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Results of IEA SHC Task 45: Large scale solar heating and cooling systems. Subtask A: "Collectors and collector loop"

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Abstract

The IEA SHC Task 45 Large Scale Solar Heating and Cooling Systems, carried out between January 2011 and December 2014, had the main objective to assist in the development of a strong and sustainable market of large solar heating systems by focusing on high performance and reliability of systems. Within this project, subtask A had the more specific objectives of investigating ways to evaluate the influence that different operating conditions can have on the collector performance, assure proper and safe installation of large solar collector fields, and guarantee their performance and yearly energy output. The results of the different investigations are presented, with a particular focus on how different parameters such as tilt, flow rate and fluid type, can affect the collector efficiency. Other presented results include methods to guarantee and check the thermal performance of a solar collector field and guidelines to design collector fields in such a way that the flow distribution is improved and the risks related to stagnation are minimized.

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Keywords: solar collector field; collector efficiency; fluid type; water; propylene glycol; tilt angle; flow rate; flow regime; FEP; stagnation; flow distribution; performance guarantee.

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Nomenclature

a_1	first order heat loss coefficient, (W m^{-2} K^{-1})
a_2	second order heat loss coefficient, (W m^{-2} K^{-1})
A_c	collector area corresponding to the collector efficiency parameters η_0, a_1 and a_2
f_P	correction factor taking into account heat losses from pipes and transmission lines in the collector field, (-)
f_o	correction factor for other things, such as non-ideal flow distribution and unforeseen heat losses, (-)
f_U	correction factor taking into account measurement uncertainty, (-)
G	total solar irradiance on the collector plane, (W m^{-2})
P_g	guaranteed thermal power output from the solar collector field, (W)
T_a	ambient temperature, (°C)
T_m	fluid mean temperature, (°C)
η	collector efficiency, (–)
η_0	peak collector efficiency, (–)

1. Introduction

The main objective of the IEA-SHC Task 45 was to assist in the development of a strong and sustainable market of large solar heating and cooling systems by focusing on cost effectiveness, high performance and reliability of systems. Within this task, Subtask A had a more specific focus on the source side of a solar heating system, i.e. the collectors and the collector loop. Specific objectives of this subtask were: improvement in the understanding and usage of collector efficiency test results; proposing requirements for collector loop installation both in terms of cost reduction and homogenous flow distribution and including precautions for safety, expansion and stagnation; procedure for guaranteeing and checking the performance of collector field and heat exchanger.

2. Influence of fluid type, flow rate and collector tilt on collector efficiency

The test conditions used during collector tests are often different from those in the real-world operation: the actual collector efficiency expression will therefore be different. In particular, this study focused on the effect of using different flow rate, tilt angle and heat transfer fluid. The influence of changes of these parameters on the collector efficiency may be different from one collector type to another; therefore different collectors were investigated.

2.1. Description of the investigated collectors

The first collector under investigation was a glazed flat plate collector (model COL-4X8-NL-SGI-SH10), manufactured by the Canadian company EnerWorks Inc [1]. The aperture and gross area are 2.72 m^2 and 2.87 m^2 respectively. The absorber is made of 0.5 mm thick aluminum foil, while the serpentine pipe and the two headers are made of copper. The glass cover consists of a 3.3 mm thick AFG Solatex tempered glass with sand pattern. The collector is insulated with mineral wool on the back and by polyisocyanurate foam along the edges.

The other two investigated collectors were the models HT-SA and HT-A 35-10 manufactured by the Danish company Arcon Solar A/S (now Arcon-Sunmark) [2,3]. The collectors are largely identical in terms of design and technical specifications and the only difference is a 0.025 mm thick FEP (fluorinated ethylene propylene) foil interposed between absorber and glass cover in the HT-SA model, in order to decrease the heat losses by acting as a convection barrier. Both collectors have an aperture area of 12.60 m^2, and the absorber consists of 18 aluminum strips covered by a selective coating. Each collector has two manifolds connected to each other by 18 horizontal copper tubes. The cover is made of an anti-reflective glass, while the insulation consists of mineral wool.

2.2. Material and method

2.2.1. Experimental test

The collectors were tested in the steady state conditions, according to the standard EN 12975-2, and under several operating conditions, in order to quantify the effects of tilt angle, flow rate and fluid type on the efficiency.

The EnerWorks collector was tested in an indoor solar simulator at the National Solar Test Facility of Canada. Twelve tests were defined: six using water and six using a 50% mass concentration of propylene glycol (PG) and water. The tested flow rates were approximately 0.6, 1.2 and 3.4 litres per minute. The six tests using 50% PG were done with a tilt angle of 60°: three of these tests were carried out with the same mass flow rates as those with water, while the other three were done keeping the same heat capacity rate as the corresponding tests with water, so to evaluate the effect of different fluids, regardless of their heat capacity. Table 1 reports the used operating conditions.

The HT collectors were installed side by side and tested outdoors, in a solar collector test facility at the Technical University of Denmark. The collectors were tested with a tilt of 45° at 5, 10 and 25 litres per minute and then with tilts of 30° and 60° at 25 litres per minute, using a PG/water mixture with 40% mass concentration. Finally, they were tested with water at 45° tilt and 25 litres per minute. Table 2 summarizes the used operating conditions.

The experimental data points were interpolated according to the method of least squares and the collector efficiency for an incidence angle of 0° was expressed by a quadratic (eq.1) and/or linear equation (a_2=0).

$$\eta = \eta_0 - a_1 \cdot \frac{(T_m - T_a)}{G} - a_2 \cdot \frac{(T_m - T_a)^2}{G} \quad \text{(eq.1)}$$

In case of the HT collectors, the incidence angle modifier was also evaluated, in order to assess the influence of the FEP foil on the optical properties of the collector.

2.2.2. Simulation model

The main disadvantage of outdoors testing is that external conditions, such as solar irradiance, diffuse radiation ratio, ambient temperature and wind speed, are not completely constant throughout an entire steady-state test, which can take several days. Consequently, the comparison of efficiency parameters obtained from tests performed in different weather conditions may be problematic, as it is difficult to distinguish the effect of the parameter under investigation from that of different weather conditions. For this reason, a simulation model for the HT collectors was created in *Soleff*, a solar collector simulation software developed at Technical University of Denmark [4].

Soleff requires a large number of input parameters, ranging from design characteristics of the collector to operating and weather conditions. Regarding weather conditions, measured data were used, while collector characteristics were found either in their data sheets or in literature [4,5]. Input parameters for which the exact value could not be found were assumed according to common values found in literature and tentatively modified in order to obtain the best fit with the experimental data. Despite many aspects considered by Soleff, this software cannot take into account the complexity of the real-world operation. For example, the software assumes uniform flow distribution in the different pipes, constant fluid properties across the collector and sudden change from laminar to turbulent regime at a Reynolds number of 2230. The last one proved to be the less accurate simplification, as measured efficiencies obtained for Reynolds numbers between 2200 and 2500 were always lower than those computed by Soleff (which assumes turbulent regime in this range) and pressure drop measurements carried out on the HT-SA collector showed transitional behaviour for Reynolds numbers between 2000 and 3000.

2.3. Results

The efficiency coefficients obtained in the different operating conditions according to the least squares method are listed in Table 1 for EnerWorks collector and in Table 2 for Arcon Solar.

Table 1: Summary of efficiency test results for the EnerWorks collector in all tested operating conditions.

Fluid	Flow rate [kg/s]	Tilt [°]	η_0* [-]	a_1* [W/(m^2 K)]	η_0 [-]	a_1 [W/(m^2 K)]	a_2 [W/(m^2 K^2)]
water	0.010	60	0.745	4.220	0.729	3.450	0.0092
water	0.020	60	0.755	4.296	0.743	3.583	0.0095
water	0.057	60	0.759	4.242	0.750	3.457	0.0120
water	0.010	90	0.742	3.995	0.727	3.263	0.0087
water	0.020	90	0.748	3.961	0.738	3.339	0.0082
water	0.057	90	0.753	3.939	0.747	3.429	0.0078
50% PG	0.010	60	0.700	4.013	0.691	3.569	0.0052
50% PG	0.020	60	0.706	3.879	0.692	3.006	0.0114
50% PG	0.057	60	0.735	4.012	0.721	2.801	0.0183
50% PG	0.011	60	0.686	3.736	0.647	1.777	0.0240
50% PG	0.022	60	0.711	3.903	0.697	3.025	0.0118
50% PG	0.065	60	0.733	4.019	0.722	2.964	0.0161

Table 2: Summary of efficiency test results for the Arcon Solar HT collectors in all tested operating conditions.

Collector model	Fluid type	Flow rate [litres/min]	Tilt [°]	η_0 [-]	a_1 [W/(m^2 K)]	a_2 [W/(m^2 K^2)]
HT-A	40% PG	5	45	0.835	3.13	0.0143
HT-A	40% PG	10	45	0.843	3.55	0.0070
HT-A	40% PG	25	45	0.845	3.80	-
HT-A	40% PG	25	60	0.850	3.71	-
HT-A	40% PG	25	30	0.832	4.04	-
HT-A	water	25	45	0.845	2.75	0.0146
HT-SA	40% PG	5	45	0.818	2.76	0.0096
HT-SA	40% PG	10	45	0.804	2.26	0.0107
HT-SA	40% PG	25	45	0.810	2.83	-
HT-SA	40% PG	25	60	0.806	2.74	-
HT-SA	40% PG	25	30	0.805	3.13	-
HT-SA	water	25	45	0.820	2.66	0.0057

In Table 1 the efficiency coefficients refer to the gross area of the collector. Those characterized by an asterisk were obtained fitting the experimental data points with a linear efficiency equation, while those without asterisk refer to complete quadratic formulation of the collector efficiency according to (eq.1).

On the other hand, the efficiency coefficients in Table 2 refer to the aperture area of the collectors. A quadratic formulation of the collector efficiency is presented whenever possible. Only when the calculated a_2 coefficient was negative, a linear formulation for the efficiency was chosen, as prescribed by the EN 12975-2 standard.

The experimental results from the HT collectors were used to calibrate the simulation models developed in Soleff, whose results were then used to access the influence of the various parameters on the collector efficiency. For the sake of brevity, Soleff results are not reported here, but can be found online at [6].

2.4. Discussion

Regarding EnerWorks collector, the influence of the different parameters on the collector performance is given in quantitative terms in Table 3. In the table the effect on the thermal losses was evaluated comparing the heat loss coefficients obtained by linear interpolation (a_1^* in Table 1). The test results showed that the largest effect was due to type of heat transfer fluid used, both in terms of peak efficiency (6%) and heat losses (9%). This was mainly due to the fact that a change in fluid type entailed a change in flow regime, due to the higher viscosity of the PG/water mixture. Also the different heat capacity played a role, but of secondary importance. In fact, as it is possible to see in Table 3, large deviations still existed, no matter whether the flow rate or the heat capacity rate was kept constant. As expected, the tilt angle had almost no effect on the peak efficiency, but was the second most important parameter affecting the heat losses. Regarding the flow rate, in the considered range, its effect was relatively small, except when a change in flow rate caused a transition from laminar to turbulent flow in the fluid passages of the collector.

Table 3: Magnitude of effects of fluid type, tilt angle and flow rate on collector efficiency parameters of EnerWorks collector.

Parameter	Effect on peak efficiency	Effect on thermal losses	Notes
Fluid type	5.9%	9.0%	when the heat capacity rate is constant
	5.3%	6.9%	when mass flow rate is constant
Collector tilt (60° – 90°)	0.7%	7%	
Volume flow rate (0.22 – 1.25 l/min/m^2)	2%	0.4%	using water as solar collector fluid
	5.8%	3.6%	using 50% PG as solar collector fluid

Similarly, the overall results for the Arcon Solar collectors are reported in Table 4. It must be noted that the values presented in Table 4 were obtained from the efficiency equations obtained through Soleff and not directly from the experimental ones. This choice was made to assure that the efficiency curves referred to the same operating conditions, which outdoors testing did not allow.

Table 4: Magnitude of effects of fluid type, tilt angle and flow rate on collector efficiency parameters of Arcon Solar collectors.

Parameter	Effect on peak efficiency	Effect on thermal losses
Fluid type	0% (same flow regime) 4% (different flow regime)	2%
Collector tilt (30° - 60°)	1%	5% - 8%
Volume flow rate (0.40 – 1.98 l/min/m^2)	2% (same flow regime)	1% (same flow regime) 3% (different flow regime)

Analysing the results, it can be seen that the peak efficiency was not significantly affected by the tilt and flow rate, as long as this did not entail a change in flow regime (see Fig. 1). The fluid type itself did not affect considerably the peak efficiency, unless the different fluids in use experienced different regimes. This can be explained by the fact that, being the peak efficiency evaluated at null heat losses, the difference in specific heat per unit volume of the two fluids plays little role. Additionally, if both fluids are in laminar conditions due to the low temperature, the heat transfer coefficient within the absorber pipe is not strongly affected by the different viscosities of the two fluids. On the other hand, if the difference in fluid entailed a different regime, the effect on the peak efficiency was not negligible. Regarding the effect on the thermal losses, the most important parameter was the tilt angle, which caused a change of 5%-8%, while both fluid type and flow rate had a much lower influence.

As can be both noted from the experimental values of peak efficiency (Table 2) and confirmed by Soleff calculations, the presence of the FEP foil negatively affected the transmittance of the collector cover, decreasing the peak efficiency between 2% and 4% Also the incidence angle modifier was penalized by the presence of the foil [7]. However, as the heat losses were between 19% and 25% lower in the HT-SA collector, the efficiency difference between the two models decreased with increasing temperatures until it became null. At this stage, any further increase in temperature entailed a better performance of the HT-SA collector.

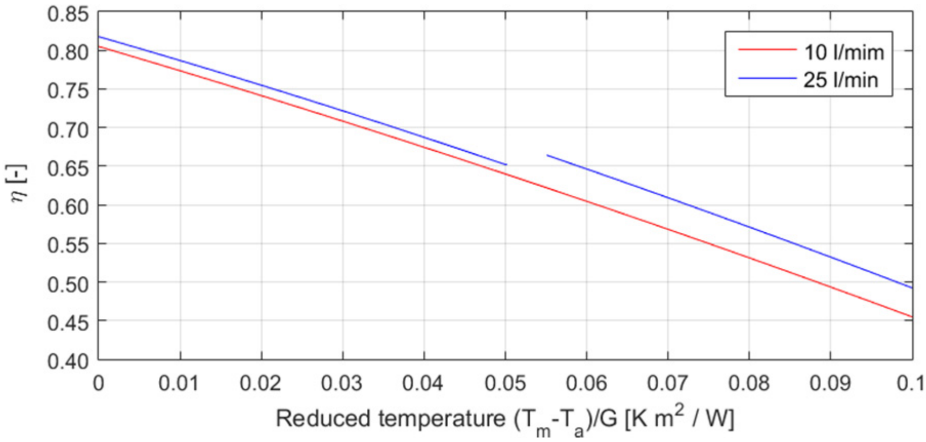


Fig. 1. Soleff efficiency curves for the HT-SA collector at 45° tilt angle and an hemispherical irradiance of 1000 W/m^2.

As the fluid temperature generally increases from relatively low (~45 °C) to relatively high values (~85 °C) along the rows of a collector field, a mixed composition of modules with and without FEP foil seems the best solution, using collectors without foil in the first part of the row and collectors with foil in the second part, in order to optimally exploit their different characteristics.

The complete presentation of the results of this study is available online [7].

2.5. Conclusions and recommendations

Investigations of different flat plate collectors showed that the collector efficiency is influenced by the heat transfer fluid, the collector tilt and the volume flow rate. The collector efficiency is increased by:

- decreasing the percentage of glycol of the glycol/water mixture used as heat transfer fluid
- increasing the collector tilt
- increasing the volume flow rate

It has been shown that flow regime (laminar or turbulent) has an important influence on both the thermal performance of a liquid-heating collector and on the ability to accurately predict collector performance. Differences between predicted performance based on current standard test conditions and actual performance in the field can be expected to be up to 10%. It is therefore recommended that test conditions used by test institutes under collector tests are as close as possible to the conditions used under operation of the solar collectors.

Collectors should be designed already thinking which kind of fluid, flow rates and temperatures they will be operated at, so that the absorber pipes can be properly sized to achieve turbulent conditions most of the times. After calculating the recommended diameter, it is advisable to check that the consequent pressure losses are acceptable.

Concerning the procedure to measure the efficiency, changes in flow regime within the investigated temperature range should be avoided, as they would affect the trend of the interpolating curve. Only single efficiency points which are characterized by the same flow regime should be interpolated. In case transition from laminar to turbulent condition occurs at a temperature lower than that at which the collector operates at, the efficiency curve could be obtained only considering the relevant temperature interval, neglecting the lower temperature level where transition occurs. In this way, a better fit can be obtained without loss of relevant information. For example, as in collector fields for district heating (DH) application, the collector inlet temperature is approximately equal to the DH return temperature (40 °C-50 °C), investigation of the collector efficiency for lower temperatures could be neglected.

3. Performance guarantee

In order to persuade investors to invest in large scale collector fields, it is very important to provide guarantees on their performance, so to reduce the uncertainties related to the investment. For this reason subtask A.3 of Task 45 focused on developing methods to guarantee and check the field performance. They comprehend guarantee on a minimum power output of the collector field in full load conditions, guarantee on the heat exchanger performance in terms of maximum logarithmic mean temperature difference across the heat exchanger [8] and guarantee on the yearly energy output of a collector field operating under specific weather conditions and with boundary conditions given by the DH network to which the field is connected [9].

3.1. Guaranteed power output

3.1.1. Collector field output guarantee

Guarantee for the collector field performance can be given in the form of a guarantee equation:

$$P_g = A_c \cdot [\eta_0 \cdot G - a_1 \cdot (T_m - T_a) - a_2 \cdot (T_m - T_a)^2] \cdot f_P \cdot f_U \cdot f_o \quad \text{(eq.2)}$$

The collector module efficiency parameters should be based on certified test results (Solar Keymark or similar). For what said before in section 2, it is preferable that the efficiency parameters refer to operating conditions as close as possible to those actually used in the collector field. Additionally, in order for (eq.2) to be representative of the collector field, the following conditions must be fulfilled:

- Total solar irradiance not lower than 850 W/m^2
- No shadow/snow/ice/moisture on solar collector and solar radiation sensors
- Ambient temperature higher than 10 °C
- Incidence angle of direct radiation lower than 30°

In order to check the collector field performance guarantee, it is necessary to measure the thermal power supplied to the heat exchanger as well as the parameters required by (eq.2). The guarantee is fulfilled if the measured power supplied to the heat exchanger is greater or equal to the output power returned by (eq.2), using the measured temperature and radiation data as input to the equation.

3.1.2. Heat exchanger performance guarantee

The heat exchanger can play an important role in the overall efficiency of the system. So, a guarantee on the heat exchanger performance is advisable, so that the net energy output of the collector field can be better estimated. The performance guarantee for the heat exchanger can be given as a maximum logarithmic mean temperature difference between the primary and secondary side of the heat exchanger [8]. If the capacity rates on both sides of the heat exchanger are approximately equal (as they should be to optimize the heat transfer) and the heat exchanger is operated in the counter-flow, then the logarithmic mean temperature difference cannot be calculated and the arithmetic mean must be used. The guarantee should be given for a certain power transferred through the heat exchanger, for example, that corresponding to a typical full load situation. It might be wise to involve the manufacturer of the heat exchanger in this guarantee. Consideration should also be given to the potential for heat exchanger fouling. Good preventative maintenance includes routine cleaning, and the performance guarantee should take into account a safety margin for reduced performance due to fouling.

4. Requirements and guidelines for collector loop installations

Uniform flow distribution within a collector and a collector array is desirable, as it both decreases the pressure drop and increases the efficiency by avoiding irreversible mixing of flows at different temperatures. Additionally, it can help to prevent stagnation phenomena in single rows of the collector array. For this reason, the hydraulic design of both the single collector and the collector array needs to be carefully studied and the influence of parameters, such as pipe diameters, pipe length and type of T-pieces, needs to be known [10]. Already in the planning and designing phase of a collector field, it is of key importance to consider how the system can avoid and/or handle stagnation, in order to prevent severe damages and guarantee a long-lasting, reliable and low-maintenance operation of the plant.

4.1. Flow distribution in solar collectors and collector arrays

Wherever hydraulic components are connected in parallel, the flow distribution will not be exactly homogeneous. This applies both to solar collectors and to the entire solar collector field. In harp-type collectors, the absorber pipes are connected in parallel, so that each absorber pipe receives a different flow. Fig. 2 shows a schematic hydraulic drawing of a large harp-type collector, along with possible flow distributions resulting from this connection.

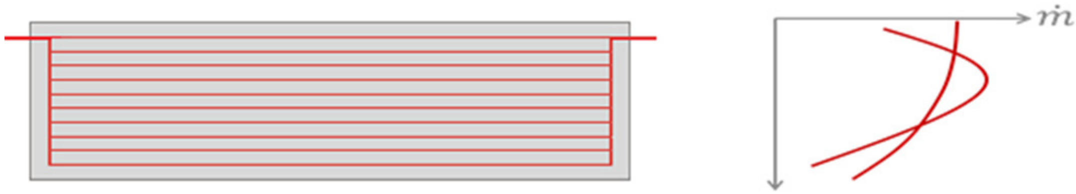


Fig. 2. Example flow distribution in a harp collector [11].

The exact shape of the flow distribution depends on several boundary conditions such as pipe geometries, operating temperature, fluid type, total mass flow, tilt angle etc. The collector hydraulics (e.g. harp or meander type) and the dimensioning of the absorber and manifold pipes are the main responsible for the flow distribution in the absorber pipes. Also the type of the T-pieces connecting pipes and manifolds influences the flow distribution, via pressure losses, as sharp edges and inset length can increase significantly pressure drop across the tee [11].

In large installations, solar collectors are connected both in series and in parallel to form several rows. Wherever hydraulic elements are connected in parallel, there is the possibility of choosing among several hydraulic layouts. The most common layouts are the Tichelmann layout, also known as Z layout, and the Non-Tichelmann, also known as U layout. In the Z connection, the flow path has the same length for each collector. The main drawback of this type of configuration is the longer pipe lengths. In general, the flow distribution in U connections is not as even as in Z connections. The main influence on the flow distribution is the pressure drop ratio between the pipes connecting the different elements in parallel and the elements in parallel themselves. In general, the higher the pressure drop of the elements connected in parallel compared to the pressure drop in the connecting pipes, the more homogeneous the flow distribution. This means that the following features have a positive effect on flow distribution between collector rows in a collector array:

- large pipe diameters in the connecting pipes (flow and return pipes)
- high pressure drop in a single collector row (many collectors in series, small pipe diameters in the collectors, etc.)

Heterogeneous flow distribution causes higher temperatures in the plant's components and can even lead to partial stagnation in parts of the collector array [12]. For practical purposes, a certain degree of inhomogeneous flow distribution can be tolerated. The German guideline VDI 6002 states that the mass flows of all collectors in an array should not differ by more than ±10%. While the source gives no explanation as to the choice of this value, the results of the "ParaSol" project suggest that it is far too restrictive, and larger amounts of uneven flow distribution may be allowed without running into problems [11].

4.2. Used methods for achieving a homogeneous flow distribution

Ideally, the main objective of the layout of a large solar thermal plant is to design the collector array hydraulics in a way that allows keeping both pipe lengths as short and the flow distribution as homogeneous as possible. Since the optimization of both of these aspects cannot be reached simultaneously, a compromise between the two needs to be found. In order to reduce piping cost, supply and return pipes can be properly dimensioned, progressively reducing the diameter of the pipes (Fig. 3.a). In combination with adjustments to the pipe diameters, the Z hydraulic design (see section 4.1) can be used to improve the flow distribution. Though, this second option has the disadvantage of increased piping length and therefore higher costs (Fig. 3.b). Another possibility to achieve homogeneous flow consists in installing balancing valves (Fig. 3.c). These are very effective, but entail higher investment cost, increased installation time and possible maintenance costs (in case of defective valves). The adjustment of the collector connecting pipe diameters is a cheaper way for achieving a homogeneous flow distribution (Fig. 3.d), but must be calculated in advance exactly and a subsequent adjustment would be very expensive. Additionally, it is not practically feasible for large installations.

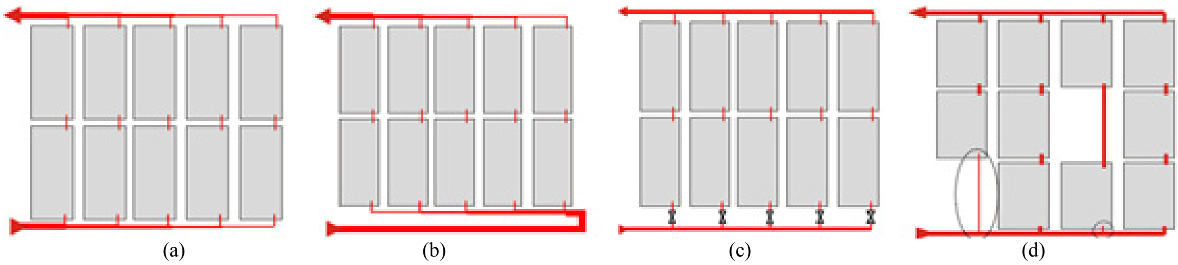
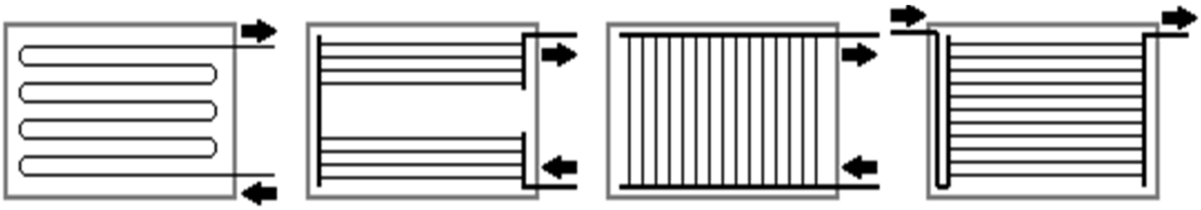


Fig. 3. Possible hydraulic configurations of a solar collector array. (a) Adjustment of the supply and return pipes diameters. (b) Tichelmann connection in combination with adjustments to the pipe diameters. (c) Installation of mechanical balancing valves. (d) Adjustment of the collector connecting pipe diameters.

4.3. Stagnation and safety systems

During stagnation the solar collector fluid evaporates, exposing the components of the collector loop to very high temperatures (up to 250 °C with modern flat plate collectors) and pressure. So, it is important that a system is designed to prevent and/or handle stagnation without suffering significant damages. Stagnation can be caused by a technical problem (pump failure), by power outages or by a lack of load.

The hydraulics of the individual collector as well as of the entire collector array determines the emptying behaviour. Collectors with favourable emptying behaviour minimize the amount of residual liquid in the module and therefore reduce the duration and extent of the critical phase of stagnation. Usually a good emptying behaviour is guaranteed by at least one pipe connection in the bottom of the collector (Fig. 4.a–Fig. 4.c), which allows the liquid fluid to be pushed out by the evaporated fluid, but also collectors with connections in the top can be designed so to have a good emptying behaviour (Fig. 4.d). Nevertheless, collectors with good emptying behaviour can still trap large amounts of fluid during stagnation, if they are poorly connected to one another. For this reason, the arrangement of the collectors in relation to each other plays a crucial part in limiting the consequences of stagnation.



(a) (b) (c) (d)

Fig. 4. Schematic presentation of different hydraulic connections in collectors with favourable emptying behaviour [13].

Stagnation can be faced in two different ways. On one hand, this can be accepted as a normal operational incident: in this case the system needs to be able to handle stagnation conditions. The other strategy consists in preventing stagnation as much as possible. Table 5 gives an overview of the different options for both strategies. It must be noted that a single measure or a combination of various measure may be chosen.

Table 5. Measures for handling and preventing stagnation.

	Stagnation handling	Overheating prevention
Passive measures	**All system sizes:** • Appropriate expansion vessel design • Use of temperature-resistant solar loop components • Dissipators based on heat transfer to air or water (e.g.: finned tube heat exchanger, stagnation cooler)	**All system sizes:** • Solar collectors with automatic cooling of the absorber (without use of electricity) • Temperature dependent changes of optical properties of absorber coatings or glazing • Drain-back (proper collector and loop design needed)
Active measures	**System "Ritter Solar" (with evacuated tube collectors):** • special hydraulic system concept with evacuated tube collectors also for large scale applications where stagnation is an accepted operating mode • No "active" cooler is needed but active control, pumps and motor-operated valves	**Medium to large systems:** • "active" coolers in the solar primary loop • night cooling **Systems with concentrating and tracking collectors – all system sizes** • automatic "defocus" of concentrating mirrors
Charac-teristics	**UPS (uninterruptible power supplies)** • no or only low capacity UPS needed (e.g., for controller + motor-operated valves + pumps) **Expansion and safety devices** • large (able to absorb liquid expansion + steam volume) • high opening pressure of safety valve (in most systems) **Emptying behaviour of collectors / system** • good emptying behavior is favorable	**UPS (uninterruptible power supplies)** • low to high capacity UPS needed (e.g., for controller + motor-operated valves + pumps + active cooling devices + actuators for defocusing) **Expansion vessel and safety devices** • small (able to absorb liquid expansion only) • opening pressure of safety valve can be low **emptying behaviour of collectors / system** • good emptying behavior is favorable but not a priority

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