Task 45 Large Systems

Requirements & guidelines for collector loop installation

Subject:	**Guidelines for requirements for collector loop installation including precautions for safety and expansion**
Date:	December 2014
Description:	State of the art of **hydraulics** (collector and collector array hydraulics) and **safety** (including stagnation) aspects of the primary solar loop is presented and analysed in a theoretical as well as practical framework.
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Introduction

Large-scale solar thermal plants (gross collector area of more than 500 m² resp. 0.35 MWth) provide a huge potential for reducing the consumption of fossil fuels and CO2 emissions. Especially in the context of district heating, industrial processes and thermal cooling, large-scale solar thermal plants are becoming more and more important. Numerous projects in Europe (especially in Denmark) but also internationally (China, Canada, Saudi Arabia, etc.) constitute powerful examples for this trend. The implementation of solar thermal energy has already proved to be technically and economically feasible and sustainable in the practical context. However, the potential is still far from being exhausted.

This document focuses on the remaining practical challenges concerning the implementation of large-scale solar thermal plants. For this purpose, the state of the art of **hydraulics** (collector and collector array hydraulics) and **safety** (including stagnation) aspects of the primary solar loop is presented and analysed in a theoretical as well as practical framework, also referring to **examples** of successfully implemented projects. It is based on international know-how collected by IEA networking activities, presented in a condensed form in this document.

The objective of this document is to present international, state of the art know-how on special issues regarding the design of large-scale solar thermal plants to project developers, plant designers, engineers, etc. In the long run, this transfer of knowledge should help to improve the engineering of large-scale plants (efficient, failsafe, simple, cost-efficient) and to identify cost reduction potentials by standardising system components and/or concepts.

First, this document gives an overview on different collector types as well as on their distribution in the international context. Different types of array hydraulics as well as current issues concerning the hydraulics (flow distribution, etc.) of individual collectors and collector arrays are discussed. The influence of certain parameters (pipe diameters, pipe length, production constraints on T-pieces, etc.) on the collector array and on the mass flow on different levels is analysed. Furthermore, a method is presented which allows for a simple technical assessment of different hydraulics specific to each plant by using a set of indicators.

The chapter on safety aspects presents the different methods and solutions for preventing or handling stagnation, taking into account that there are significant differences between large-scale and smaller combi systems on this matter. Apart from stagnation, further safety issues considering large-scale plants and their respective solutions are discussed. An overview on the different types of primary loops based on already implemented large-scale solar thermal projects is given. Variations in the selection of collectors, hydraulic connections and the differences in the operation (flow speed, pressure loss, etc.) of the plants are analysed.

1 Collectors and collector array hydraulics

1.1 Collector types and flow distribution)

The temperature level required for a particular application and the temperature difference (ΔT) between mean collector and ambient temperature are the decisive parameters for selecting the type of collector. Further factors are the geographic location (available solar radiation, yearly mean temperature) and the price/performance ratio of the collectors. The three collector types usually installed in large-scale projects are:

- Flat plate collectors
- Evacuated tube collectors
- Concentrating collectors

In large-scale projects in Europe the predominant collector type is the **flat plate collector**. Standard collectors typically operate at a mean temperature of 40 °C to 60 °C while special, optimised collectors can reach 80 °C: not only single-glazed collectors with selective absorber coating and low-iron solar glass but also double-glazed flat plate collectors with an additional barrier to convective heat losses, that is, an additional transparent element between the absorber and the covering layer. These convection barriers usually consist of thin layers of ETFE or EPP or sometimes another sheet of glass. Double-glazing results in higher collector efficiency at high operating temperatures and therefore they allow for solar thermal plants to operate at a higher temperature level. When choosing a collector type (single-glazed or with additional convection barrier), the expected solar yield needs to be compared to the collector costs. In large-scale solar thermal plants, collectors using harp absorbers (see Figure 1 on the left) as well as meander absorbers (see Figure 1 on the right) are installed.

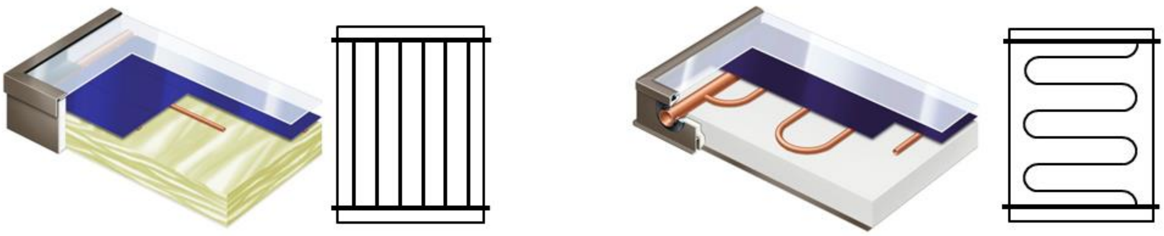


Figure 1: Schematic drawings of small flat plate collectors with harp absorber (left) and with meander absorber (right) (source: Viessmann Deutschland GmbH, 2008)

In moderate climatic regions, the second most common collector type (after flat plate collectors) are **evacuated tube collectors.** These collectors reduce convection and conduction losses through a high vacuum and therefore achieve acceptable efficiency rates even at higher operating temperatures (80-120 °C, special evacuated collectors up to 140 °C, e.g. CPC-VRK). For this reason they are installed in applications that require high operating temperatures (e.g. industrial heat, thermal cooling).

Furthermore, at low radiation levels these collectors achieve higher solar yields than flat plate collectors.

While in Europe mainly **heat pipe** and **Sydney pipe** collectors are used, the prevalent collector type installed in Asia are **filled-type evacuated tube collector**. In the latter collector type the heat is directly transmitted via the inner glass pipe which has exterior coating. Due to the higher thermal mass in the pipe, these systems can be operated at a lower temperature level compared to the previously mentioned types of evacuated tube collectors.

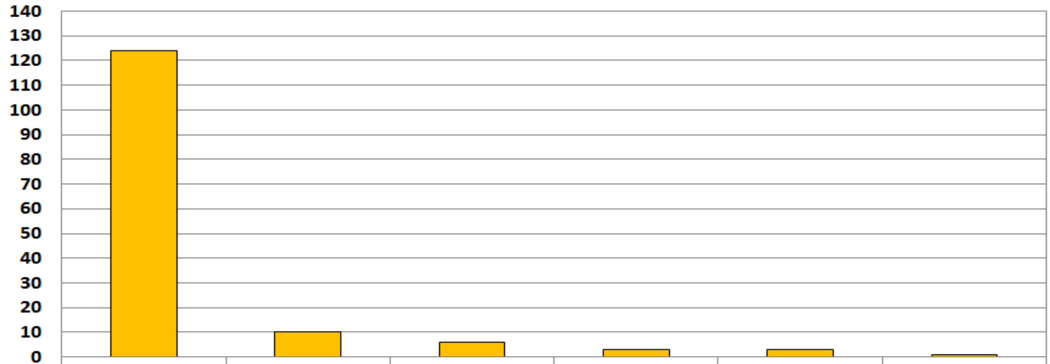
In addition to evacuated tube collectors **evacuated flat plate collectors** with satisfactory maintain performance over years, due to the adoption of better technology for maintaining the vacuum, have been designed recently. Like evacuated tube collectors these collectors reduce convection and conduction losses through a vacuum. In this way it is possible to ensure acceptable efficiency rates at operating temperatures up to 200 °C.

CPC collectors make use of a higher proportion of solar radiation by deploying mirrors which reflect the radiation on to the back side of the absorber. This also results in a bigger usable area of the absorber. The disadvantage with this technology lies with the requirement of bigger distances between the absorbers but is put off by achieving a higher solar yield. Mainly **evacuated CPC collectors** are used but there are also **flat plate CPC collectors** where the absorber is placed vertically in a CPC mirror. The heat transmission pipe is located in the focal point of the mirror and the heat transmission fluid flows directly through it.

Parabolic trough collectors are recently finding their way into commercial installations after having been tested in R&D projects. Here a mirror tracks the position of the sun (parabolic concentrator or Fresnel mirror, etc.) and focuses the radiation directly on to the absorber installed in the focal point of the mirror. These systems can only use the beam solar radiation which is why they are usually implemented in geographic positions with low cloud coverage. The operating temperatures for these collectors range from 120 °C to 250 °C.

1.1.1 Collector types of implemented large-scale solar thermal plants

Figure 2 shows the collector types used in 149 large-scale plants for process heat (gross collector area of more than 500 m²) and district heating (gross collector area of more than 1,000 m²). The projects are mainly located in Europe or include European project partners. (SHIP-Plants, 2014; SDH – solar district heating, 2014)



	FPC	ETC	UG	ETC-R	PTC	FPC+R
Number of Plants	124	10	6	3	3	1
Apert. Area	571235 m²	20055 m²	7645 m²	5936 m²	7595 m²	1200 m²

Figure 2: Comparison of collector types used in 149 European large-scale solar thermal plants for process heat and district heating (FPC - flat plate collectors; ETC – evacuated tube collectors; UG – unglazed collectors; PTC –parabolic trough collector; FPC+R - CPC flat plate collectors; ETC-R – CPC evacuated tube collectors (SHIP-Plants, 2014; SDH –solar district heating, 2014).

As mentioned above, the predominant collector type for large-scale solar thermal plants are flat plate collectors. In 124 out of the 149 plants these collectors were installed amounting to a total aperture area of 571,235 m². Evacuated pipe collectors were implemented to a much smaller extent (10 plants with 20,055 m²) as well as CPC evacuated pipe collectors (4 plants with 7,136 m²). Only very few plants used unglazed collectors (6 plants with 7,645 m²) and parabolic trough collectors (3 plants with 7,595 m²).

Figure 3 shows a further analysis comparing the collector efficiency lines of different collector types installed in large-scale solar thermal plants. Displayed are the collector efficiency lines of 13 different collectors, six of which are single-glazed flat plate collectors (green lines), two double-glazed flat plate collectors (red lines), four evacuated pipe collectors (yellow lines) and one evacuated flat plate collector (brown line).

The diagram not only shows the differences in the theoretical efficiencies of the different collector types, it also shows that there are significant disparities among collectors of the same type. For example, the efficiency of flat plate collectors ranges from 32 % to 46% for FPC and 53% for double covered FPC at collector operating temperatures of 70 °C and lies between 6 % and 26% for FPC and 36% for double covered FPC at 100 °C. In order to achieve a high yield with the solar thermal plant it therefore is not only essential to choose the right collector type, but also the one best suited for the required operating temperature in terms of efficiency.

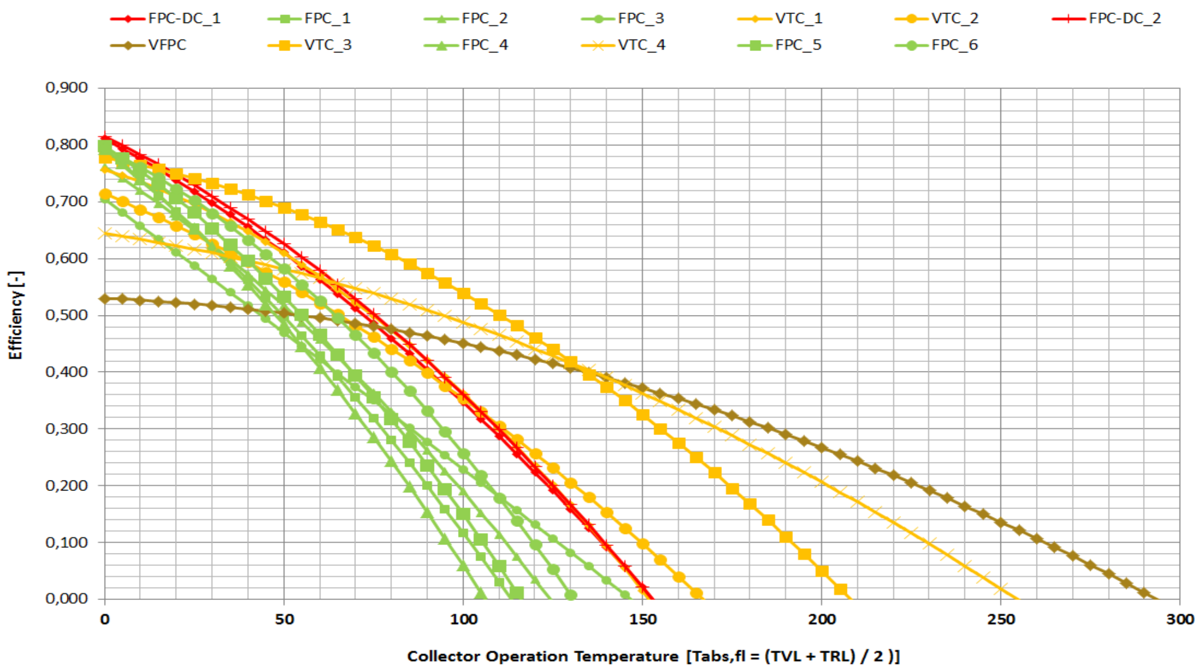


Figure 3: collector efficiency diagram of different collector types installed in large-scale solar thermal plants (green lines– single-glazed flat plate collectors; red lines – double-glazed flat plate collectors; yellow lines – evacuated pipe collectors; brown lines– evacuated flat plate collectors)

1.1.2 Flow distribution in collectors

Wherever hydraulic components are connected in parallel, the mass flow distribution between these components will not be homogeneous. That is, in general each parallel component receives a different mass flow, in other words: the mass flow distribution is uneven or inhomogeneous.

This also applies to solar collectors: In harp-type collectors, the absorber pipes are connected in parallel between two manifold pipes, and as explained above, in general each absorber pipe receives a different mass flow. Figure 4 shows a schematic hydraulic drawing of a large-area harp-type collector, along with possible flow distributions resulting from this connection. 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 main influence on the flow distribution in the absorber pipes is the basic hydraulic collector type (e.g. harp or meander type) and the dimensioning of the absorber and manifold pipes.

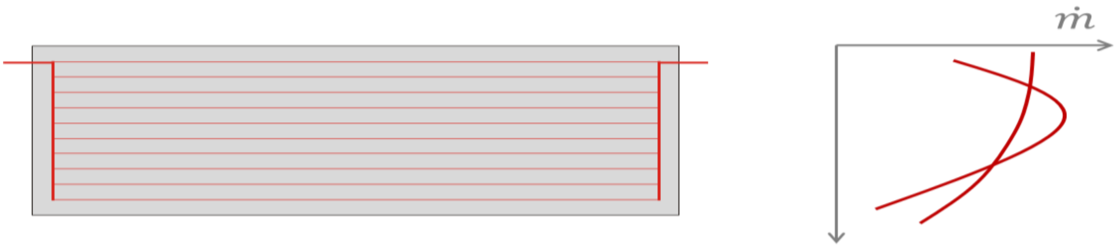


Figure 4: Example flow distribution in a harp collector (Philip Ohnewein, 2013)

Furthermore, the quality of production of the T-pieces (connecting absorber and collecting pipes) also exerts a certain influence on the flow distribution, via pressure losses. The “ParaSol” project has revealed that the geometry of T-pieces is often not ideal due to manufacturing constraints (seeFigure 5). (Philip Ohnewein, 2013)

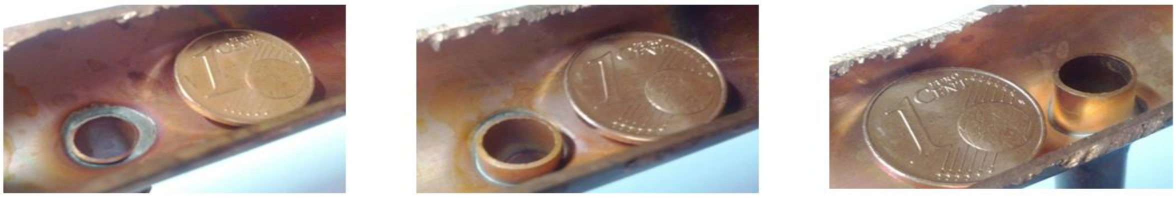


Figure 5: Examples of different penetration depths of the absorber pipe into the collector manifold pipe, as commonly found on the market (Philip Ohnewein, 2013).

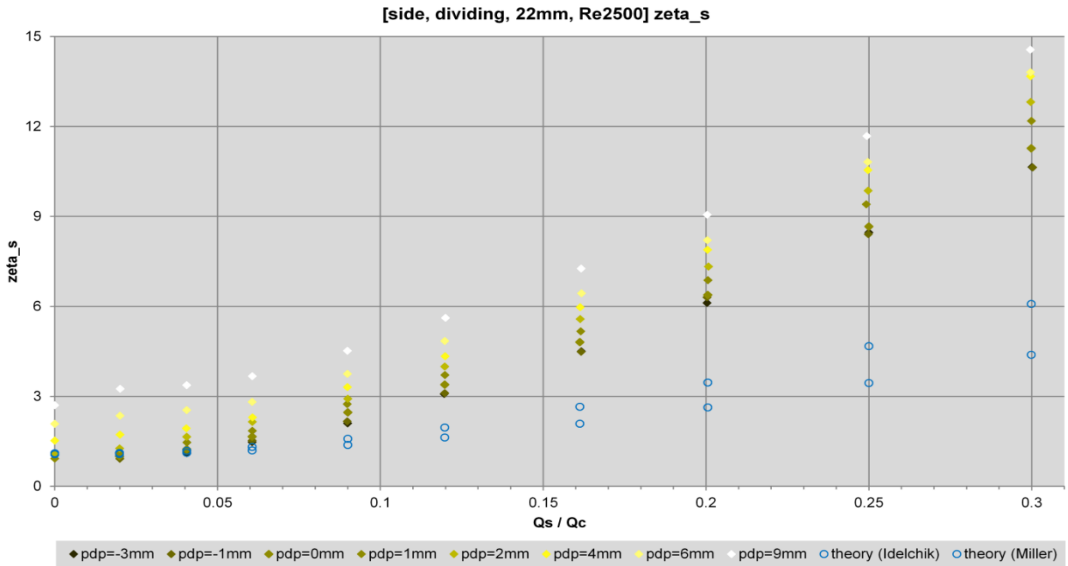


Figure 6: Pressure loss coefficient $\zeta_{c,s}$ (dividing flow, side tube) for a 22 mm collector manifold pipe, Re = 2500 for different volume flow ratios between side and common volume flows. Bright colours represent deeper penetration of the absorber pipe into the manifold pipe. Results from theoretical approaches (valid only for pdp=0 mm and Re > $2x10^5$) are displayed as circles (Philip Ohnewein, 2013).

Experimental studies on non-ideal T-pieces show a clear influence of the penetration depth on the pressure loss coefficients and therefore also on the mass flow distribution within a collector. In Figure 6, the pressure loss coefficients $\zeta_{c,s}$ measured in an experimental setting are shown and compared to data calculated based on theoretical approaches available in textbooks, considering sharp-edged T-pieces in both cases. At present it is not yet possible, however, to draw a detailed conclusion on how T-pieces influence the mass flow in collectors and collector arrays. (Philip Ohnewein, 2013)

The mass flow distribution of a harp collector, measured in the laboratories of AEE INTEC, is shown in Figure 7. It reveals that there is a large difference between the mass flow of the first (16) and the last (1) absorber pipe. The difference in mass flow across the absorber pipes amounts to more than 100%, meaning that the absorber pipe with maximum mass flow gets more than double the mass flow of the minimum one. According to VDI 6002 (VDI – Verein Deutscher Ingenieure, 2004), the mass flow should not vary more than ±10%.

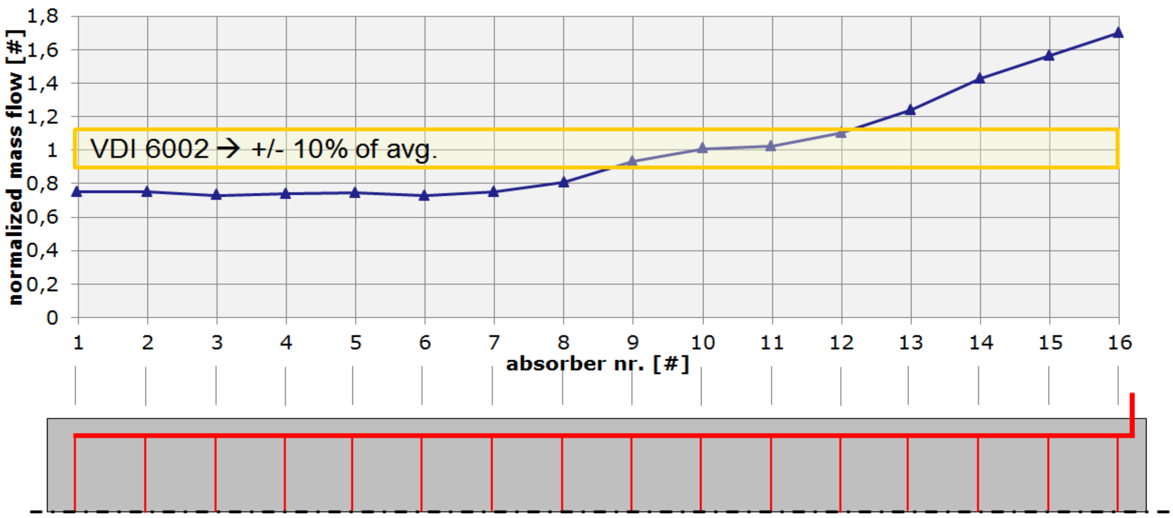


Figure 7: Flow distribution in a small-sized harp collector (experimental measurements). The maximum disparity of the flow distribution proposed by VDI 6002 is marked in yellow. (Philip Ohnewein, 2013)

The mass flow distribution of the individual collectors also influences the flow distribution on the level of the collector array. This is true for harp as well as meander collectors.

1.2 Collector array hydraulics

1.2.1 Basic types of collector array hydraulics

In large installations, solar collectors - regardless of their type - are connected in series or in parallel to form rows of collectors. These collector rows are subsequently interconnected to form a collector array. There may be more intermediate hydraulic layers, but the principle does not change: The basic principle of connecting collectors either in parallel or in series is applicable for all types of collectors used in large-scale solar thermal plants. The objective in connecting collectors is to increase their hydraulic length, that is, the thermally active pipe length the fluid must flow through between return and supply pipes. Higher thermal lengths enable achieving a large and useful temperature increase, but also have other advantages such as higher absorber pipe Reynolds numbers or better flow distribution, especially for large solar thermal installations.

Harp collectors are connected in series to form a collector row, while the absorber pipes of each collector are arranged in parallel (seeFigure 8). When using harp collectors, the mass flow of each collector row passes through each collector consecutively, resulting in different temperatures in the collectors.

Figure 8: Example collector row hydraulic with harp collectors. All absorber pipes in a collector are connected in parallel while the collector itself is in series with the other collectors.

On the other hand, meander collectors in large installations are usually connected at 4 points, so all meanders are connected in parallel (seeFigure 9). There are, however, also alternatives where smaller groups of collectors are connected in parallel, and the groups are then connected in series. In the connection shown in figure 9, each of the meander collectors operates at the same return temperature, in contrast to the situation shown in figure 8 where the collectors get different return temperatures and have different mean operating temperature.

Figure 9: Example collector row hydraulic (Non-Tichelmann) with meander collectors. The absorber pipes of all collectors are connected in parallel.

As mentioned previously, the prevalent collector type for large-scale solar plants in Europe are large area collectors, most commonly flat plate collectors constructed as harp or meander collectors. Besides these collectors, especially in Asia evacuated pipe collectors are installed frequently also in large-scale solar plants. They are connected into rows in series; depending on the internal design, individual evacuated pipes can be combined into groups (see Figure 10).

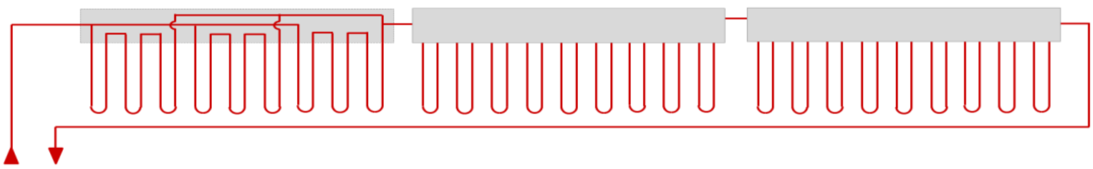


Figure 10: Example collector row hydraulic with direct flow through the evacuated pipes.

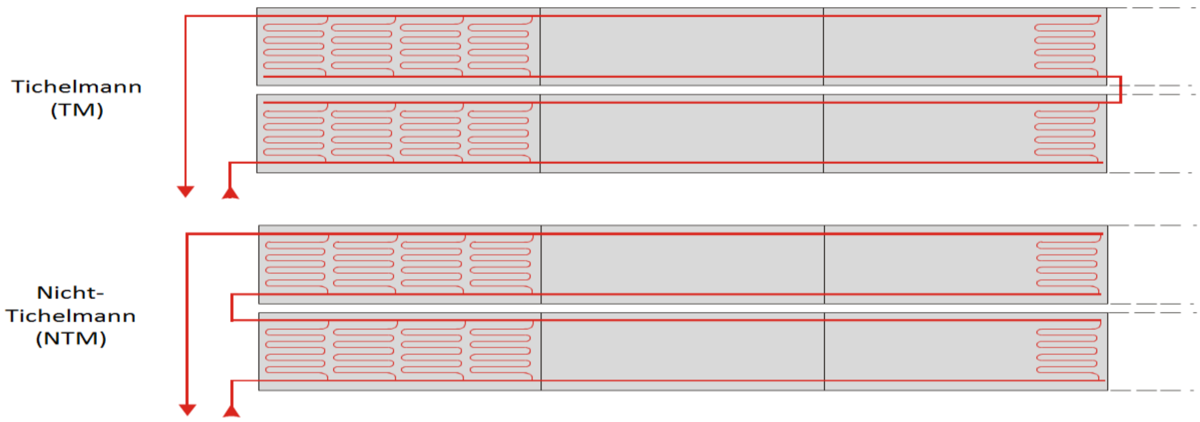


Figure 11: Example collector row hydraulic with meander collectors. Two groups are connected in series according to Tichelmann and non-Tichelmann layout. The absorber pipes within each collector are arranged in parallel.

1.2.2 Hydraulic levels of solar thermal plants

In order to understand and describe the hydraulics of a collector or collector array it helps to divide the solar thermal plant into various, interconnected hydraulic levels. With each step from one level to the next the elements, pipe dimensions, diameters and lengths change. The dimensions (diameter, length) of the pipes in relation to each other determine the mass flow within the respective hydraulic level which again influences the mass flow behaviour of the subsequent level. It is crucial to understand the effects of pipe dimensioning on each hydraulic level in order to fully comprehend the hydraulics of a collector and collector array.

Figure 12 shows the different hydraulic levels of an example collector array. The connections between the different hydraulic levels are marked by black circles. The absorber pipes are usually the lowest hydraulic level. The absorber pipes are connected in parallel via the collector manifold pipes. These form the second hydraulic level and are themselves connected to the flow and return pipes of the collector row. The collecting pipes of the entire collector array can be regarded as the highest hydraulic level.

As mentioned previously, the collectors of a solar thermal plant are first connected in parallel or in series, or in a combination of parallel and series, to form a row. Several rows are generally connected in parallel to form groups, and one or several of these groups may be connected in parallel to form what is called a collector array.

Wherever elements of any hydraulic level (be it absorber pipes, collectors, collector rows or collector groups) are connected in parallel, we have the choice between several hydraulic layouts: The most common layouts are the Tichelmann (TM) layout, also known as Z layout, and the Non-Tichelmann (NTM), also known as U layout (see Figure 11). Other types are possible but are rarely found as they have no advantage over TM or NTM, except for peculiar practical conditions such as obstacles area of the collector array. In the Tichelmann connection, the flow path (consisting of flow and return pipes, collector manifold pipes and absorber pipes) has the same length for each single absorber. This generally results in a good hydraulic behaviour in terms of flow distribution between the collectors and absorbers, making sure that each collector row / each absorber gets a comparable share of the total array mass flow.

The main advantage of a Tichelmann connection, the more homogeneous flow distribution, comes with the drawback that it requires longer pipe lengths. The flow distribution in Non-Tichelmann connections is not as even as in Tichelmann connections. The main influence on the flow distribution, however, is the pressure drop ratio between the manifold pipes and the hydraulic elements that are connected in parallel. This will be further explained in section 1.2.4.

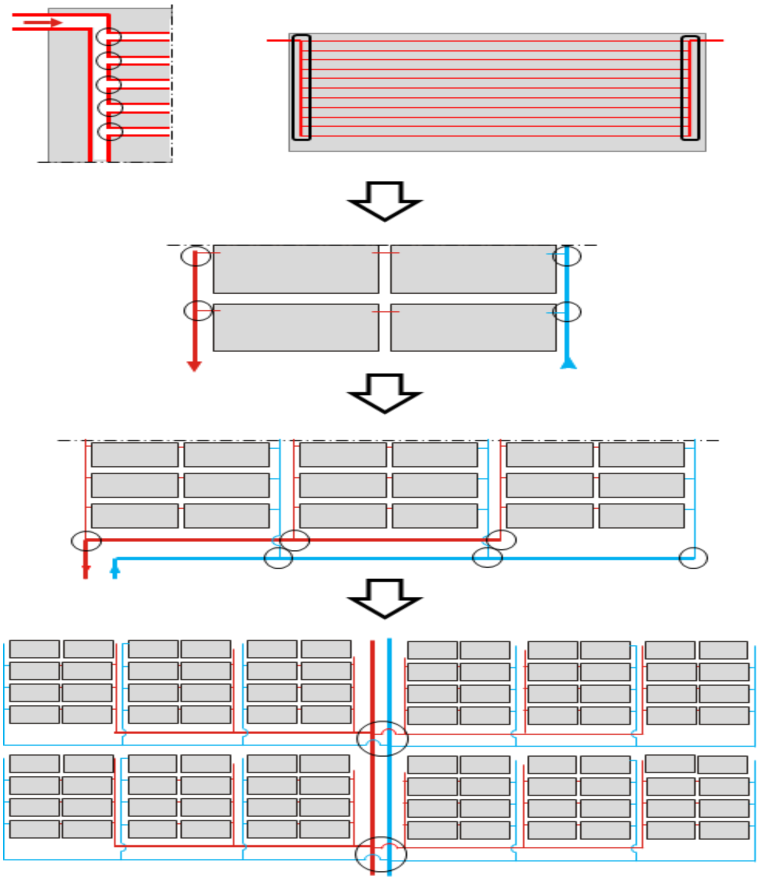


Figure 12: Hydraulic levels of an example collector array: collector manifold to absorber pipes, collector rows, collector groups and collector array.

1.2.3 Mass flow distribution in the collector arrays

In a collector array, one or more collector rows are connected in parallel, regardless of the type of collector used and regardless of the chosen hydraulic connection. Inevitably, this connection in parallel leads to an uneven distribution of the mass flows between the collector rows, meaning that not all the rows get the same share of the total mass flow.

This phenomenon occurs with Tichelmann as well as Non-Tichelmann connections, yet to different degrees. Figure 13 shows the mass flow distribution between the rows of a collector array using large-area meander collectors, connected in parallel according to Tichelmann (TM) and Non-Tichelmann (NTM) layout. The Non-Tichelmann (NTM) connection leads to a higher mass flow into the first collector row and a relatively low mass flow into the last collector of the array. On the other side, the Tichelmann layout causes a mass flow disparity between the central and the edge collector rows (VDI, 2004; Jones GF, Lior N, 1994; Bajura R. A., Jones E. H., 1976).

In general, the following rule holds: The higher the pressure drop of the elements that are connected in parallel, compared to the pressure drop in the connecting pipes (manifold pipes), the more homogeneous is the resulting flow distribution. In other words: In order to obtain homogeneous flow distributions, it is important that the elements connected in parallel have high authority compared to the connecting elements. This means, for example, that the following features have a positive effect on flow distribution between collector rows in a collector array:

- large pipe diameters in the connecting manifold (flow and return pipes)
- high pressure drop in a single collector row: large number of collectors connected in series, not too large pipe diameters inside the collectors, etc.

Technical guidelines for solar thermal systems have been released, and several R&D reports and text books summarize the state of knowledge (VDI, 2004; Jones GF, Lior N, 1994; Bajura R. A., Jones E. H., 1976).

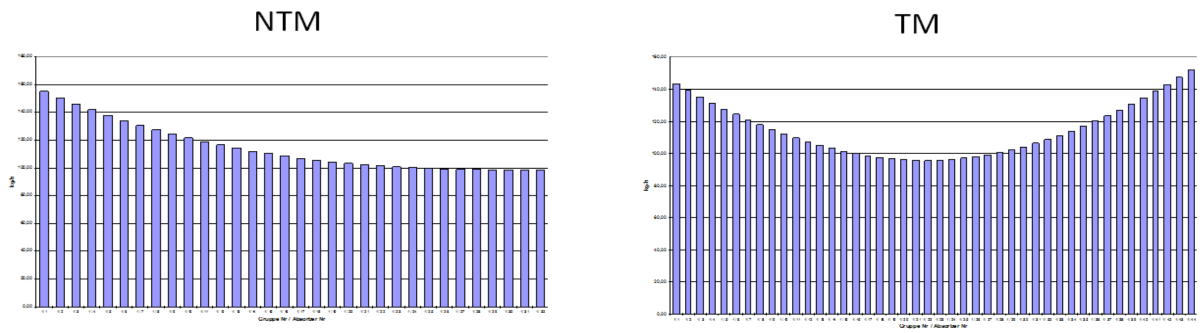


Figure 13: Mass flow distribution of meander collectors in parallel (left: Non-Tichelmann connection, right; Tichelmann connection) (Philip Ohnewein, 2013).

Uneven flow distribution causes a series of hydraulic and technical phenomena and therefore limits the number of collector rows that can be connected without resorting to valves that regulate the mass flow for each collector row. Homogeneous flow distribution reduces the total pressure loss and leads to constant flow temperature levels in the different plant components which again leads to higher thermal and electric efficiency (Wang & Wu, 1990). On the contrary, heterogeneous flow distribution causes higher temperatures in the plant's components and can even lead to partial stagnation if parts of the collector array reach the boiling temperature of the heat transfer medium (Glembin et al., 2010).

For practical purposes, a certain degree of inhomogeneous flow distribution can be tolerated. The German guideline VDI 6002 includes the recommendation that the mass flows of all collectors in an array should not differ by more than ±10%. This is equivalent to the following equation for the so-called "flow skewness factor": $\dot{V}_{max} = 1{,}22 \cdot \dot{V}_{min}$

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 in solar installations without running into problems. (Philip Ohnewein, 2013) has more details on this matter. In the "ParaSol" project, indicators for calculating the hydraulic and thermal limits to connecting large-scale collector arrays have been developed (see chapter 1.3).

1.2.4 Used methods for achieving a homogeneous mass flow

One of the main objectives of the layout of a large solar thermal plant is to design the collector array hydraulics in a way that allows for economic piping, keeping pipe lengths as short and flow distribution as homogeneous as possible.

Besides different methods of active hydraulic adjustment (control valves), there always remains the possibility to just tolerate certain disparities in the mass flow and to not take into consideration any further action. A proactive approach, however, to achieve maximum homogeneity in the mass flow distribution is based on the dimensioning of the supply and return pipes: as shown in Figure 14, the diameter of the pipes can be reduced gradually. As mentioned previously, the Tichelmann hydraulic design can help to achieve a more homogeneous mass flow distribution in the collector array. In combination with adjustments to the pipe diameters it is possible to achieve a more homogeneous mass flow. The disadvantage of this method, however, lies with the increase of piping needed for the collector array and therefore higher costs (see Figure 14 (b)).

Another possibility is to install mechanical balancing valves (see Figure 14 (c)). Balancing valves are very effective, but potential source of errors, as it is also contradictory to the minimization of the levelized solar energy cost. Employing balancing valves and other accessories such as air bleeders in the collector array has several cost-relevant disadvantages: higher initial cost (additional investment), increased installation time (for the necessary mass flow balancing) and possibly high ongoing costs (in case of defective valves). The adjustment of the collector connecting pipe diameters is instead another way for achieving a homogeneous mass flow. As shown in Figure 14 (d), these can be used instead of balancing valves or in combination with balancing valves. Despite the decisive advantage through lower costs as mentioned, adjustments to the collector connecting pipes diameter must be calculated in advance exactly and a subsequent adjustment would be very expensive.

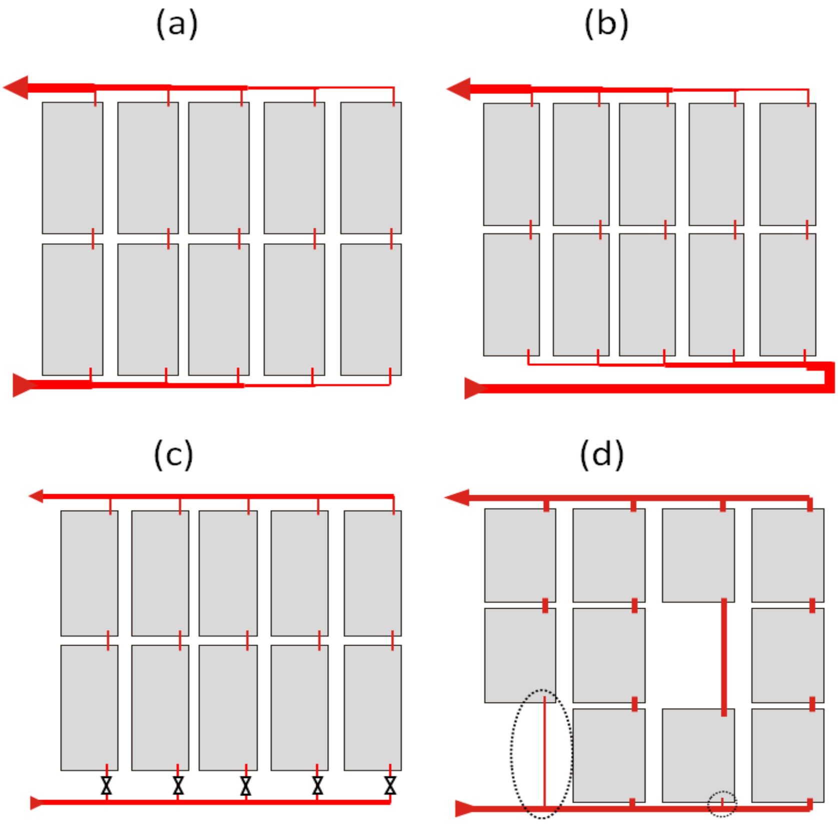


Figure 14: Methods for achieving a homogeneous mass flow distribution. (a) Adjustment of the supply and return pipes diameters. (b) Tichelmann connection in combination with adjustments to the pipe diameters. (d) Installation of mechanical balancing valves. (d) Adjustment of the collector connecting pipe diameters.

1.3 Key figures for evaluation of large collector hydraulics

One of the most important tasks in the design of large-scale solar thermal plants is the hydraulic dimensioning of the collector array. Specific indicators developed in the “ParaSol” project provide a straightforward way to conduct a simple technical characterisation, evaluation and comparison of different hydraulic designs. Further indicators allow for an economic assessment of solar thermal heat generation costs. (Philip Ohnewein, 2013)

The following 11 indicators provide a quick overview on the main technical phenomena of large collector arrays and facilitate a direct comparison of different hydraulic concepts. All indicators can be calculated in a theoretic analysis at the design time of a plant and therefore allow for a more sophisticated and more economic collector array design.

Stagnation distance: [K]

Uneven flow distribution in solar collector arrays results in uneven temperature distribution. Absorber pipes with the smallest mass flows reach the highest temperatures. In extreme cases, the local boiling temperature of the heat transfer fluid is exceeded and partial stagnation occurs, an effect that must be avoided.

The 'minimum stagnation distance' is defined as the temperature difference between the local boiling temperature and the hottest of all absorber pipe flow temperatures, taking into account the entire collector array. In contrast, the 'average stagnation distance' refers to the average flow temperature of the entire collector array. The comparison between the minimum and the average stagnation distance provides a straightforward way to assess the risk for partial stagnation to occur at some spot of the collector array.

One has to keep in mind that there is not one threshold value that the minimum stagnation distance should not fall below. Rather, relatively small stagnation distances may occur in normal plant operation, depending on system design, the choice of heat transfer medium, system pressure and operating conditions.

From the point of view of collector array design, as a rule one can conclude: large collector arrays, inhomogeneous flow distribution, small operating pressure and high flow temperatures all lower the minimum stagnation distance.

In case the flow temperatures are elevated, also the ratio of minimum to average stagnation distance, expressed in percent, is significant. In any case, small values are an indication of increased risk for partial stagnation.

Maximum flow velocity [m/s]

While it is not easy to set a specific threshold value for the flow velocity in a solar collector array, very high flow velocities are not permissible as they elevate the risk for erosion corrosion which could damage the pipe walls or eventually destroy them. Hence, high flow velocities have to be avoided by increasing pipe diameters or by changing the array layout. The key figure presented here is defined as the maximum flow velocity in all collector array pipes (all connecting pipes, absorber pipes and header pipes in collectors), regardless of the used pipe material.

Absorber pipe Reynolds number [#]

For the same design conditions, different absorber pipe Reynolds number can be attained based on the temperature levels, heat transfer fluid, solar collector design and the chosen solar array layout (hydraulic lengths). Higher absorber Reynolds numbers imply improved heat transfer in the absorber and thus increase the thermal efficiency of the system. Since flow conditions vary significantly within a collector array, this key figure is defined as the range of minimum and maximum absorber Reynolds numbers, taking into account all absorber pipes of the array.

Specific metal mass of array piping [kg_{steel}/m^2_{gr}]

Different solar array layout options require a different extent of pipe work, both in terms of pipe length and pipe diameters. Minimizing the piping effort is one way to reduce the solar energy cost. In order to encompass different design options into one value, this key figure includes the metal mass of all collector array pipes (outside the collectors) in relation to the overall gross area of all collectors in the array. Steel is assumed since it is most commonly used as piping material.

Piping network length [cm / m^2_{gr}]

The total network length of the collector piping is another measure for the overall piping effort of a collector array. For the definition of this key figure, the total network length (as opposed to the total piping length) is set in relation to the overall gross area of the collector array. This key figure differs from the previous one, the metal mass, in that it does not focus on the piping itself, but on the effort that has to be made in order to place the piping of the collector array. This is especially important in case the collector array pipework is laid underground: In this case, the piping network length.

Specific copper mass in the solar collector [kgCu / m^2_{br}]

Depending on the chosen collector array design, increasing the header pipes in the inside of solar collectors presents a way to obtain more homogeneous flow distribution and decrease pressure losses. This, however, is at the expense of the solar collector price which is strongly affected by the amount of metal used for the collector-internal piping. This key figure sums up the weight of all copper pipes in the collector, relative to the collector gross area. We chose copper since it is widely used as piping material and it is expensive. The absorber plate, often made of aluminum, is not taken into account.

Thermal capacity of the collector array [kJ/m^2_{br}K]

Capacitive energy losses occur in a solar plant due to the overall thermal capacity of the collector array which needs to be heated from ambient to operating temperature levels at least once per operating day. In other words, the absolute heat capacity of all collectors, the collector array piping and the heat transfer fluid is characteristic for the start-up losses of a collector array. Pipe lengths and dimensions, the heat capacity of the collectors and the employed heat transfer fluid must be known (see section 4.2 for an example). The heat insulation of the collector array piping is neglected, and no distinction is made between pipes exposed to air or to terrain. The key figure is expressed relative to the total array gross area.

Total pressure loss of the collector array [bar]

This key figure is defined as the total pressure loss of the collector array alone, at specific operating conditions. It comprises friction and minor pressure losses in the collector array, including the connecting pipes, main supply and return pipes and any hydraulic elements installed in the collector array (e.g. balancing valves). Hydraulic elements typical of the technical cabinet (e.g. heat exchanger, non-return valve etc.) are not taken into account, because they are hardly affected by the collector array design.

The significance of this key figure is associated with safety aspects. While there is not a specific maximum allowable value for the total pressure loss of the collector array, the pressure loss is limited by safety-related technical reasons such as: actual operating and maximum permissible pressure in the solar collector, stagnation distance (see above), pump pressure head, pump NPSH (Net Positive Suction Head), filling pressure of the expansion vessel, and last but not least dimensioning of the safety valve. Depending on the collector array layout, very large systems might reach a limit range.

Ratio of hydraulic to thermal power [W_{hyd} / kW_{th}]

Considering merely the absolute pressure loss of a collector array is not sufficient for comparing different layout options or for giving an estimation of the expected operating cost due to pump electricity. The effort of the pump (in terms of hydraulic power) in order to generate a defined solar thermal power output, at specific operating conditions, is a better measure of the operating cost.

Efficiency loss due to uneven flow distribution [%]

Uneven temperature distribution between the solar collectors leads to a decrease in the overall thermal efficiency of an array. This is due to the fact that collector efficiency curves decay stronger than linear: Due to this, the efficiency decrease of collectors operated at higher temperatures (smaller collector flow rates) is stronger than the increase that can be gained at lower temperatures (higher collector flow rates).

For this key figure, the theoretical thermal efficiency of a collector array with perfectly even flow distribution – but otherwise identical to the real one – is calculated. The key figure is defined as the ratio between the overall thermal efficiency of the array with the real (more or less uneven) flow distribution to the theoretical idealized thermal efficiency.

Overall emptying behaviour [in words]

In terms of operating safety, stagnation presents a serious risk, especially for large collector arrays with efficient collectors and high power outputs. Collectors and collector connections behaving well in case of stagnation are one key for handling this risk, although strategies exist for handling stagnation or overheating. For this key figure, the emptying behavior of a collector and collector array is assessed in qualitative way.

1.3.1 Example comparison of two collector arrays with different hydraulics

The objective of the following comparison is to conduct a technical evaluation of the hydraulics of two different collector arrays. The aim is not to state preferences or give recommendations for a specific collector type or array design. Figure 15 shows two reference collector arrays with a gross collector area of 4,800 m² each. The array on the left uses harp absorbers (16 harp collectors in series in each row, and 20 rows combined in parallel). The array on the right uses meander collectors (two groups connected in series form a row; each group consists of 16 collectors connected in parallel). (Philip Ohnewein, 2013)

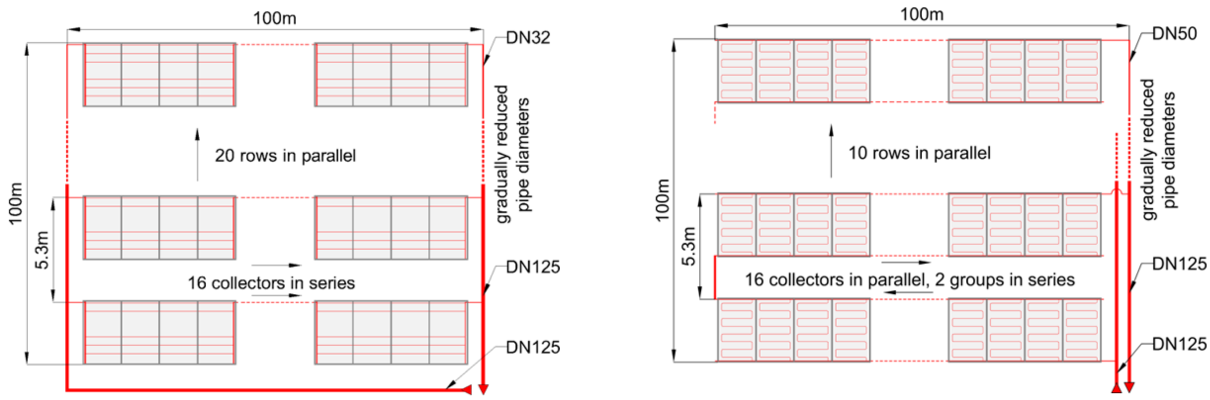


Figure 15: Hydraulic layout of the two reference collector arrays with a gross collector area of 4,800 m² each. The collector array on the left uses harp collectors, the one on the right meander collectors (Philip Ohnewein, 2013).

Table 1: General simulation results and the results of the characteristic indicators for both reference collector arrays in Figure 15: Hydraulic layout of the two reference collector arrays with a gross collector area of 4,800 m² each. The collector array on the left uses harp collectors, the one on the right meander collectors (Philip Ohnewein, 2013).Figure 15 (Philip Ohnewein, 2013).

General simulation results	Harp collector array	Meander collector array

Collector area: gross, aperture	4800 m$^2_{gr}$, 4492 m$^2_{ap}$	4800 m$^2_{gr}$, 4492 m$^2_{ap}$
Thermal output: absolute, relative	2769 kW, 577 W/m$^2_{gr}$	2763 kW, 576 W/m$^2_{gr}$
Supply temperature	86.3°C	86.2°C
Absorber temperature (supply): max, min	89.6°C, 84.2°C	89.0°C, 82.8°C
Total mass flow skewness factor	1.43	1.75

Collector array key figures	Harp collector array	Meander collector array
Stagnation distance: min, mean min/mean	41.0 K, 44.4 K, 92.3%	41.5 K, 44.4 K, 93.6%
Maximum flow velocity	1.69 m/s	1.71 m/s
Absorber Reynolds number: min, max	3451, 8812	2839, 7169
Specific metal mass of array piping	0.84 kg$_{steel}$/m$^2_{gr}$	0.50 kg$_{steel}$/m$^2_{br}$
Piping network length	~6.3 cm/m$^2_{gr}$	~2.1 cm/m$^2_{gr}$
Specific copper mass in the solar collector	1.28 kg$_{Cu}$/m$^2_{gr}$	1.96 kg$_{Cu}$/m$^2_{gr}$
Thermal capacity of the collector array	11.3 kJ/m$^2_{br}$·K	9.6 kJ/m$^2_{br}$·K
Ratio of hydraulic to thermal power	1.37 W$_{hyd}$/kW$_{th}$	1.27 W$_{hyd}$/kW$_{th}$
Total pressure loss of the collector array	1.94 bar	1.78 bar
Efficiency loss due to uneven flow distribution	0.03%	0.04%
Overall emptying behaviour	bad	good

Table 1 gives an overview on the indicators calculated for the two reference collector arrays presented above (Philip Ohnewein, 2013).

The calculation results of the mass flow distribution are satisfactory for the harp as well as for the meander collector arrays (absorber temperature (supply): max, min). Accordingly the numbers for stagnation distance (minimum and mean value as well as min/mean ratio) and the corresponding risk for partial stagnation can be considered as good. The overall efficiency loss due to uneven flow distribution (0.03 % for the harp collector array; 0.04 % for the meander collector array) is another indicator for low risk of partial stagnation.

However, even though the gross collector area and the specific mass flow of both collector arrays are identical, the absorber Reynolds numbers (min, max) differ substantially. This difference is the main reason for the slightly higher thermal power, higher flow temperature and the overall better thermal efficiency of the harp collector array compared to the meander array.

The maximum flow velocity in the collector fields are not in the absorber pipes but in the connecting pipes. Even though they can be considered as relatively high (1.69 m/s for the harp collector array and 1.71 m/s for the meander collector array), they still remain within an acceptable range. The overall pressure loss of both collector arrays does not pose any safety-related problems. The “ratio of hydraulic to thermal power”, however, shows that the harp collector array needs more electric energy for the same thermal output. While the harp collector array requires 1.37 W$_{hyd}$ in order to generate 1 kW of thermal power, the respective value for the meander collector array is 1.27 W$_{hyd}$ which constitutes a reduction of 7 %.

Due to the different internal pipe diameters, the specific copper mass of the meander collector (2.10 kg$_{Cu}$/m$^2_{gr}$) is considerably higher than that of the harp collector (1.37 kg$_{Cu}$/m$^2_{gr}$). However, due to the structure of the meander collector array, the piping network length is shorter length (2.1 cm/m$^2_{gr}$ vs. 6.3 cm/m$^2_{gr}$). As a consequence, the “specific metal mass of array piping” of the meander collector array (0.50 kg$_{steel}$/m$^2_{gr}$) lies clearly below that of the harp collector array (0.84 kg$_{steel}$/m$^2_{gr}$).

2 Stagnation and safety systems

2.1 Stagnation and its effects

Stagnation describes a situation where a solar thermal plant's operation is interrupted. The heat transfer medium stops to circulate in the collectors and the heat generated by the absorbers is not transported to the storage or the consumers. The stagnation can be caused by a technical problem (e.g. malfunctioning of the solar pump), by power outages or by a lack of load. During stagnation the collector medium is evaporated which leads to the energy being transported to other system components very efficiently. Consequently the components of the collector loop are exposed to very high temperatures; up to 300°C with evacuated pipe collectors and 200°C with modern flat plate collectors.

Large-scale solar thermal plants for industrial use are especially exposed to situations where stagnation is possible, for example due to insufficient load at the weekends or during maintenance work. Therefore, technologies and methods to avoid stagnation or reduce its negative effects on the different parts of the system are of high importance. In the context of large-scale solar thermal plants for district heating, stagnation is a rather infrequent phenomenon due to the theoretically unlimited storage volume of the network. Here stagnation is usually caused only by technical failures.

Avoiding stagnation and considering its effects is essential already at the planning stage of a solar thermal plant, regardless of which application purpose it is designed for, in order to prevent damages and to guarantee a long-lasting, reliable and low-maintenance operation of the plant.

2.1.1 The 5 phases of stagnation

The process of stagnation can be divided into 5 phases according to Hausner & Fink (2000) who have conducted comprehensive measurements on stagnation. In the following, these five, clearly distinguishable phases are described for a system with a non-return valve in the supply pipe. The liquid can be drained into to expansion vessel via both the supply and return pipe but the system can only be refilled via the return pipe.

- Phase 1 – expansion of the liquid:

  When the solar pump stops to operate, the collector temperatures rise quickly and homogeneously until evaporation sets in somewhere in the collector. The increase in system pressure is still rather small.

- Phase 2 – ejection of the fluid through evaporation

  The reaching of the boiling point, subject to local pressure conditions, in the collector triggers the evaporation process and consequently the system pressure rises very quickly. In this phase the emptying behaviour of the collector and collector array determines how much of the heat transfer medium is ejected out of the system by the steam.

- Phase 3 – emptying of collector by boiling – phase with saturated steam:

The increase in pressure decelerates and the remaining liquid heat transfer medium in the absorber and collector pipes evaporates slowly. In this phase the pressure, the strain on the components and the steam spread reach their maximum.

- Phase 4 – emptying of collector – phase with overheated steam:

  The collector becomes increasingly dry, it overheats and this causes the rate of efficiency to drop. As a result the steam volume can fall even further and withdraws to the collector area despite the fact that solar irradiation continues. In this way the system is partly refilled. This condition can continue to be stable for a very long time. With corresponding collector designs (collector connection via which the collector is filled up again lies on the top) saw tooth like pressure fluctuations of a higher amplitude can occur.

- Phase 5 – refilling of the collector:

  The collector is refilled via the return pipe.

2.1.2 Extreme strains and critical phases during stagnation

Hausner (2000) identified phase 3 of the stagnation process as the critical phase for the system componens and the heat transfer medium. The amount of liquid still in the collector and therefore available for evaporation (liquid not ejected in phase 2) determines the duration of this phase in which extreme thermal strain is inflicted on the system components. Due to the dynamics of the heating process, the expansion of the saturated steam volume also depends on the amount of remaining fluid. In absorber constructions where larger amounts of liquid cannot be drained or ejected, the increased evaporation of water leads to a concentration of glycol and other additives which again results in a higher boiling temperature of the residual liquid. The consequence of this is that a significant amount of residual fluid is not evaporated but exposed to extremely high temperatures over a long period of time which again leads to an accelerated degradation of the heat transfer medium. This is why collectors should be constructed in such a way that the system can be drained as thoroughly as possible during phase 2 (see Figure 16).

The highest system pressure and thus the highest thermal strains do not occur on cloudless days but rather when clear sky and clouds alternate. Measurements in moderate climatic regions revealed that on such days the radiation levels can reach more than 1,200 W/m² for a short period of time (a few minutes) leading to significantly higher volumes of steam and extensive strain on the system components. (Hausner & Fink, 2000)

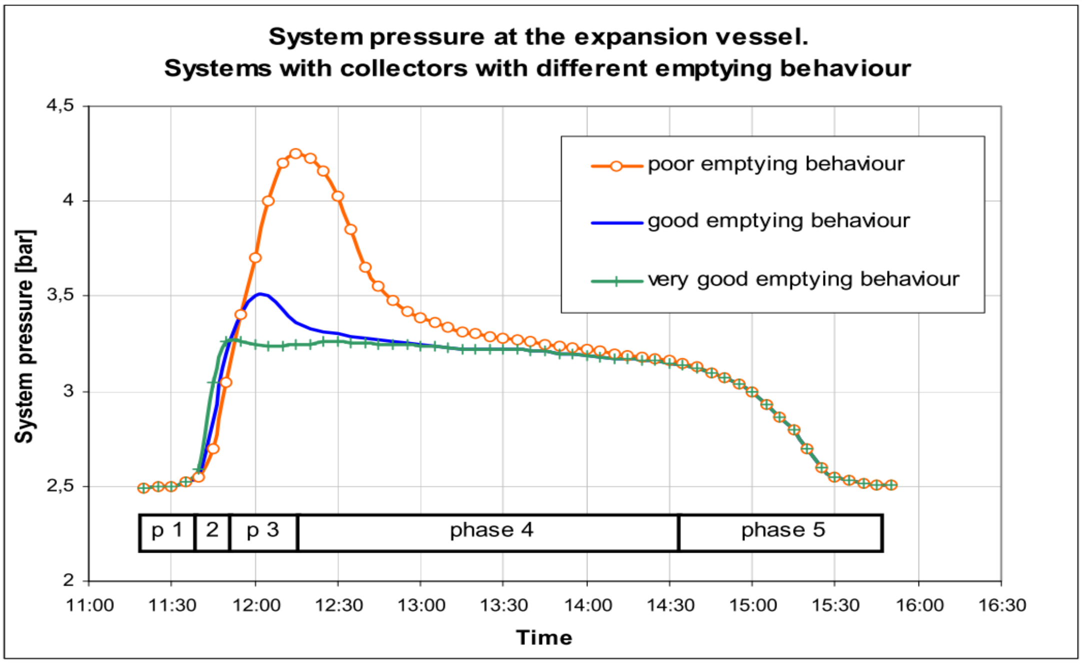


Figure 16: Schematic representation of the system pressure on the expansion vessel for collectors or systems with different emptying behaviour (Hausner & Fink, 2000)

2.1.3 Influence of the collector and collector array hydraulics on stagnation behaviour

The hydraulics of the individual collector as well as of the entire collector array determine the emptying behaviour and therefore also the duration and extent of stagnation. Other influential factors, especially on the risk of partial stagnation, are the flow distribution in the collectors and the collector array as a whole and the operation mode (low flow, high flow) (see also chapter 1.3).

Emptying behaviour of individual collectors

Collectors with favourable emptying behaviour minimise the amount of residual liquid in the collector and therefore reduce the duration and extent of the critical phase of stagnation (phase 3). Consequently the hydraulics inside the collectors should be designed in a way that allows for a good emptying behaviour, therefore reducing the adverse effects of stagnation.

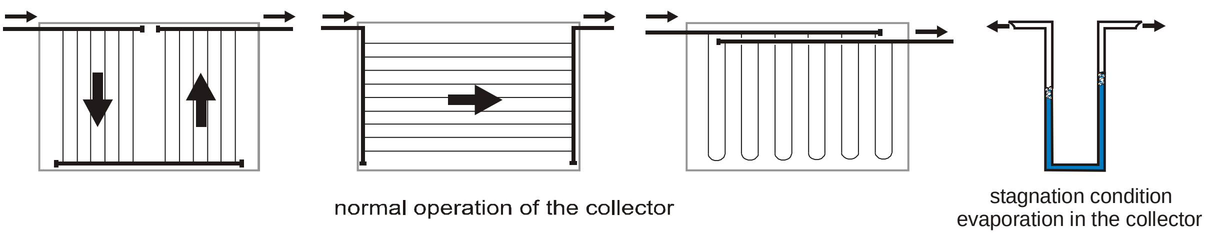


Figure 17: Schematic presentation of different circuitries in collectors with poor emptying behaviour. (Hausner & Fink, 2000)

The supply and return pipes in Figure 17 are connected at the top of the collector while the absorber pipes run vertically. This type of hydraulic connection allows for liquid to accumulate in the lower bends which results in a poor emptying of the collector and large amounts of energy therefore remain in the collector. In the case of stagnation this liquid is converted into steam, reaching a large part of the system in form of saturated steam. The hydraulic connection solutions in the collectors shown in Figure 18 lead to a much better emptying behaviour.

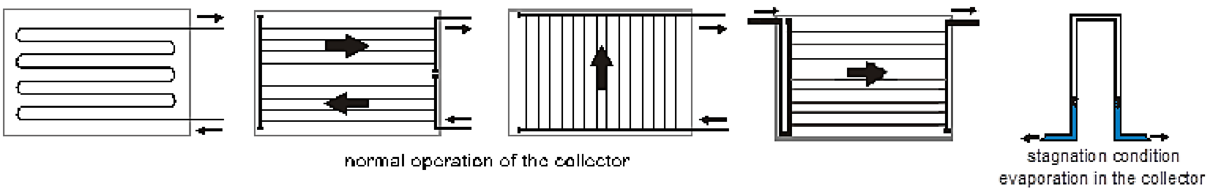


Figure 18: Schematic presentation of different hydraulic connections in collectors with favorable emptying behaviour. (Hausner & Fink, 2000)

The supply and return pipes are connected to the bottom of the collectors which allows for the heat transfer medium to be drained easily in the case of stagnation. The emptying behaviour therefore is much more favourable than in the examples shown above. If this is implemented consistently the duration and extent of the critical stagnation phase (phase 3) can be reduced significantly. Ideally the parts with saturated steam barely reach the collector level.

Emptying behaviour of collector arrays

In order to achieve a good emptying behaviour on the collector array level not only the internal collector hydraulic connection but also the arrangement of the collectors in relation to each other plays a crucial part. The array hydraulic connection shown in Figure 19 on the left will lead to a long and extensive formation of steam in the array even if the emptying behaviour on the collector level is good. Due to minor differences one of the collectors becomes penetrable to steam earlier on in phase 2 which prevents the second collector from being drained completely. The residual liquid in the second collector is evaporated and leads to a circular flow of steam which is partially condensed in the condensation stretch of the pipe. The residual liquid leads to a greater volume of steam in the system.

In contrast, the connection shown on the right inFigure 19 provides a good emptying behaviour as both collectors can be drained completely and independently from each other during phase 2.

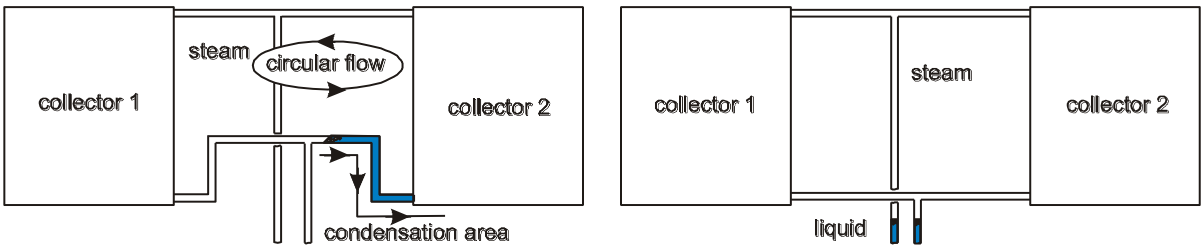


Figure 19: Connection of collectors leading to a) poor emptying behaviour, b) good emptying behaviour (Hausner & Fink, 2000).

Flow distribution and operation mode

The flow distribution of individual collectors, collector rows and arrays strongly influences the probability of partial stagnation. Highly heterogeneous mass flows lead to an uneven distribution of temperatures in the collectors and in the collector array. Partial stagnation can be triggered if the boiling temperature of the heat transfer medium is reached at some point in the collector.

Figure 20 shows the mass flow and temperature distribution in a collector row (meander collector) with heterogeneous mass flow. At the end of the collector the temperatures rise above the boiling point due to the uneven distribution of temperatures. The risk of stagnation can be calculated using the indicator “stagnation distance” presented in chapter 1.3. Another influencing factor on the risk of partial stagnation is the operation mode. Systems with low mass flow velocities (low-flow systems) generally reach a higher temperature difference between the supply and return pipes of the collector. The risk of reaching the boiling point and therefore causing partial stagnation is even higher when combined with a heterogeneous mass flow. With high-flow systems, on the other hand, the ΔT between supply and return pipe is smaller which limits the risk of partial stagnation.

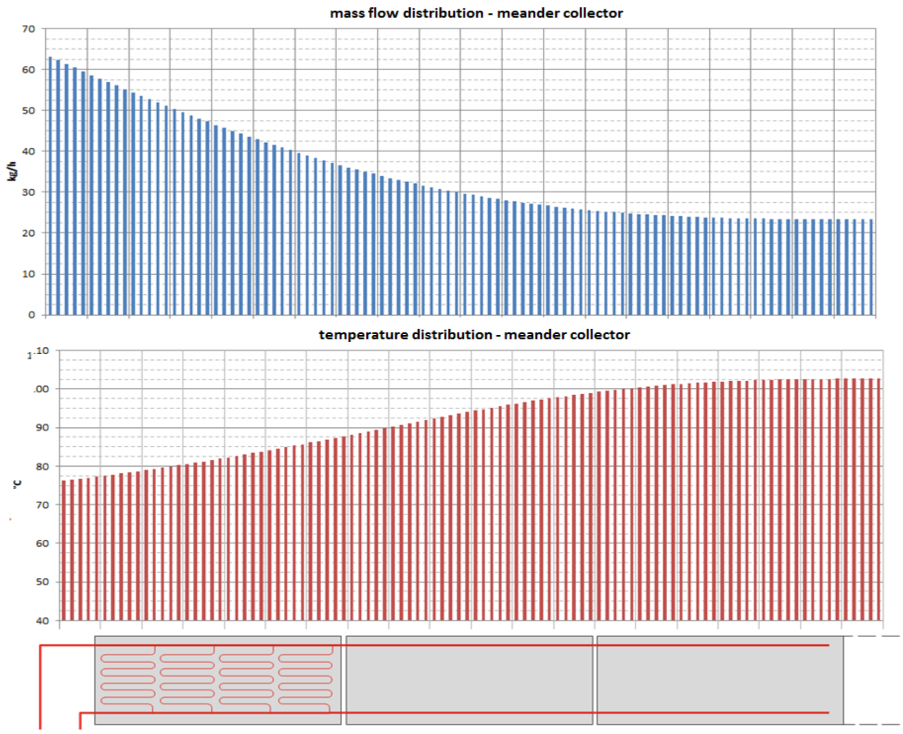


Figure 20: Example mass flow and temperature distribution of a meander collector row

2.2 Basic solutions for unproblematic stagnation behaviour

Usually expansion vessels are installed into the loops carrying heat transfer fluid. They absorb the expansion of the fluid caused by temperature differences and therefore avert damages due to high pressure. Another obligatory equipment is a safety valve which opens once a certain maximum pressure is reached. The opening of the safety valve, however, leads to a partial draining of the collector system if there is no collection mechanism is in place. The replacement of the heat transfer fluid therefore leads to higher costs and maintenance work. In smaller solar thermal plants, designed for domestic use, expansion vessels generally are dimensioned big enough to absorb the variations of volume of the heat transfer fluid caused by different temperatures and by evaporation.

On the other hand, large-scale solar thermal plants, especially the ones for district heating, generally do not provide more energy than the base load of the consumers and stagnation therefore does not occur frequently. It is usually only caused by technical problems or power outages. As mentioned above, however, in the industrial context stagnation can also happen during to vacations, maintenance work or production stand stills (e.g. at weekends).Therefore, precautions to prevent stagnation need to be taken with large-scale solar thermal plants as well, similar to smaller plants. There are two different basic strategies. On the one hand, it is possible to just accept stagnation as a normal operational incident and to make sure the system can handle stagnation conditions. Another strategy, however, is based on preventing stagnation as far as possible by taking measures to avoid the evaporation of the heat transfer medium and steam.

Table 2 next page gives an overview on the different options for both strategies, handling as well as preventing stagnation. Independent of the strategy or system chosen, a single measure can be taken or a combination of various may be necessary.

Table 2: 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 • Drain-Back concepts (special designed collectors and collector field hydraulics needed) **Small to medium systems (< 100 to 700 $kW_{th,p}$):** • Dissipators based on heat transfer to air (e.g.: finned tube heat exchanger) [< 350 $kW_{th,p}$] • Dissipators based on heat transfer to water (e.g.: stagnation cooler) [100 - 700 $kW_{th,p}$]	**All system sizes:** • Solar thermal collectors with automatic cooling of the absorber (without use of electricity) • Temperature dependent changes of optical properties of absorber coatings or glazing
“active” measures	**System “Ritter Solar” (with evacuated tube collectors):** • The German company Ritter XL Solar provides a 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 (e.g. > 350 $kW_{th,p}$):** • “active” cooler solutions in the solar primary loop **Systems with flat plate collectors – all system sizes** • Night cooling **Systems with concentrating and tracking collectors – all system sizes** • automatic „defocussing“ of the concentrator 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 (capable to absorb liquid expansion + steam volume) • high opening pressure of safety valve (in most realized systems) **emptying behavior 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 defocussing) **Expansion vessel and safety devices** • small (capable to absorb liquid expansion only) • opening pressure of safety valve can be kept low **emptying behavior of collectors / system** • good emptying behavior is favorable but not high priority

2.2.1 Strategies for preventing stagnation

If the evaporation of the heat transfer fluid and therefore stagnation is not accepted as operational condition, active and passive strategies need to be applied to prevent it from happening. The active strategy is based on keeping the maximum temperature of the heat transfer fluid and the system pressure below the boiling point by installing a safety valve that opens at a certain maximum pressure level. Table 3 presents the different evaporation temperatures according to the pressure level (data in absolute pressure and in bar) of water and of various water/glycol mixtures.

Passive strategies like self-draining systems (drainback systems), prevent stagnation by completely draining the collector array once a certain maximum temperature is reached. It is therefore impossible for any fluid to evaporate in the collectors.

Table 3: Evaporation temperatures of different heat transfer fluids at different levels of absolute pressure (Mauthner & Hausner, 2013)

pressure [bar_{abs}]		**Antifrogen N 20 vol-%**	**Antifrogen L 20 vol-%**	**Antifrogen N 40% vol-%**	**Antifrogen L 40 vol-%**
	Water	Water/ p-glycol	Water / e-glycol	Water / p-glycol	Water / e-glycol
1.0	99.6	101.1	102.1	103.6	106.1
2.0	120.2	121.7	122.7	124.2	126.6
3.0	133.5	135.0	136.0	137.5	140.0
4.0	143.6	145.1	146.1	147.6	150.0
5.0	151.8	153.3	154.3	155.8	158.3
6.0	158.8	160.3	161.3	162.8	165.3
7.0	164.9	166.5	167.4	168.9	171.4
8.0	170.4	171.9	172.9	174.4	176.8
9.0	175.3	176.9	177.8	179.3	181.8
10.0	179.9	181.4	182.4	183.9	186.3
11.0	184.1	185.6	186.6	188.1	190.5

Corresponding to Table 2 the following active and passive strategies are currently applied in large-scale solar thermal plants for the prevention of stagnation:

Night cooling:

If flat plate collectors are used night cooling can be implemented manually or automatically using the plant control system. It is based on avoiding stagnation conditions by cooling away the solar yield collected during the day. For this purpose the pumps of the solar loop are switched on during the night, therefore using the collector field to dispose of energy and cooling down the upper part of the tank. The night cooling mode can either be limited by a fixed interval (e.g. 120 minutes) or controlled by implementing a temperature-based control mechanism. The degree to which the tank can be cooled during the night depends on two criteria; on the one hand stagnation conditions need to be avoided for the following day and on the other hand the energy demand of the consumer needs to be met. (Fink & Hausner, 2000)

Theoretical research conducted on the calculation program SOLAR revealed that even under unfavourable conditions (assuming a clouded sky during the night, humid weather conditions and no wind) at least 15 % to 20 % of the heat generated by the solar thermal plant during the day can be disposed of. This value can reach 35 % to 45 % for cloudless, cool nights with gentle winds. (Berechnungsumgebung SOLAR, 1998-2013)

Active cooling in the primary loop to prevent stagnation:

Especially in the case of collectors with poor emptying behaviour, temperature-based re-cooling can help to prevent stagnation or otherwise high temperatures on the individual system components (e.g. isolation, mounting parts, solar pump, membrane of the expansion vessel). This active form of cooling in the primary solar loop can be provided by electric water-to-water or water-to-air coolers. Figure 21 provides an example for integration of a re-cooler into the supply pipe of the solar primary loop. The disadvantage with electrically operated re-coolers lies with its complete failure in case of power outages if there is no emergency power supply available. In this, admittedly, very rare occasion the system would need to be partially drained via the safety valve. The additional electricity consumption for the re-cooling reduces the overall energy efficiency of the solar thermal plant. Also, electric as well as thermal re-cooling devices can be considered as pretty cost-intensive. Nevertheless, automatic re-cooling solutions are considered as very reliable and effective. Furthermore, in combination with night cooling, the electricity consumption for re-cooling can be reduced by 15 % to 35 % depending on the probability of stagnation.

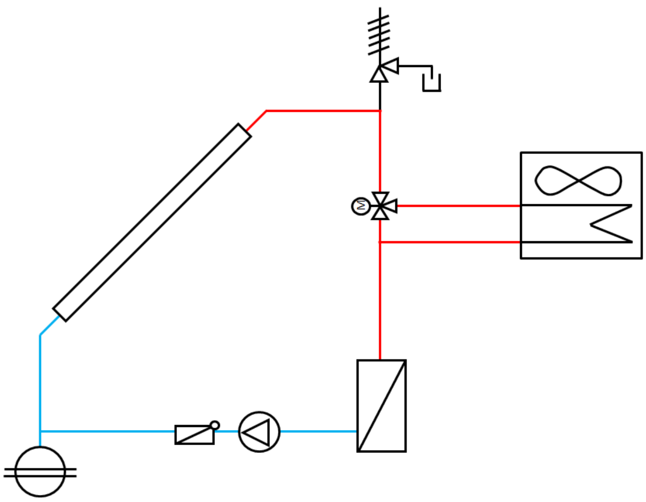


Figure 21: Example hydraulics of a system with active re-cooling in the primary solar loop in order to prevent stagnation

Drain back systems:

Drain back systems avoid evaporation by completely draining the entire collector array into a tank (drain back tank) by gravity as soon as a previously determined temperature is reached. If the collector array is drained completely, evaporation is impossible and consequently the negative effects on the system components can be prevented. For drain back systems it is therefore crucial to install collectors and collector arrays with a good emptying behaviour. Figure 22 shows an example of a hydraulics diagram of a solar thermal plant with drain back system. In the case of standstill, e.g. stagnation, the collector array is drained via the return pipe and the liquid is collected in the drain back tank. It is not necessary to install a non-return valve in the primary solar loop. The system is refilled using the solar pump.

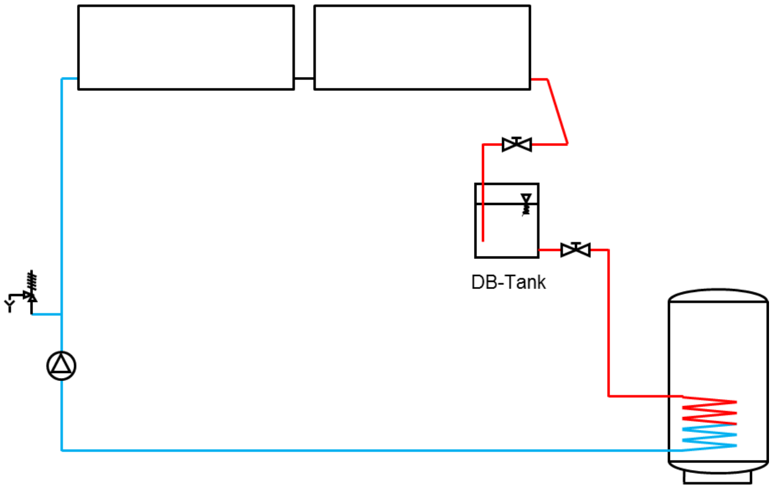


Figure 22: Example hydraulics diagram of a drain back system

2.2.2 Strategies for handling stagnation

If stagnation is considered an acceptable operational situation of the plant there must be strategies in place for handling stagnation. This implies that the volume expansion due to temperature changes of the heat transfer fluid as well as of the steam can be handled and controlled. By using collectors with good emptying behaviour the amount of steam and the thermal strains on the entire system can be reduced significantly. The components of the collector loop and composite materials need to be resistant to high temperatures; otherwise they need to be protected by additional cooling measures. The thermal strain can be reduced considerably by applying appropriate strategies (see Table 2). There still remains, however, the possible threat of degradation of the heat transfer fluid if a mix of water and glycol is used. The heat transfer fluid therefore needs to be exchanged more often which results in time and cost intensive maintenance work. In the following the strategies mentioned in Table 2 for the handling of stagnation are presented.

Stagnation cooler:

In medium-sized solar thermal plants of up to 50 m² finned pipe coolers can be installed. They are made of aluminium, simple and economic and can achieve an additional improvement of the stagnation behaviour. If the finned pipe cooler is replaced by a stagnation cooler even more heat can be dissipated via a smaller heat exchanger surface. Therefore, this solution can also be applied to large-scale solar thermal plants. As can be seen in Figure 23 an overflow valve is opened automatically in the case of stagnation and the heat transfer fluid is transported to the stagnation cooler. The heat transfer medium is collected in a tank until the stagnation process is over. The size of the tank is designed to capture the maximum steam volume but at least the whole heat transfer fluid of the entire collector field. From this tank the fluid is filled back into the system automatically after stagnation is over. Unlike a finned pipe cooler, a stagnation cooler requires additional resources, softened water and therefore increased operational and maintenance work. The advantage, however, is that the expansion vessel and pressure maintaining system need to be dimensioned only for a limited range of liquid expansion.

Apart from smaller projects in research and development, in 2010 a stagnation cooler was installed successfully for a solar thermal plant with 500 m² in Austria (Stiglbrunner, Brunner, Heigl, Muster-Slawitsch, Putz, & Hausner, 2010).

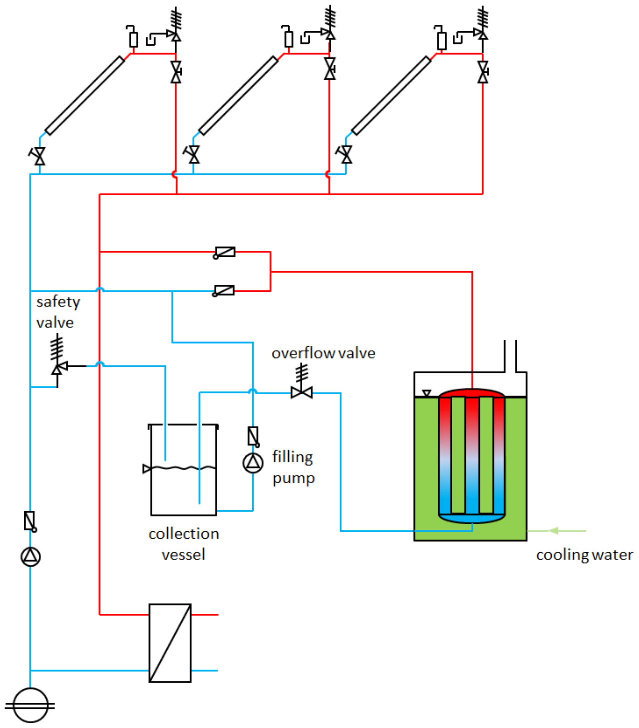


Figure 23: Example hydraulics diagram of a stagnation cooler in solar thermal plant

Adjustments to the hydraulics of the primary solar loop:

For smaller solar thermal plants used for domestic hot water and heating generally expansion vessels are installed in order to handle stagnation and additional steam volume (Detailed Information referring to the influence of system hydraulics on the emptying behaviour and on the dimensioning of the expansion vessel have been released in Hausner & Fink (2000)). For large-scale plants the company Ritter XL has designed a comparable strategy for handling stagnation called "aqua system". As can be seen in Figure 24 the primary and secondary solar loops are not separated. The heat transfer medium is water. In the event of stagnation a ball valve between supply and return pipe is opened automatically in order to allow for the system to be drained into the storage tank via both pipes. The tank as well as the system as a whole is designed to be able to absorb expansions of the liquid during normal operation as well as steam during stagnation.

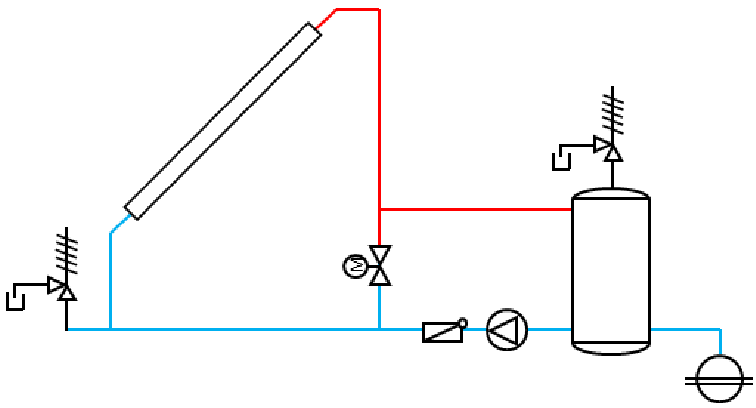


Figure 24: Example hydraulics diagram of a large-scale solar thermal plant with „aqua system"

Active cooling in the primary loop during stagnation:

Another possibility to reduce the thermal and pressure strains during stagnation is active cooling using electric re-cooling systems. Its integration is comparable to re-cooling systems used for the prevention of stagnation (see chapter 2.2.1 and Figure 21).

However, it needs to be considered that the implementation of active re-cooling systems requires additional resources compared to the previously mentioned cooling systems (adjustments to the hydraulics of the primary loop, stagnation cooler). Electric air or compressor coolers need a large amount of electricity to dissipate the heat in the collector array while water coolers require cold water and electricity for the circulation pump of the cooling water cycle. Furthermore, these systems may fail due to technical problems or power outages.

2.3 Safety solutions

Apart from measures for handling or preventing stagnation, solar thermal plants also need to be intrinsically safe which requires additional safety devices to be installed in the primary solar loop. The main safety equipment for all solar thermal plants as well as for any pressurized heat generating circulation system is the safety valve (DIN EN 12828 2011). Safety valves in the primary loop allow for the liquid or evaporated heat transfer fluid to be ejected into the environment or a collector tank once a maximum pressure level is reached in the system. The maximum pressure level is determined by the component with the lowest pressure rating and has to be coordinated with the heat load of the system. If a safety valve is triggered the plant cannot resume operation automatically, the safety valve needs to be inspected first.

The safety valve is the main safety device in use (basic safety concept). Currently there seem to be no other obligatory or standard safety solutions for large-scale solar thermal plants. An analysis of various international large-scale plants revealed that there are significant differences in the implementation of safety concepts. In the following an overview is given on established safety concepts for solar thermal plants. In all cases an expansion vessel is installed into the return pipe to handle the expansion of the volume of the heat transfer fluid due temperature variations.

Basic safety concept

Figure 25 presents the basic safety concept of a solar thermal plant. The safety valve is opened as soon as the maximum permitted pressure is reached, therefore allowing for steam or liquid to be discharged into the environment. Normally the safety valve is connected to a discharge pipe through which the entire volume of the solar loop is collected into a tank. Therefore the volume of the tank is designed to capture the maximum steam volume but at least the whole heat transfer fluid of the entire collector field. The safety valve can be connected to the supply pipe (see Figure 28) as well as to the return pipe of the primary loop and may be located before or after the solar pump. Different triggering pressures are determined depending on the position of the safety valve

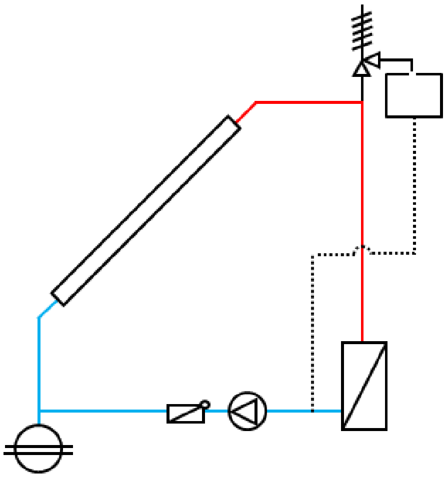


Figure 25: Example hydraulics diagram of a primary loop with a “basic safety concept”

Overflow valve parallel to safety valve

A further possible solution is to install an overflow valve parallel to the safety valve (see Figure 26). Overflow valves are characterised by a flatter response to the triggering pressure and close automatically when the pressure sinks below a certain, previously determined level. The triggering pressure of the overflow valve is below the safety valve (e.g. 0.5 bar lower). When the pressure rises above the maximum, determined level the overflow valve will open first and the tank will then collect the heat transfer fluid. The safety valve therefore will be only in use when the overflow valve is not working properly. This kind of system gives the possibility for the plant to be refilled automatically after a standstill or stagnation. The collecting tank is usually operated at atmospheric pressure.

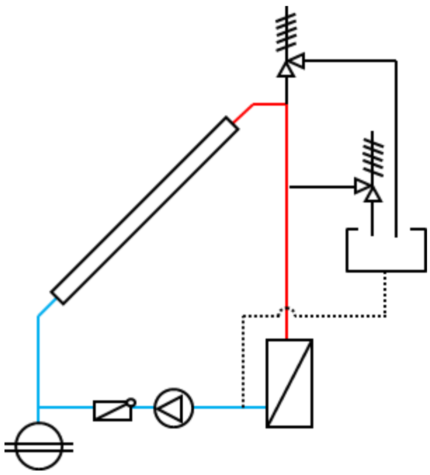


Figure 26: Example hydraulics diagram of a primary loop with a safety concept including one main safety valve and an overflow valve in combination with a collecting vessel

Internal shut-off valves in the collector array:

Internal shut-off valves allow for partial separation of collectors or collector groups from the collector array in the case of damaged collectors or maintenance work. If for this purpose three-way valves are installed, the heat transfer fluid from the collector rows or groups can be collected in a mobile tank and the standstill and refilling of the whole plant can be prevented. Furthermore, refilling is straightforward and easy when three-way valves are installed because the collector rows can be filled simply one after another. Figure 27 presents an example of a hydraulics diagram using this safety concept, including internal shut-off valves in each row of the collector array and one central safety valve.

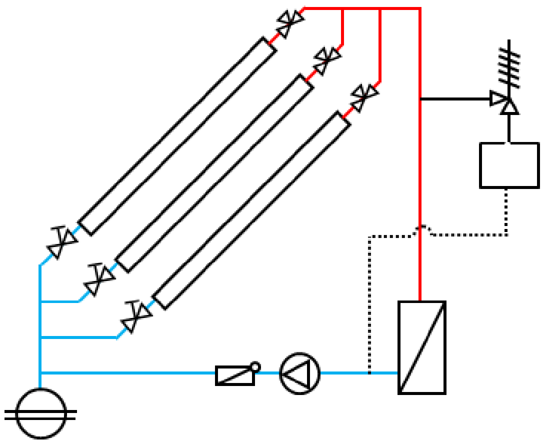


Figure 27: Example hydraulics diagram of a primary loop with a safety concept including three-way valves in the collector array and one main safety valve in combination with a collecting vessel

Depending on the safety concept it is also possible to install safety valves in individual collector rows or groups. Shut-off valves facilitate the separation of collector rows from the array for maintenance work or for the start up of the plant. They are also important in the case of damages to collectors. The safety concept presented in Figure 28 also features a central overflow valve for the drainage or refilling of the array after stagnation or high system pressure.

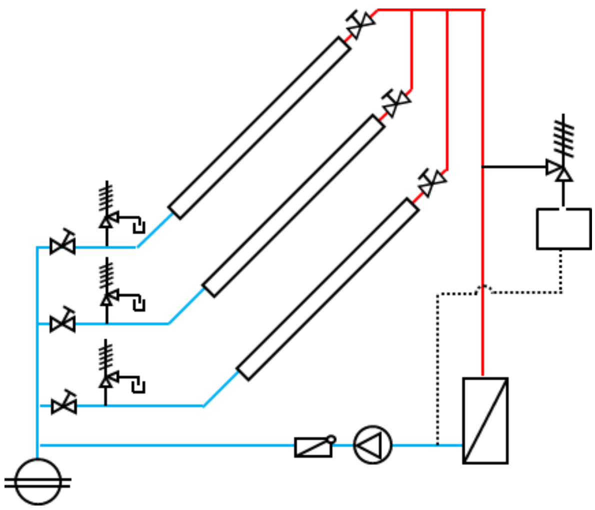


Figure 28: Example hydraulics diagram of a primary loop with shut-off valves and safety valves in the collector array and a main overflow valve in combination with a collecting vessel

3 Primary loop of example large-scale solar thermal plants

3.1 International differences concerning hydraulics benchmarks

In the following, 24 examples of realized large solar thermal plants are presented in order to identify the differences in the primary solar loop. Apart from the differences mentioned above concerning the type of collectors, the collector array hydraulics and the handling of stagnation (i.e. the safety concept), there are significant differences regarding the operation of the plant (flow velocity, pressure loss, etc.).

Table 4 gives an overview on the most important hydraulics benchmarks of 24 large-scale solar thermal plants. The gross collector areas of the examples presented range from 430 m² to 17,500 m². These large-scale plants are located in Europe as well as in China and Canada.

High flow velocities in the absorber pipes usually improve the efficiency of a solar thermal plant. However, very high flow velocities also increase the risk of erosion corrosion of the pipe material, leaving damages or even completely destroying the pipes (see section 1.3). Furthermore, high velocities in the absorber pipes require higher pumping power. Research has revealed that most large-scale solar thermal plants are operated in low-flow mode (at around 15 kg/m²h) but there are also systems running in high-flow mode (30 to 80 kg/m²h). It is not possible to draw a general conclusion on flow velocities in large-scale solar thermal plants.

Pressure losses in the collectors and the piping network are an important factor for determining the design of a solar thermal plant. High pressure losses require increased pump power and thus effectively limit the maximum area of collectors that can be connected in series. The case studies presented below reveal significant differences regarding pressure loss. For example, while the pressure losses for the system using flat plate collectors, implemented by “SOLID” and “Ramboll Energy” range between 350 mbar and 4,000 mbar (up to 5,000 mbar), for the plants implemented by “Ritter XL Solar” using vaccum tube collectors this value lies up to 1,6000 mbar. The thermal lengths of the example plants range from 10m to 150m.

Table 4: Hydraulics and plant benchmarks of international large-scale solar thermal plants

	Max. Serial Length of the collector field [m]	Max. Collector Area in Series [m²]	Delta p over the entire collector field [mbar]	Specific flow [kg/m²h]	Type of Collector	Meander/ Harp/U-Tube	Gross Collector Area	Pipe Material	Connection Method
Solid	30	63	350	35	FPC-DC	Harp	1134	steel	welding (gas welding)
	50	175	1400	17	FPC	Harp	3782		
NRCan		57	2840	14	FPC	Meander	2293	Steel in the energy centre, pre-insulated steel pipe underground, copper above the ground	Threaded, welded, soldered (respectively)
CIB Solar	10	17		60	VTC	U-Tube	1900	stainless steel	welding
	16	50		30	VTC	U-Tube	2200		
PlanEnergi	85	189			FPC	Harp	10600	Black steel (pre insulated)	Piping: Welding Collectors: Threaded
Ramboll Energy	150	369	5000	14	FPC	Harp	10000	Black steel	
	121	295	4000	14	FPC	Harp	10000		
	85	182	5000	15	FPC-DC	Harp	10000		
	85	182	5500	15	FPC-DC	Harp	12094		
	85	207	5000	14	FPC	Harp	17500		
TECSOL	7	13	250	80	VTC	U-Tube	430		
	11	25		50	FPC	Meander	1500		
Ritter XL Solar	12		1100	23	VTC	U-Tube	1330	Black steel	welding
	13		1600	22	VTC	U-Tube	3388		
	13		1100		VTC	U-Tube	687		
					VTC	U-Tube	1031		
					VTC	U-Tube	527		
					VTC	U-Tube	505		
					VTC	U-Tube	737		
					VTC	U-Tube	550		
AiguaSol		76	730	16	FPC	Harp	516	copper	welding (12% silver)
		17		35	FPC	Meander	990		
				18	LFC		3000		

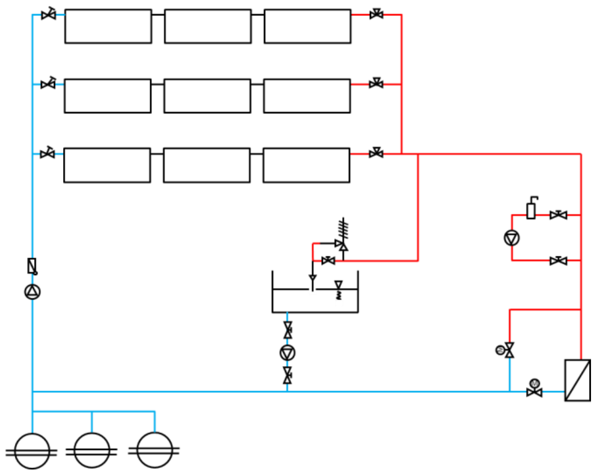
FPC: Flat Plate Collector; FBC-DC: Flat Plate Collector (Double Covered); VTC: Vacuum Tube Collectro directly streamed; LFC: Linear Fresnel Collector

3.2 Selection of example large-scale solar thermal plants

The following examples of international large-scale solar thermal plants show the wide range of hydraulics solutions that have been implemented. The focus lies on safety techniques and on the methods applied for handling or avoiding stagnation. Furthermore, the different methods for filling and venting are presented.

3.2.1 Jaegerspris, Denmark

Location:	Jaegerspris, Denmark
Application:	Solar-based district heating combined with a CHP plant (1,240 households)
Operation launched in:	2010
Collector area installed Collector type:	10,044 m² Flat plat collector
Storage technology:	2 x 740 m³ hot water storage
Safety concept:	• Only one central pressure relief valve • One three-way valve per collector row • cascade of expansion vessels • Empty collector arrays are filled manually via a pump installed in the return pipe • Night-time cooling to avoid stagnation • Deaeration of the supply pipe via a bypass located in the control room during commissioning phase and if necessary also during normal operation



Picture source: http://www.jp-kraftvarme.dk/

Further information: http://www.jp-kraftvarme.dk/

3.2.2 University campus „Riad“

Location:	University campus “Princess Noura”, North of Riad
Application:	Integration into district heating (domestic hot water for 65,000 persons, heating, thermal cooling)
Operation launched in:	2012
Collector area installed Collector type:	36,305 m² Flat plate collector (meander)
Storage technology:	6x150 m³ (steel)
Safety concept:	• In order to avoid stagnation the solar loop can be cooled using a water-to-water cooler • If the cooling is not sufficient or does not work a overflow valve is opened • Subsequently the heat transfer medium is collected in a tank via a steam separator • If the pressure falls below the triggering pressure of the overflow valve the system can be refilled manually via the return pipe.

Picture source: Millennium Energy Industries, AEE INTEC

Further information: http://millenniumenergy.co.uk/

3.2.3 Wels, Austria

Location:	Wels, Austria
Application:	Integration into district heating
Operation launched in:	2011
Collector area installed Collector type:	3,105 m² CPC evacuated pipe collector
Storage technology:	3 m³ hot water storage (hydraulic separator)
Safety concept:	• Water serves as heat transfer medium • Implementation of an antifreeze loop to avoid frost damage • No need for separation of the system • No valves (safety valves, etc.) directly in the collector array • Safety valve in the control room (in the return pipe) and directly on the buffer storage tank • Hydraulic balancing only via variations of pipe diameters • Only one, manual venting valve in the control room • In the case of stagnation a ball tap between supple and return is opened which allows for the system to be drained via both pipes. • The entire system is designed to handle fluid expansion and steam without problem
Picture source: Ritter XL Solar GmbH Further information: http://www.ritter-xl-solar.com/referenzen/	

3.2.4 Graz, Austria

Location:	Graz, Austria
Application:	Direct integration into district heating
Operation launched in:	2009
Collector area installed Collector type:	3,855 m² Flat plate collector with double-glazing
Storage technology:	64,6 m³
Safety concept:	• Each sub array is equipped with a safety valve, a circuit control valve and a manual venting device • A overflow valve a with a lower trigger pressure as well as a steam separator is installed in the control room • The collector array is filled manually via the return pipe • An auxiliary vessel is installed in order to protect the membrane of the expansion vessels
Picture source: SOLID Further information: http://www.solid.at	

3.2.5 Valencia, Spain

Location:	Valencia, Spain
Application:	Solar cooling
Operation launched in:	2010
Collector area installed	650 m²
Collector type:	UHV flat plate collector
Storage technology:	80 m³
Safety concept:	• Each parallel sub array is equipped with a circuit control valve as well as a manual venting valve • No safety valve in the sub arrays • A safety valve is installed in the control room in combination with a collecting tank • An additional venting valve is installed in the control room • A water-to-air cooler is used in order to avoid stagnation
Picture source: SRB Energy Further information: http://www.srbenergy.com	

3.2.6 Drake Landing, Canada

Location:	Okotoks, Alberta, Canada
Application:	Integration into district heating (housing estate with 52 one family houses/single occupancy)
Operation launched in:	2007
Collector area installed	2,293 m²
Collector type:	Flat plate collector
Storage technology:	• Short-term storage: 2 x 120 m³ (steel) • Seasonal storage: borehole storage (34,000 m³, 144 boreholes)
Safety concept:	• Each parallel sub array is equipped with a safety valve, a regulating valve and a manual venting valve • Additionally, a venting and safety valve are installed in the control room • The collectors are filled manually • A water-to-air cooler prevents stagnation • Two membrane expansion vessels balance the pressure
Picture source: Doug McClenahan, Natural Resources Canada Further information: http://www.dlsc.ca/	

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