - User's guide. Solar-Institut Jülich, Fachhochschule Aachen.

MATHWORKS (n.d.) *Simulink* [WWW] The MathWorks, Inc. Available from: http://www.mathworks.com/help/toolbox/simulink/index.html [Accessed: 28/08/14].

REITER et al. (2014a) Performance Optimisation of Polymeric Collectors by Means of Dynamic Simulation and Sensitivity Analysis. *Energy Procedia - Proceedings of the 2nd International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2013),* Volume 48, pp. 181-191.

REITER et al. (2014b) Simulationsgestützte Leistungsanpassung von Kunststoffkollektoren. In: *24. Symposium Thermische Solarenergie, Bad Staffelstein (DE), May 2014*. Regensburg (DE): Ostbayerisches Technologie-Transfer-Institut e.V. (OTTI), pp. 34-35.