IEA SHC Task 49

SolarPACES Annex IV

Solar Process Heat for Production and Advanced Applications

Overheating prevention and stagnation handling in solar process heat applications

Technical Report A.1.2

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1 Introduction

Solar process heat plants need to be able to operate reliably in all operation modes. Other than for conventional closed hot water or steam supply systems, solar thermal applications require specific technical solutions to cope with the phenomenon of stagnation. As explained in detail in this report, stagnation describes the state of a solar thermal system in which the flow in the collector loop is interrupted and solar radiation is further absorbed by the solar thermal collector and thus heats the fluid in the solar thermal collector up to a temperature where the absorbed energy equals the losses. Compared to conventional heat supply technologies this means that in case of technical defects, power blackout or simply due to a lack of heat demand (i.e., temporarily no available heat sink) some solar thermal collector fields (depending on the type of collector that is being applied) cannot be simply shut down so that they are further heated up. Without appropriate measures for overheating prevention and stagnation handling, the solar thermal systems would overheat. Depending on the solar thermal collector concept, different effects have to be avoided for regular operation conditions:

- The loss of heat transfer medium that has to be released to the atmosphere because of too high system pressures.
- Too high temperatures that lead to damage of the solar thermal collector or parts of the collector loop.

A challenge for solar thermal process heat installations is the handling of stagnation and overheating situations without danger of system failure and the need for additional maintenance work. This is not only true for solar thermal collectors, but for the whole installation.

For small to medium scale residential solar thermal applications, measures to control stagnation can be regarded as state of the art. Typically, pressure release through the safety valve can be avoided by larger expansion vessels and, if needed, simple heat dissipaters in the solar loop.

The same concepts may work for larger scale solar thermal applications as well, but when it comes to industrial applications designed for higher supply temperatures and equipped with more efficient solar thermal collectors other strategies such as additional active cooling devices for overheating prevention or de-focussing (in case of tracked collectors) may be prefered in order to guarantee a long-term, reliable and low-maintenance operation.

This report gives an overview of topics related to stagnation and overheating in general, and specifically of solar assisted process heat applications. The report focusses on the following main topics:

- Definition of terms
- Introduction to stagnation and overheating of collectors and collector fields
- Overheating prevention and control measures for solar process heat applications
    - Measures for solar process heat applications with non-concentrating collectors
    - Special challenges for concentrating and tracked collectors
- Good-practice examples of implemented measures
- References to related literature

2 Definitions of terms

To distinguish clearly between different situations and measures how to deal with the situations, three different temperatures are introduced and defined: the design temperature, the operation temperature and the stagnation temperature.

Design temperature

Design temperature is the maximum temperature a solar thermal collector or collector loop part can stand without being damaged. The design temperature of the entire solar loop is determined by the collector loop component with the lowest design temperature.

Operation temperature

Operation temperature is defined as the maximum temperature of a solar thermal collector or the collector loop where “normal” operation shall be pursued.

The operation temperature is a set temperature for each application and depends mainly on the temperature required at the point of solar thermal system integration. The operation temperature is the parameter that mainly influences the choice of the solar thermal collector technology and collector loop parts.

The operation temperature of the solar loop mainly depends on the process supply and return temperatures as well as on the number of heat exchangers, which finally determine the demanded solar loop supply and return temperatures. If there is storage capacity for solar heat installed, of which the storage temperature can potentially be higher than demanded for the supply of the process, the operation temperature of the collector loop is determined by the maximum storage temperature.

Stagnation temperature

Stagnation temperature is the temperature reached when stagnation persists until the losses of the solar thermal collectors equal the absorbed energy. The stagnation temperature depends on the ambient conditions (ambient temperature and hemispherical irradiance) and reaches different values depending on these conditions. The standard stagnation temperature defined by the international standard EN ISO 9806:2013 /1/ give the value for the stagnation temperature at 1000 W/m² hemispherical irradiance and 30 °C ambient temperature. This standard stagnation temperature is usually used to describe the highest temperature reached by the solar thermal collectors.

Stagnation

Stagnation describes the state of a solar thermal system in which (by any reason) the flow in the collector loop is interrupted although sufficient solar irradiance is available for operation of the collector loop.

If stagnation persists and solar irradiance is still being absorbed by the collector, temperatures and pressure in the collector loop will increase. When the temperature raises higher than the operation temperature, two things can happen:

- The design temperature is reached: The solar thermal collectors or parts of the collector loop reach a temperature where (parts of) the collectors (or the collector loop) are damaged. Obviously, this has to be avoided using appropriate measures.

- If the first does not apply and the stagnation persists, the collectors reach their specific maximum absorber temperature (= stagnation temperature). This temperature depends on the collector design and the current weather conditions (mainly irradiance and ambient temperature) and the heat transfer medium conditions inside the collector and/or collector loop.

Overheating

A solar thermal system overheats as soon as the operation temperature is exceeded. Overheating occurs, for example, if the energy delivery by the collectors exceeds the energy demand and heat storage capacity or if the control is leading to operation conditions where higher temperatures than aimed for occur (examples are given in Chapter 3). If no precautions are taken, the collectors will either be damaged or soon reach their stagnation temperature. Still, some parts of the collector loop may still be damaged if not selected properly in accordance with the specification of the collector.

Stagnation prevention, overheating prevention and stagnation handling

In the terminology and logic of this report “stagnation prevention” describes all the measures that prevent a no-flow situation from occuring. Above all, this means to ensure that even for longer power cuts the solar loop is still operable. In practice, such a concept for “stagnation prevention” applies only for the short time until the solar loop can be brought to a state where either further overheating (with stagnation = no flow) is avoided or stagnation can be allowed because it is handled and managed in a way that will cause no damage. Therefore, we do not call this “stagnation prevention” in this report, but rather “overheating prevention” or “stagnation handling.”

Stagnation handling

Stagnation handling (e.g., using control measures) is necessary **if stagnation is an accepted operation mode.** If this is the case, then measures must be included to prevent the solar loop components from severe system damage caused by the high temperature and pressure loads caused by stagnation.

Overheating prevention

Overheating prevention is necessary **if stagnation is not an accepted operation mode.** If this is the case, measures must be included to prevent the solar thermal system from stagnation, avoiding the corresponding temperature and pressure stress.

3 Introduction to stagnation and overheating of collectors and collector fields

This chapter gives an overview of the reasons for stagnation: when/why may stagnation occur, what are the consequences, under what circumstances does it lead to overheating, and what can be done to handle stagnation situations.

3.1 Reasons for stagnation

Stagnation describes the state of a solar thermal system in which (by any reason) the flow in the collector loop is interrupted and solar radiation is (or could be) further absorbed by the stagnating collector. More general, Harrison et al. /12/ describe stagnation conditions as "any situation under which the solar thermal collector cannot adequately reject absorbed solar heat to its primary heat transfer fluid, thereby causing the solar thermal collector, and/or its components, (including the heat-transfer fluid contained within its flow passages) to increase in temperature above a desired maximum level." Conditions like this can occur during periods of sunshine when the flow of the heat transfer fluid is interrupted due to technical defects, such as power failures, component failures (e.g., circulating pump, system servicing or repair) and pump-controller intervention due to energy storage capacity limitations or any other reason for a (temporarily) lack of heat demand.

Stagnation behavior is crucial for the long-term, reliable and low-maintenance operation of solar thermal systems. Particularly when it comes to industrial applications, the standstill behavior is important for manufacturers and operators in times when the installed solar thermal capacity cannot be fully utilized. This may occur due to technical defects (e.g., malfunction of the solar loop pumps), a missing heat sink (e.g., on weekends or holidays or maintenance and repair times) or power blackouts. This operating state places all the components in the collector circuit under considerable stress, which is quite different to that encountered in normal operating conditions.

For solar heat for industrial processes, some of solar collectors that are appropriate to meet the required conditions would be damaged when too high temperatures occur. For example, some tracked collectors achieve high operating/design temperatures, but would be destroyed if stagnation occurs and they are not defocused. In general, an important technological challenge for large solar thermal systems in industrial applications is how to achieve sound stagnation behavior at times when the heat of the collector system cannot be stored. In this respect, effective measures to cope with overheating and stagnation are an important aspect to minimize operational costs (maintenance work), to increase the service lifetime of the solar thermal system and its components, and to be able to ensure production guarantees.

3.2 Stagnation and stagnation temperature

Stagnation describes the state of a solar thermal system in which the flow in the collector loop is interrupted. If at this time solar radiation is further absorbed by the collector, the temperature of the solar thermal collector and the heat transfer medium increases. If no action is taken and no damage occurs leading to leakage etc. then the temperature will rise (for persisting stagnation conditions) until the heat losses of the solar thermal collector are equal to the absorbed solar radiation. The maximum temperature reached is called the stagnation temperature T_{stag}. In Figure 1 the development of the collector (or collector loop) temperature over time is outlined exemplary.

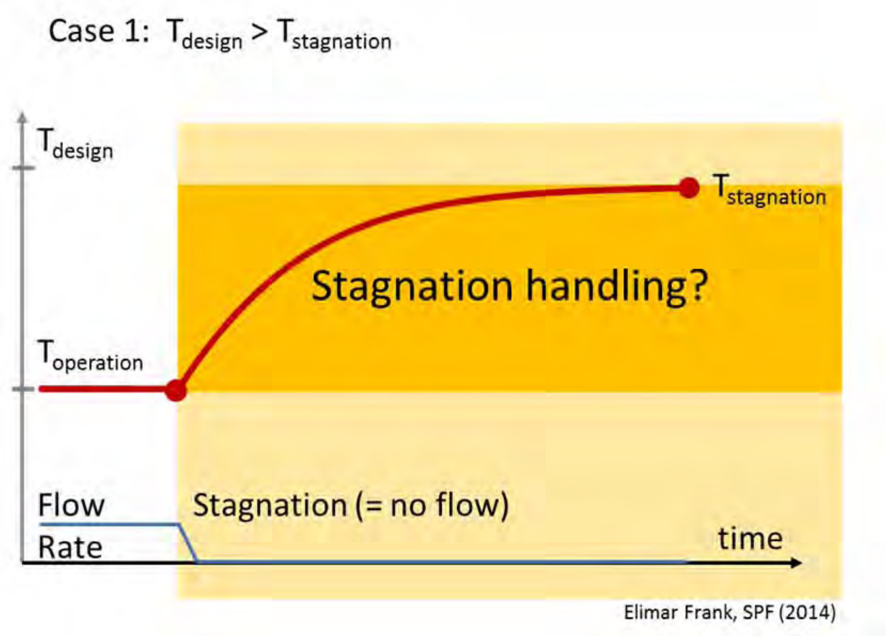


Figure 1: Sketch of temperature over time in case of stagnation and $T_{design} > T_{stagnation}$. The accented area in the graph is the time with stagnation (= no flow) and a stagnation handling concept may have to be foreseen in order to protect the heat transfer fluid or parts of the collector loop.

When the stagnation temperature is reached the thermal output of the solar thermal collector $\dot{Q}_{coll}$ drops to zero. The thermal output of a solar thermal collector can be approximated using the following equation:

$$\dot{Q}_{coll} = A \cdot G \cdot \left(\eta_0 - a_1 \cdot \frac{(T_{m,f} - T_a)}{G} - a_2 \cdot \frac{(T_{m,f} - T_a)^2}{G} \right) \qquad \text{eq. 1}$$

$\dot{Q}_{coll}$	Thermal output of the collector [W]
A	Collector area [m²]
η_0	peak efficiency (conversion factor) [-]
a_1	heat transfer coefficient at $(T_m - T_a) = 0$ [$Wm^{-2}K^{-1}$]
a_2	temperature-dependent heat transfer coefficient [$Wm^{-2}K^{-2}$]
$T_{m,f}$	mean fluid temperature in the collector [°C]
T_a	ambient temperature [°C]
G	hemispheric solar irradiance on collector plane [Wm^{-2}]

The temperature that is reached with $\eta_{coll} = 0$ (if this is lower than the design temperature of the collector, see above) gives the stagnation temperature T_{stag} of each collector and can be calculated from the efficiency curve equation (with $T_{m,f} = T_{stag}$):

$$T_{stag} = \frac{\sqrt{G \cdot \eta_0 \cdot a_2 + (a_1/2)^2} - a_1}{a_2} + T_a \qquad \text{eq. 2}$$

T_{stag} equilibrium (stagnation) temperature [°C]

To give an indication of the range of possible stagnation temperatures for certain given conditions, Figure 2 shows the power output related to the gross area of a selection of different types of solar thermal collectors that can reach the stagnation temperature without being destroyed. The power output can be calculated using the efficiency curve parameters (usually given by data sheets and/or test reports) with relation to the gross area of a solar thermal collector.

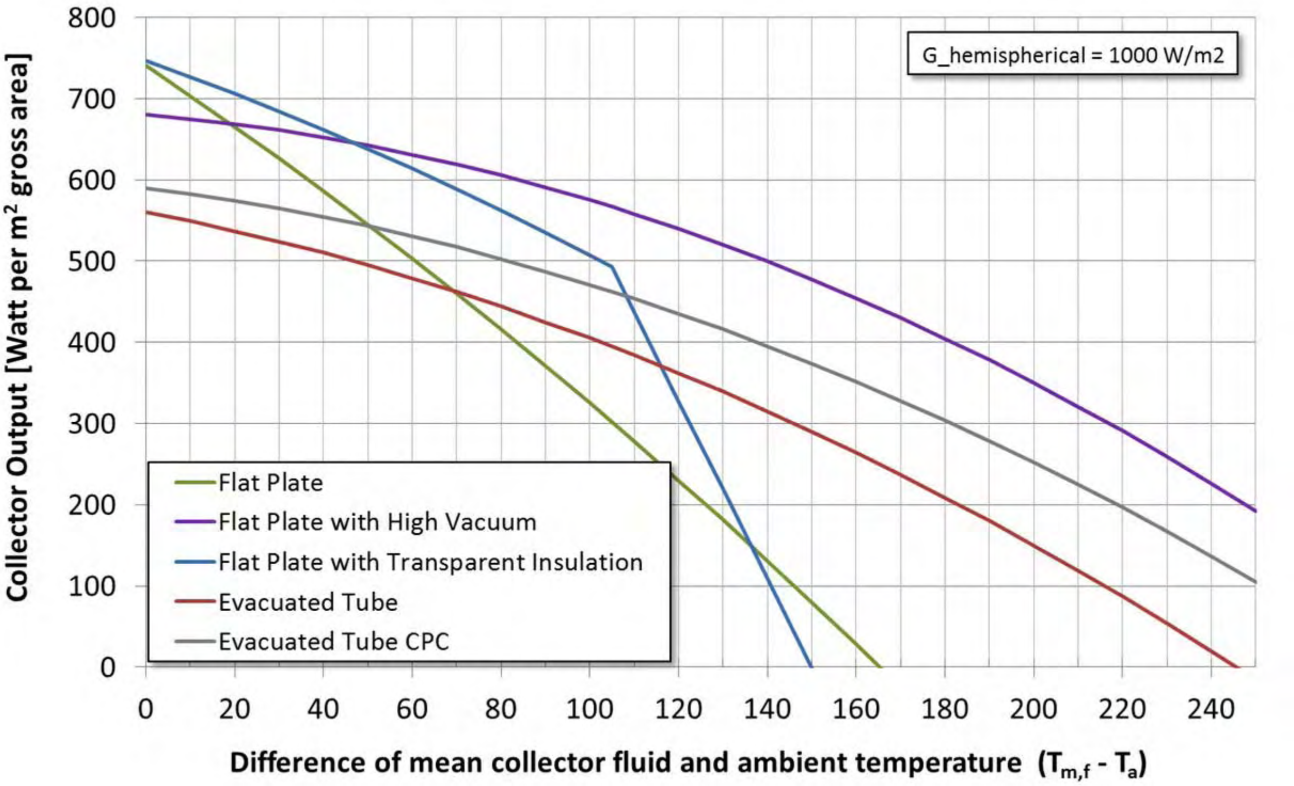


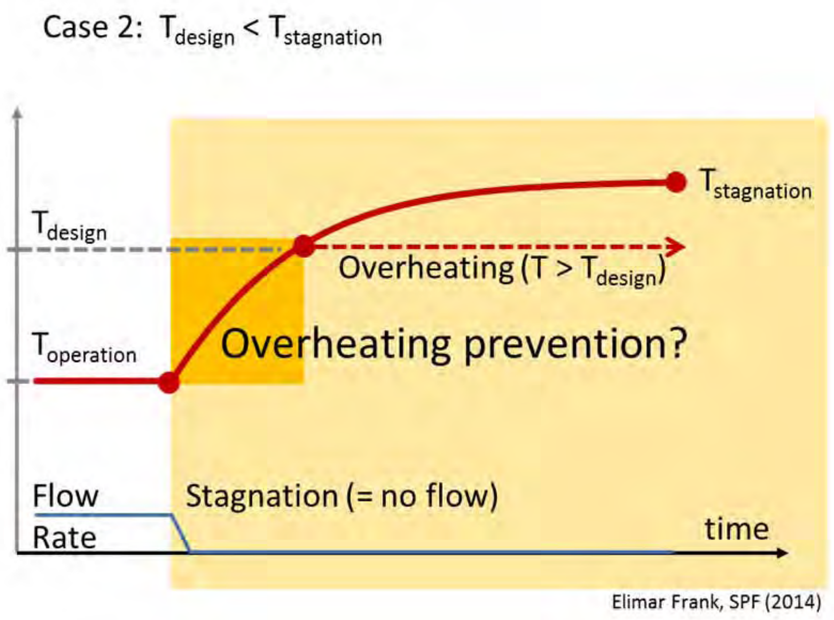
Figure 2: Exemplary collector output related to gross area for normal hemispheric solar irradiance G of 1'000 W/m² for different types of collectors. Note: The output curve of the flat plate collector with transparent insulation as displayed here is only valid for Tamb = 0 °C as the overheating prevention concept in this specific collector starts to decrease the output at 105 °C.

As shown in Figure 2 the maximum temperatures of the solar collector are highly dependent on the solar thermal collector technology used. Even for non-concentrating or non-tracked collectors stagnation temperatures may reach values well above 300 °C (e.g. advanced vacuum tube collectors or high-vacuum flat plate collectors) under conditions as described above. Table 1 shows the parameters that have been assumed for the calculation of the power curves presented in Figure 2 as well as the calculated stagnation temperatures related to those collectors based on eq. 2.

Table 1: Collector parameters and calculated stagnation temperatures

Type	η_0 (gross) [-]	a_1 (gross) [$W/m^2.K$]	a_2 (gross) [$W/m^2.K^2$]	T_{stagn} (T_a = 0 °C) [°C]	T_{stagn} (T_a = 20 °C) [°C]
Flat Plate	0.74	3.65	0.005	165	185
Vacuum Tube	0.56	1.05	0.005	246	266
Vacuum Tube CPC	0.59	0.69	0.005	281	301
Flat Plate (high vacuum)	0.68	0.45	0.006	301	321
Flat Plate (transp. ins.)	0.75	1.94	0.005	150	150

For some collectors, the stagnation temperature is only a theoretical value as it cannot be tested because the collector would be destroyed before reaching the stagnation temperature. In this case, the design temperature is lower than the stagnation temperature (and naturally is between the operation temperature chosen for a certain application and the theoretical stagnation temperature). This is true for many high concentrating collectors (which are usually tracked if they have a concentration factor higher than 25), but also other collector concepts can be in this category (e.g., those using plastic parts that do not stand a certain temperature). Thus, they need an overheating prevention that is described in Chapter 4. This situation is outlined in Figure 3.



Elimar Frank, SPF (2014)

Figure 3: Sketch of temperature over time in case of stagnation and $T_{design} < T_{stagnation}$. The accentuated area is the time with stagnation (= no flow). As the collector temperature (or collector loop part temperature, if that is the "weakest" part) should not exceed the design temperature an overheating prevention concept has to be foreseen.

Note: Without overheating prevention a solar thermal collector always reaches its specific stagnation temperature, regardless if a single, empty collector is exposed to the sun (e.g., during construction) or an entire filled and pressurized collector field while system still-stand is exposed to the sun. The difference at the system level is when the high stagnation temperatures evaporation of the heat transfer fluid occurs (depending on system pressure), which leads to increased pressure and temperature stress not only in the collector itself, but also affects the collector loop components.

Note: The (current) stagnation temperature can vary as depends on the current weather conditions, such as ambient temperature and irradiance.

The processes during stagnation have been investigated theoretically and experimentally (cf. e.g. /2/, /3/, /4/, /5/, /6/, /12/, /13/, /14/, /15/) and are explained for fields of flat plate collectors in more detail in /14/. An excerpt of /14/ with some additions and adaptions is given in the Annex of this report.

3.3 Damaging due to overheating

This section outlines briefly what could happen to those collectors (or parts of the collector loop) that would be damaged when overheating occurs (especially concentrating/tracked collectors). The concept to prevent overheating always has to address the lowest design temperature of any part in the collector loop (see the example for the Göss Brewery in Chapter 5).

For a parabolic trough collector system, overheating will have different effects and causes. During the overheating process the absorber tubes and the whole pumping and cooling systems are affected, depending on the design temperature reached. Each component acts differently to the heat according to its nominal temperature indicated through the manufacturers. In general the components that can be affected are:

- The pumping system, which has a maximum temperature of usage. In case of overheating the rubber seals or other non-metallic components may be destroyed.
- The absorber coating resists up to a specific temperature, above this temperature the coatings start to degenerate.
- For collectors with a high concentration factor, it is possible that the tube itself overheats to such an extent that permanent deformation occurs.
- The thermal oil that resists until a particular temperature depending on the oil that is used. The thermal oil will lose its efficiency.
- The rubber seals in the piping system have a nominal temperature. Above these temperatures the seals will crumble and leaks can appear in the system.

It is important to know that unless leakages of the high temperature liquids occur there is, normally no danger for humans. Leakage of the different liquids can, however, have a negative impact on the environment because of the oil used in the absorber tubes and the danger of ignition.

These elements will most likely not destroy the entire collector system, but if destroyed they are quite easy to replace. Of course as each component has a different nominal temperature, it is important to uphold and control these temperatures in the system.

4 Stagnation handling and overheating prevention for solar process heat applications

This section describes different measures to prevent overheating, such as control strategies, defocusing in case of tracking collectors, heat dissipation and others.

To avoid damage caused by too high a temperature and overpressure, every closed circuit is filled with heat transfer fluid is equipped with expansion vessels that are able to absorb the expansion of liquids due to temperature increases. Furthermore, a pressure controlled safety valve is mandatory, which opens as soon as a defined maximum pressure is reached and vaporos heat transfer fluid is released. Openings of the safety valve lead to a partial emptying of the system (liquid and vapor) with loss of heat transfer fluid thus causing additional costs and maintenance.

In the case of conventional small-scale solar thermal systems for domestic applications, the expansion vessels are typically designed in a way that both the expansion of the collector fluid as well as the extra volume of the vaporized fluid can be absorbed. This means larger, and therefore, more costly expansion vessels are needed.

State of the art large-scale solar thermal systems, for example, solar assisted district heating networks, are typically designed in a way that the solar heat supply does not exceed a constant base load heat demand of the heat sink. In such systems, stagnation can only be caused by a technical malfunction or a power outage, which rarely occurs. However, in large-scale solar thermal systems for industrial applications stagnation can occur much more frequently, for example as a result of process dependencies, weekend shutdowns or company holidays. In addition, particularly in industry, it is inevitable that an energy supply system requires low maintenance and therefore stagnation handling or automatic overheating prevention must be guaranteed and losses of heat transfer medium avoided.

Different strategies for managing the expansion and stagnation include either that the entire solar loop is designed similar to the conventional small-scale solar thermal systems that can cope with steam (stagnation handling) or the evaporation of heat transfer fluid is (mostly) avoided (overheating prevention).

In Table 2 lists the different options for both strategies: stagnation handling and overheating prevention. Depending on the chosen strategy, either one or a combination of the listed options can be applied for solar process heat applications, and will mainly depend on the system size, the collector technology used and the load profile of the industrial heat consumer.

In the subsequent Chapters 4.1 Stagnation Handling and 4.2 Overheating Prevention the measures mentioned in Table 2 are explained schematically in more detail and in Chapter 5 examples of solar process heat applications are presented.

Table 2: Stagnation handling and overheating prevention measures in solar process heat applications /2/

	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$_{th,p}$):** • Dissipaters based on heat transfer to air (e.g.: finned tube heat exchanger) [< 350 kW$_{th,p}$] • Dissipaters 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 • Solar thermal collectors with heat pipes properly designed to limit their operating temperature range (dry out limit)
“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

4.1 Stagnation handling

Stagnation handling is necessary if evaporation in the solar loop is an accepted operating mode. Stagnation handling implies that there is controlled absorption of both the volume of liquid expansion and the steam volume. In addition, temperature resistant collector loop components and compound materials are needed or need to be protected with additional cooling measures. It is preferred to reduce the steam volume and high temperature loads systems with good emptying behaviour.

The advantage of the stagnation handling measures explained next is that they function independent from the electrical supply or only require a low capacity uninterruptible power supply (UPS) (e.g., for solar loop control + motor operated control valve).

A disadvantage, especially for large-scale solar thermal systems, is that the costs for expansion vessels can be high due to the large steam volumes that may occur in the case of stagnation.

4.1.1 (Passive) heat dissipaters in the solar primary loop

For small domestic hot water and space heating solar thermal systems stagnation control with expansion vessels is state of the art.

For medium-scale solar thermal systems simple and inexpensive finned-tube heat exchangers made of aluminium can be used to significantly reduce the steam range and hence the steam volume (see Figure 4).

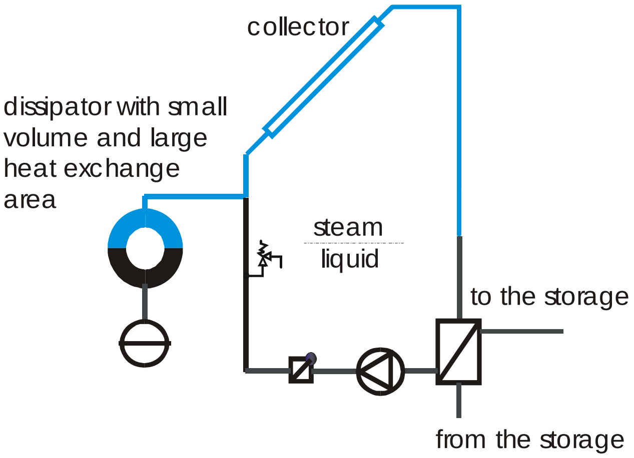


Figure 4: Possible placement of dissipators like air coolers in the solar primary loop /3/ /10/.

With a simple finned-tube heat exchanger as indicated in Figure 4 (dissipater) around 750-1000 W per meter can be dissipated /3/ whereas with insulated piping at boiling conditions 25..35 W can be removed. Nevertheless, for larger systems passive air-coolers, such as finned-tube heat exchangers may not be sufficient to protect temperature-sensitive components from steam and hence more efficient heat exchangers are necessary. One solution is to replace the passive air coolers with evaporative coolers (see Figure 5) so that more heat can be dissipated using a smaller heat exchanger surface. This technology is still in the early stages of development, but its functionality was demonstrated within the framework of an Austrian demonstration project for a 500 m² solar thermal system in 2010 /20/.

Other than for the air cooler, the evaporative cooler depends on additional resources, namely softened cooling water, and therefore require additional efforts to operate and maintain. On the other hand, the expansion vessels or the pressure holding system can be designed for fluid expansion only.

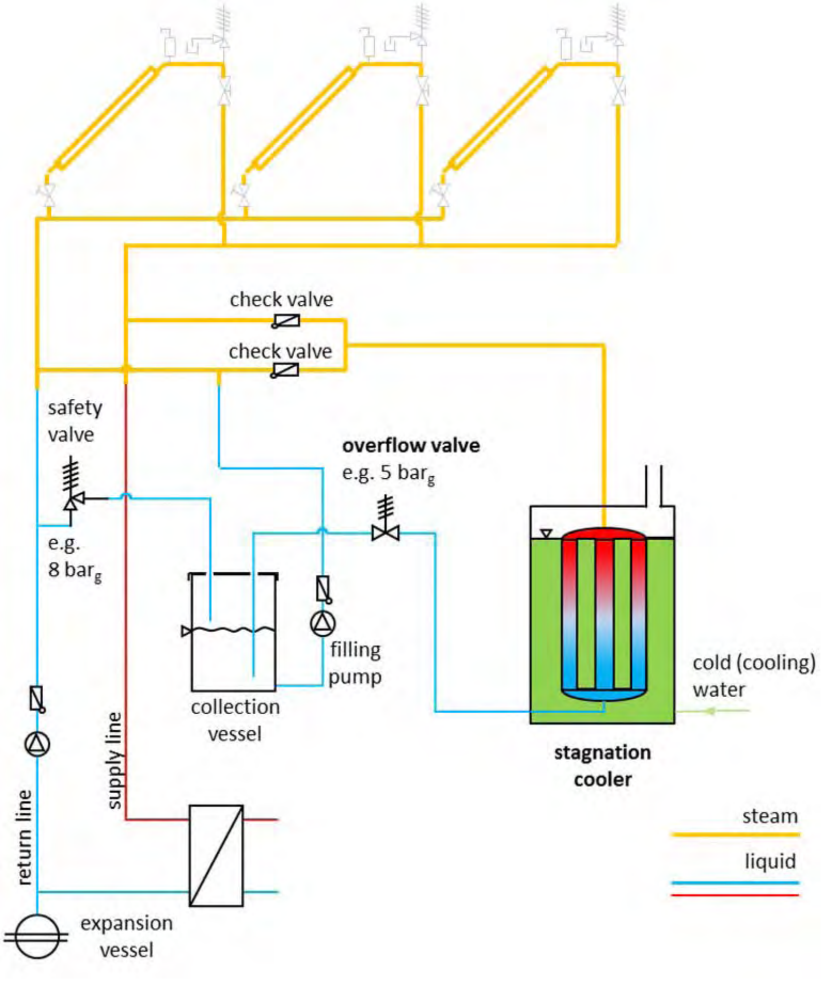


Figure 5: Schematic diagram of an evaporative cooler for the reduction of steam volume while stagnation for medium-scale solar thermal systems /20/.

Functionality	In the case of stagnation, the overflow valve opens due to system overpressure (e.g., 5 barg) and the medium is pushed through the stagnation cooler. The positioning of the check valves ensure that the collector field is emptied via both the supply and the return line and that steam cannot penetrate further into the system. In the stagnation cooler the medium is condensed and cooled down below 100 °C before the liquid medium enters the (atmospheric) collection vessel. As soon as the system pressure goes below a defined pressure (e.g., 2.5 barg), a filling pump automatically re-fills the system.
Advantages	The concept works independent of the electrical supply.
Disadvantages	The expansion vessels in the solar primary loop need to be designed for liquid expansion (the volume occurring when the opening pressure of the overflow valve is reached).
Comments	Good emptying behaviour of the system is preferred. All system components within the collector loop, including the entire stagnation cooler loop, need to be designed to withstand the temperature stress determined by the opening pressure of the overflow valve. Little practical experience (one demonstration in Austria with 500m²).

4.1.2 System “Ritter Solar”

A special system that can cope with steam is provided by the German company Ritter XL Solar for evacuated tube collectors.

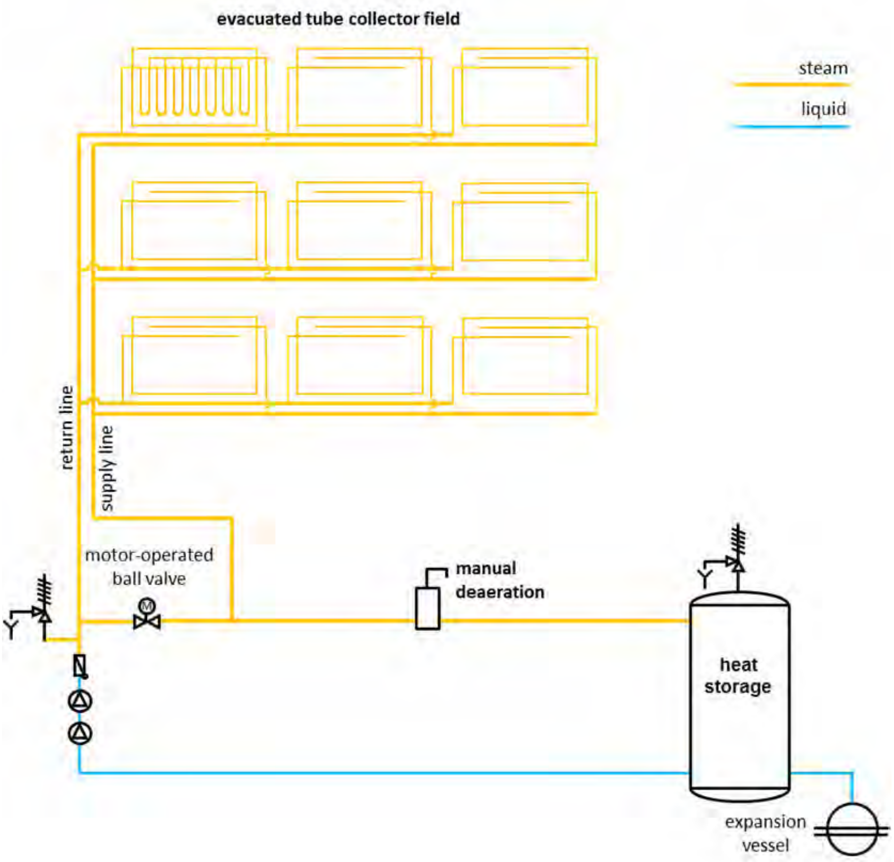


Figure 6: Schematic diagram of the system “Ritter Solar.”

Functionality	During stagnation the motor-operated ball valve opens (e.g., if maximum temperature in the storage is reached) and the system is emptied via both the return and the supply line. Liquid expansion + steam volume is absorbed by the expansion vessels and steam that reaches the heat storage condensates. The system is refilled automatically by the expansion equipment (pressure holding system or expansion vessels) as soon as the system cools down and system pressure drops.
Advantages	Only low capacity (hence cheap) UPS is needed to operate the controller and the motor-valve in case of power outages.
Disadvantages	The expansion vessels in the solar loop need to be designed for liquid expansion + steam volume. For frost protection the system demands extra energy in winter.
Comments	In this special arrangement from Ritter XL Solar no temperature-sensitive components are harmed in the entire solar loop and no system separation is necessary (water-based system). Because only water is used in the solar loop the system needs to be protected against frost in winter by circulating warm media.

4.2 *Overheating prevention*

Overheating prevention is necessary if evaporation in the solar loop is **not** an accepted operating mode. Overheating prevention implies that the maximum temperature the solar fluid can reach is limited to a temperature quite below the corresponding evaporation temperature at the maximum system pressure that is determined by the safety valve.

In Table 3 shows the evaporation temperatures at different pressure levels (figures refer to relative pressure in bar_g) of water and different water/glycol mixtures.

Table 3: Evaporation temperatures as a function of the pressure and the heat transfer fluid used. Note: Thermal cracking of glycol starts (for most glycols) around 140-..160 °C and therefore those glycols should not be operated in or above this temperature range. The system pressure then has to be limited in order to allow the liquid to reach saturation below that temperature.

relative pressure [bar(g)]	**Water** [°C]	**Water / p-glycol** (20 Vol-%) [°C]	**Water / e-glycol** (20 Vol-%) [°C]	**Water / p-glycol** (40 Vol-%) [°C]	**Water / e-glycol** (40 Vol-%) [°C]
0.0	100	102	102	104	106
0.5	111	113	114	115	118
1.0	120	122	123	124	127
1.5	127	129	130	131	134
2.0	134	135	136	138	140
2.5	139	140	141	143	145
3.0	144	145	146	148	150
3.5	148	149	150	152	154
4.0	152	153	154	156	158
4.5	155	157	158	159	162
5.0	159	160	161	163	165
5.5	162	163	164	166	168
6.0	165	166	167	169	171
6.5	168	169	170	172	174
7.0	170	172	173	174	177
7.5	173	174	175	177	179
8.0	175	177	178	179	182
8.5	178	179	180	182	184
9.0	180	181	182	184	186
9.5	182	184	185	186	188
10.0	184	186	187	188	190

p-glycol: propylene-glycol (Antifrogen L)

e-glycol: ethylene-glycol (Antifrogen N)

4.2.1 Overheating prevention as part of the collector concept

As described above, system overheating can degrade heat transfer fluids, accelerate scaling, cause premature component failure, and reduce system performance. Solar thermal systems incorporate safety devices in the thermal loop in order to avoid these hazards. Such devices normally are system-level temperature limiting sub-systems that add to the cost and design complexity of solar thermal systems.

There are different opportunities for overheating protection embedded in the collector concept, for example:

- Mechanically using, for example, flaps or other ways of dissipating heat to the environment.
- Based on material properties, such as thermo-tropic absorber coating /17/ and /18/.
- Based on the use of properly designed heat pipes /19/.

As an example, the overheating prevention concept for solar thermal collectors with a transparent insulation (honeycomb) produced by the company TIGI is described in this section.

The overheating problem is especially critical in systems that incorporate high performance collectors. As a result of its low heat losses, TIGI's honeycomb collector can reach internal temperatures of over 250 °C under such circumstances if not limited by overheating prevention. TIGI introduces collector-level overheating prevention (OPD), which enables the retention of the collector’s high efficiency under normal working conditions, but quickly transitions to fast excess thermal energy release to the atmosphere when a pre-set temperature is reached (see Figure 8). Thus, TIGI solves the overheating challenge at its source.

Figure 7 shows the collector output related to gross area plotted versus collector mean temperature for a high end flat plate collector, honeycomb collector and honeycomb collector with an integrated overheat protection device.

For maintenance-free extended product life, the engineering aim was to design a passive mechanism with no moving mechanical elements such as valves, and with no need for electrical elements. TIGI opted for a closed loop heat-pipe technology for its ability to transfer large amounts of thermal energy with minimal mass transfer utilizing latent heat under phase change conditions. Unlike normal closed loop heat-pipes, the kick-in is designed to only start above a pre-selected temperature. The solution is based on a closed loop heat pipe that contains a dual fluid composition in contrast to conventional heat pipes that typically are comprised of a single fluid in the vacuum. The OPD shows fast transition between thermal isolation and thermal coupling between collector interior and external environment. It is based on a fluid loop that is independent of the primary heat transfer loop. The proprietary solution is protected by multiple patents.

The TIGI OPD includes the following elements:

- An internal evaporator thermally coupled to the absorber plate.
- A condenser, external to the collector's case, to dissipate heat to the atmosphere.
- A closed loop pipe connecting the evaporator and the condenser.
- An evaporator filled with ethylene glycol/water up to about 90% of its volume.
- The system is neither pressurized nor evacuated.

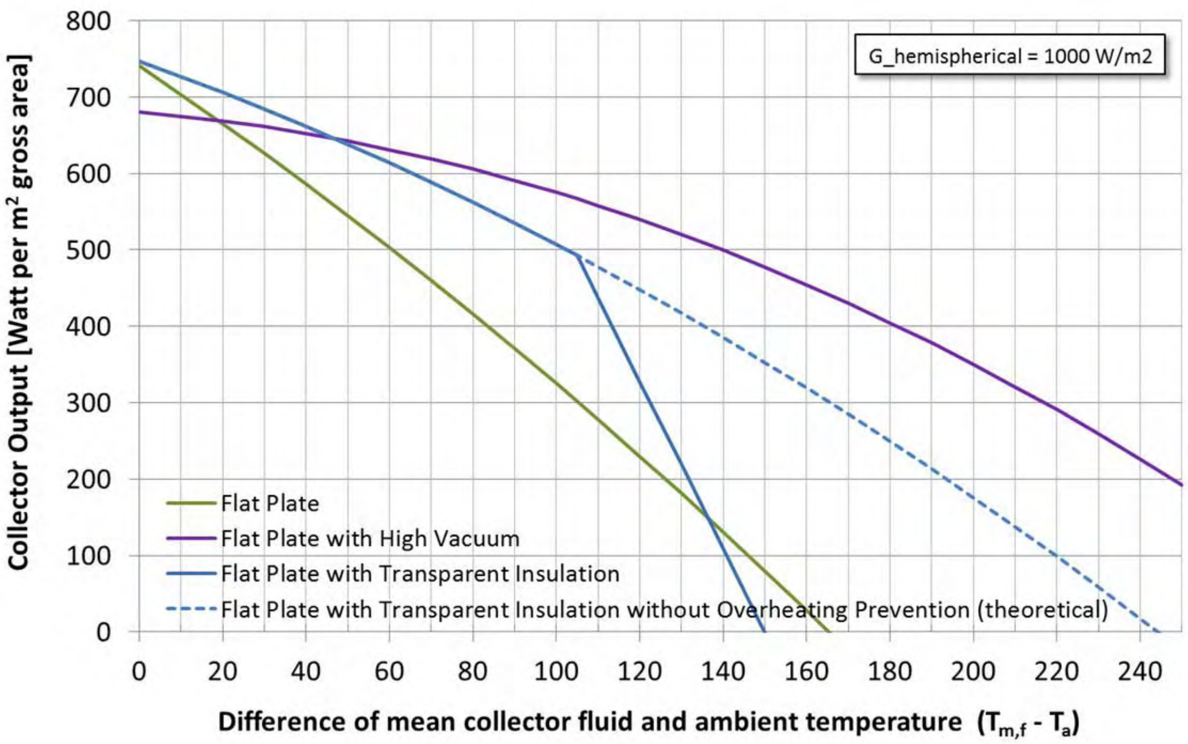


Figure 7: Collector output related to gross area for normal hemispheric solar irradiance G of 1'000 W/m² for an exemplary flat plate collector, a flat plate collector with high vacuum, a flat plate collector with transparent insulation (honeycomb) that has an overheating prevention device and the (theoretical) output of the same collector without overheating protection (dotted line). Note: The output curve of the flat plate collector with transparent insulation as displayed here is only valid for Tamb = 0 °C as the overheating prevention concept in this specific collector starts to decrease the output at 105 °C.

Figure 8 shows the major component layout for the TIGI collector level overheating prevention mechanism based on a closed loop heat pipe.

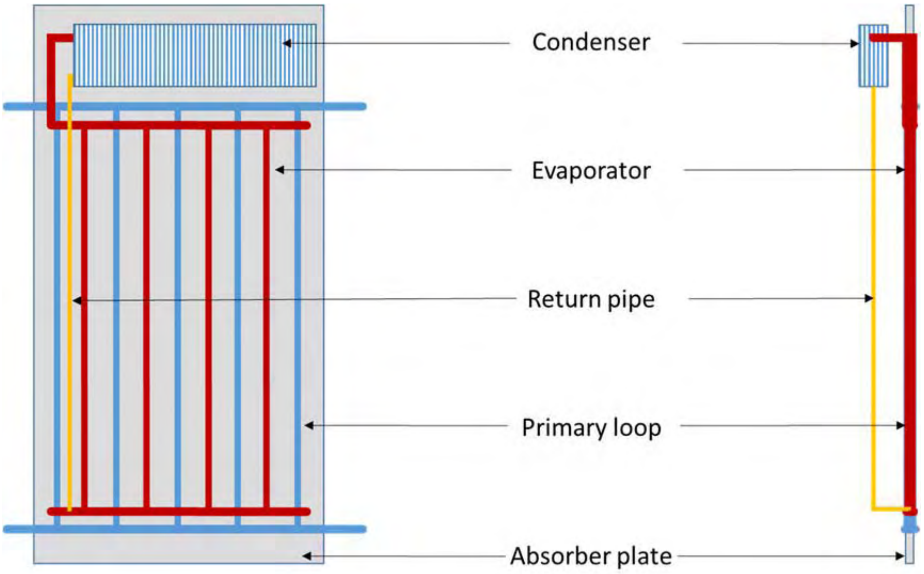


Figure 8: Overheating device kick in is reached when the absorber temperature reaches the boiling temperature of the liquid in the secondary harp. Not dependent on water in primary circulation.

Functionality	Passive overheating prevention device (OPD) at the collector level. Closed loop heat-pipe is used for fast transition between thermal isolation and thermal coupling between collector interior and external environment. The mechanism kicks-in when the absorber reaches a pre-selected temperature (around 105 °C). After kick-in, a large amount of thermal energy is transferred utilizing latent heat under phase change conditions. The solution is based on a closed loop heat pipe which contains a dual fluid composition. It is based on a fluid loop which is independent of the primary heat transfer loop.
Advantages	• No moving mechanical parts, no electrical parts. • No losses until a pre-determined temperature is reached (currently ~ 105 °C) and then transitions to very fast heat dissipation. • Dry stagnation temperature (1000 W/m², 30 °C ambient, 15° inclination) < 130 °C. • Does not reach glycol cracking temperatures - reduces maintenance costs. • Dramatically reduces steam in primary circulation. • Eliminates the cost related to system-level overheating protection. • Simplifies design complexity related to overheating prevention.
Disadvantages	
Comments	Solar Keymark certified and has undergone multiple robustness tests.

4.2.2 (Active) cooler solutions in the solar primary loop

Especially in the event of unfavourable conditions on the collector and/or system level that prevents the opportunity to obtain optimum emptying behaviour additional active re-cooling devices should be used to avoid stagnation of the system or overheating system components up to their maximum temperature resistance (e.g., insulation, valves, pumps, and membrane of expansion tank).

The disadvantage of active re-cooling devices is that they depend on electricity and so will not function during power outages if there is not an additional emergency power supply available. In this case, which rarely occurs, partial emptying of the system over the safety valve would be the consequence. In case of stagnation due to a lack of heat demand, which is by far the most critical issue for solar process heat applications, those “active” cooling solutions are highly efficient and reliable.

Water / Water heat exchanger

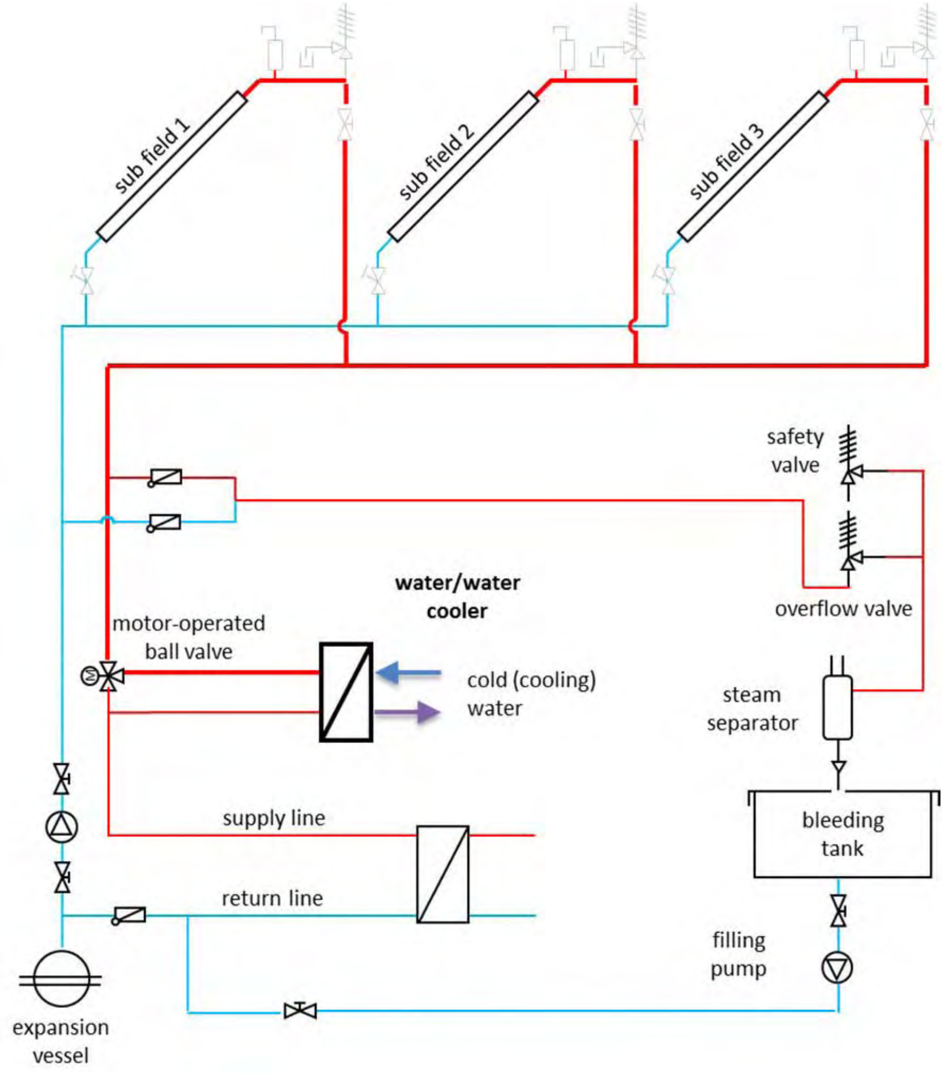


Figure 9: Schematic diagram of an active water/water cooler in the solar primary loop.

Functionality	In case of system overheating a water cooler (e.g., water/water plate heat exchanger) is activated by the control system as soon as a maximum temperature is detected in the solar supply loop. In case of emergency an overflow valve opens and medium passes a steam separator before the liquid medium is released to a bleeding tank. As soon as plant pressure is lower than the activation pressure of the overflow valve, the system can be re-filled again (filling pump).
Advantages	The expansion equipment needs to be designed for liquid expansion only. Cheap and reliable solution.
Disadvantages	A medium capacity UPS is needed to operate the controller, a motor-valve and the pump on the cooling water side in case of power outages. High demand for resources (cooling water).

Water / Air heat exchanger

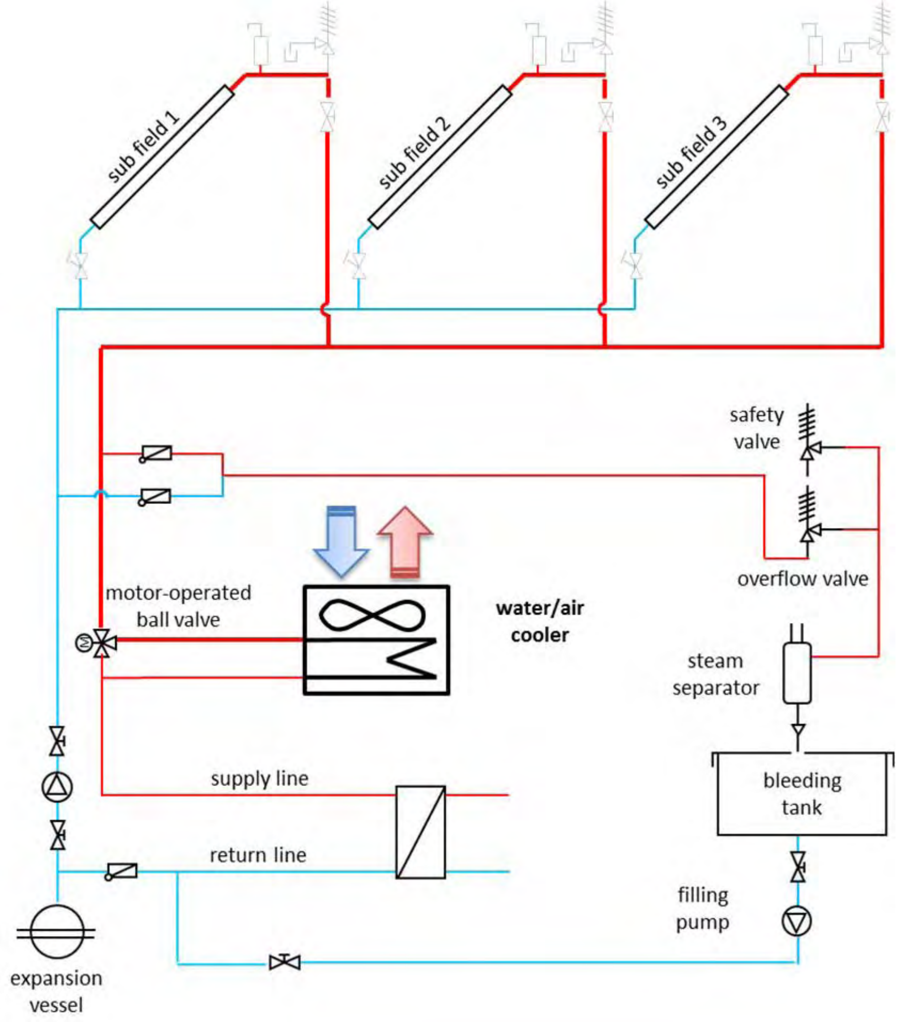


Figure 10: Schematic diagram of an active water/air cooler in the solar primary loop.

Functionality	In case of system overheating a fan-driven water-to-air heat exchanger is activated by the control system as soon as a maximum temperature is detected in the solar supply loop. In case of emergency an overflow valve opens and medium passes a steam separator before the liquid medium is released to a bleeding tank. As soon as plant pressure is lower than the activation pressure of the overflow valve, the system can be re-filled again (filling pump).
Advantages	The expansion equipment needs to be designed for liquid expansion only. Reliable solution in combination with UPS.
Disadvantages	A high capacity UPS is needed to operate the controller, a motor-valve and the air cooler in case of power outages. Expensive. High parasitic electricity demand for operation.
Comments	--

4.2.3 Drain-back systems

Another option to avoid steam formation is to drain the entire system at a pre-defined temperature below the manifold of the collector field. These so-called drain-back systems (or concepts) avoid overheating of the heat transfer medium. However, still high (even stagnation) temperatures will occur in the collector (field) – therefore the drain-back concepts can be seen as both an overheating prevention regarding the heat transfer medium and collector loop parts that will not be affected by too high temperatures that occur due to the production and propagation of steam (but not as an overheating prevention for the collector itself) and stagnation handling measure.

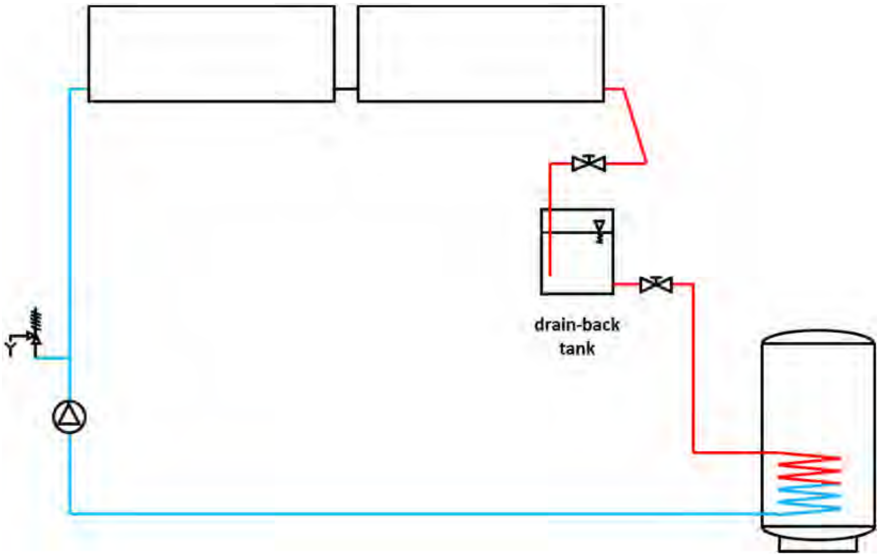


Figure 11: Schematic diagram of a drain-back system.

Functionality	Either when the heat from the collector field cannot be used or stored (e.g., when the store is fully loaded) or when the collectors cannot provide heat due to low sunshine, the solar loop pump stops (e.g., temperature controlled) and the entire collector field is drained automatically. The drained collector fluid is collected in a drain-back tank. When heat can be gained from the collectors and used, the circulation can start again: the solar loop pump is switched on and the whole collector circuit is filled with water from the drain-back tank and circulation starts in a few minutes. In case of emergency the drain-back system is equipped with a safety valve as well.
Advantages:	No separate expansion equipment - liquid expansion is absorbed by the drain-back tank. The system is operated with water as heat transfer fluid. No ageing and maintenance associated with glycol-filled circuits occurs. Simple design with few components, very reliable operation. The concept works very safely and independent from the electrical supply.
Disadvantages:	Much experience with small and medium systems, but limited practical experiences in very large-scale solar systems for process heat (one example

	is given in Chapter 5.1.3). So far only used for low-temperature solar process heat applications <100 °C. In principle the drain-back concept is also suitable for higher temperatures operated at higher corresponding system pressures. However, higher temperatures and pressures increase system complexity and might be limited due to safety concerns.
Comments	Perfect emptying behaviour is required (the entire collector field wiring to the drain back tank need to be routed downwards). In regions were frost can occur many drain-back systems are operated with water/glycol (instead of water) to avoid severe system damage due to freezing.

For regions where frost can occur, damages caused by freezing need to be avoided, which can be a special challenge for drain-back systems. The following requirements are important:

a) Perfect emptying behaviour of the entire solar loop: Above all, this includes that all fluid channels must be sloped and drain completely, internally in the collectors and also in all external piping and manifolds. For small individual systems, this is achieved easily. Big systems require specially designed pipework (sometimes specially elevated collector supports/frames need to be install so that collector pipework at reach the required slope). It is essential that all piping is routed and sized in a way that all collectors and exterior piping drain fast and completely when the pump is switched off. To get all collectors in circulation after start-up and during operation, all collectors and pipework must be completely filled with only water during start-up, any air bubbles (including the air bubbles that develop through outgassing of water during operation), must be “flushed” downward to the airspace in the drain-back tank, which is in itself quite a special component with provisions for filling correctly, damping sound, arresting steam and preventing any air bubbles flowing into the outlet downwards.

b) **Very reliable controllers + the choice or distribution of collector sensors** + **pump control criteria (software)** must ensure that the flow is never switched on while under freezing conditions combined with shading or covering with snow of a considerable part of collectors. If during filling one shaded part of the piping or absorbers becomes blocked by ice, draining of that channel is also blocked and frost damage is possible in all the system parts that drain through that blocked channel.

c) **Installers: all of the installing crew must be specifically skilled**, that is they must have experience and be well instructed to understand and obey the installation requirements. Commissioning of the system should only be done after careful inspection.

d) **Maintenance** and repairs must be done by skilled personnel, to avoid **frequently made mistakes**: the most prominent being to falsely judge that a system needs to be filled and then to overfill the system causing massive damage from frost in the first winter night.

Some experiences from the Netherlands are presented in section 5.1.3.

Small drain-back systems (for single households) can be considered a proven technology and the above mentioned requirements are implemented quite well by the manufacturers and installers when installing a range of small standard systems that are widely applicable in standard dwellings with inclined or flat roofs. These systems have proven reliable and require almost no maintenance.

Quite a large fraction of the large systems have had serious problems causing high costs for repairs and changes. This is due to the fact that **most large systems are not**

standard. Almost every project is “different” and “new” thus requires individual design and engineering, and of course careful installation by experienced crews.

In many large systems errors were made in the design and installation causing frost damage and often expensive changes in the system to correct the errors.

Many of the systems that required repairs and changes were **filled with water/glycol** to eliminate any risk of further frost problems.. These systems are now operating, as far as known, without problems (and show no noticeable ageing of glycol and no glycol-related problems like clogging or circulation problems).

The postive experiences with many glycol filled drain-backs makes it an attractive option for eliminating frost risk in new systems by always filling them with a water/glycol mixture.

Lessons learned to prevent expensive problems in large installed systems are:

1. Use only non-ferrous material. Strictly follow recommendations and standard designs of the producer/supplier and use only components from the assortment of the producer.
2. If the individual installer or system designer has no practical experience with large systems, which is often the case, then the selection of the individual system design should be made **by or in close cooperation with the system manufacturer**.
3. Project supervision and installation work must be done in close cooperation or under the responsibility of the manufacturer.
4. If the risk of frost damage is considered too high then the this risk may be eliminated by filling the system with water/glycol, as experience so far shows no negative effects on the performance and maintenance.

4.2.4 Defocussing for concentrating and tracking collectors

The objective of the defocussing (moving the receiver out of focus of the beam irradiance) is to prevent overheating of the receiver and the heat transfer fluid.

To defocus the receiver algorithms are implemented in a programmable logic controller (PLC) controlling the movement of the parabolic trough collector so that every time that a fixed limit temperature is reached or a stop of the mass flow of the heat transfer fluid occurs the collector tracks to a position where less radiation is absorbed and, therefore, there is a decrease in the temperature so that no overheating is produced.

5 Examples of projects

5.1.1 Brewery Goess, Austria

For an Austrian brewery a large-scale solar process heat application was commissioned in June 2012. A total of 1,500 m² of solar thermal collectors combined with a 200 m² pressurized solar energy storage provide heat for the mashing process to heat up mash to 58 °C..78 °C. The collector field consists of 10 parallel rows of 10 collectors with 15 m² gross collector area each. Due to the frost protection system separation between the primary loop and secondary loop was achieved using a plate heat exchanger with a capacity of 1,000 kW. The primary loop is filled with a water/glycol mixture (40 Vol-%) and for overheating prevention three measures were used, 1) night cooling, 2) temperature controlled water cooler, and 3) pressure-controlled safety valve.

Night cooling

Night cooling is achieved using a hydraulic configuration as shown in Figure 12.

Night cooling can be manually or automatically switched on with a timer via the implemented control system (“SCADA system[1]”). In case of longer production standstills on weekends, during overhaul work periods, or company holiday’s the solar thermal generated heat during the daytime may be dissipated over the collector field during the night. To do this, hot water from the top of the solar energy storage is circulated via the plate heat exchanger and through the entire solar thermal collector field, which operates like a large radiator in the cold night hours.

Functional description “night cooling”

As soon as the night cooling function is activated (manually or automatic), the valves 250-1, 250-5 and 140-1 are opened and the pumps in the secondary (P_S-02) and primary (P_S-01) loop start. The night cooling function is switched off either after a pre-defined time (e.g., 120 minutes) or automatically as soon as the temperature TT_240-1 falls below a certain value (e.g., 60 °C).

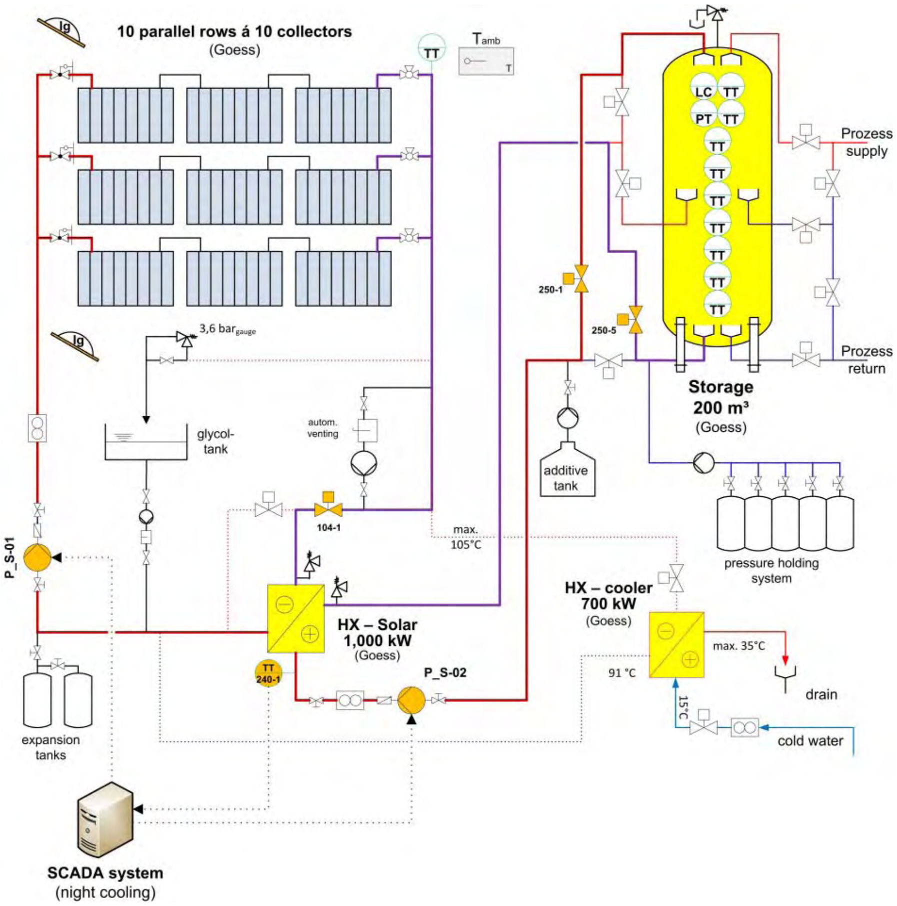


Figure 12: Hydraulic night cooling concept built for the brewery in Goess, AT.

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[1] SCADA: Supervisory Control and Data Acquisition

Temperature-controlled water cooler in solar primary loop

Due to technical and economic considerations, it was decided to attach a water cooler executed as plate heat exchanger to the solar primary loop as the main device for overheating prevention in the brewery Goess. The hydraulic configuration is shown in Figure 13.

The plate heat exchanger is designed in a way that the maximum thermal power from the solar thermal collector field of 700 kW (lower as the peak power while normal operation due to the high temperatures) can be cooled with cold fresh water. The maximum solar primary loop supply temperature of 105 °C is cooled down to around 90 °C while cold water with 15 °C is heated up to 35 °C and released to the effluent (due to legal the requirement that the cold water not be heated up further in this case).

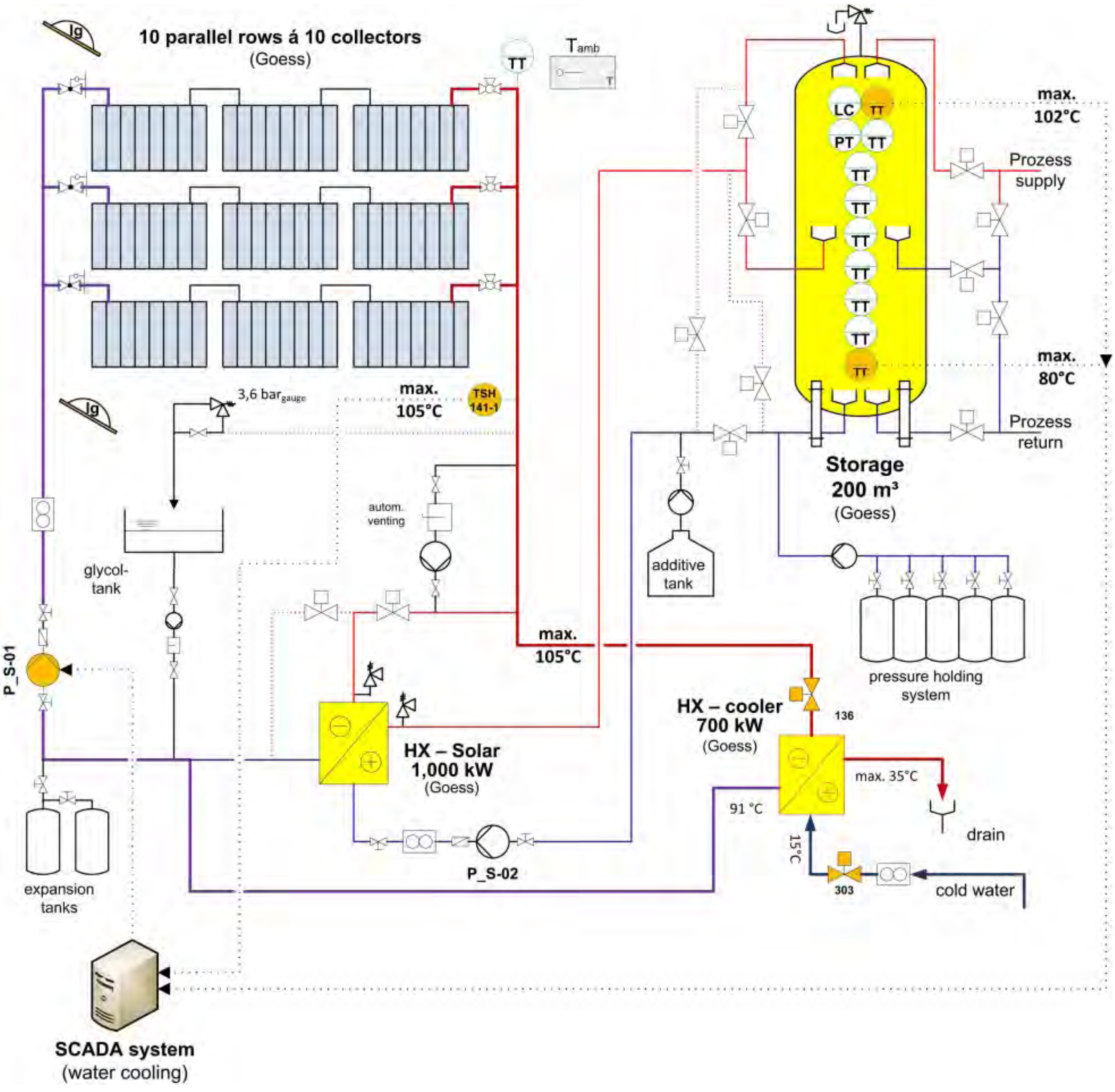

Figure 13: Hydraulic integration of the water cooler at the brewery in Goess, AT.

Functional description “water cooler”

The cooling mode is controlled by the SCADA system and mainly depends on the temperature set points. As soon as one of the three following criteria is fulfilled the motor-operated valves 136 and 303 are automatically opened and solar secondary pump (P_S-02) is switched off (temperature set points can be modified by authorized personnel:

- TSH 141-1 >105 °C
- T storage top > 102 °C
- T storage bottom >80 °C

Pressure-controlled safety valve

The expansion vessels in the solar primary loop as well as the vessels for the pressure holding system in the secondary loop are designed to absorb only the liquid expansion. However, if both night cooling and water cooling fail (e.g., due to malfunction, power outages, etc...) a pressure controlled safety valve opens and the heat transfer medium is released to an atmospheric glycol tank.

An additional UPS is not foreseen.

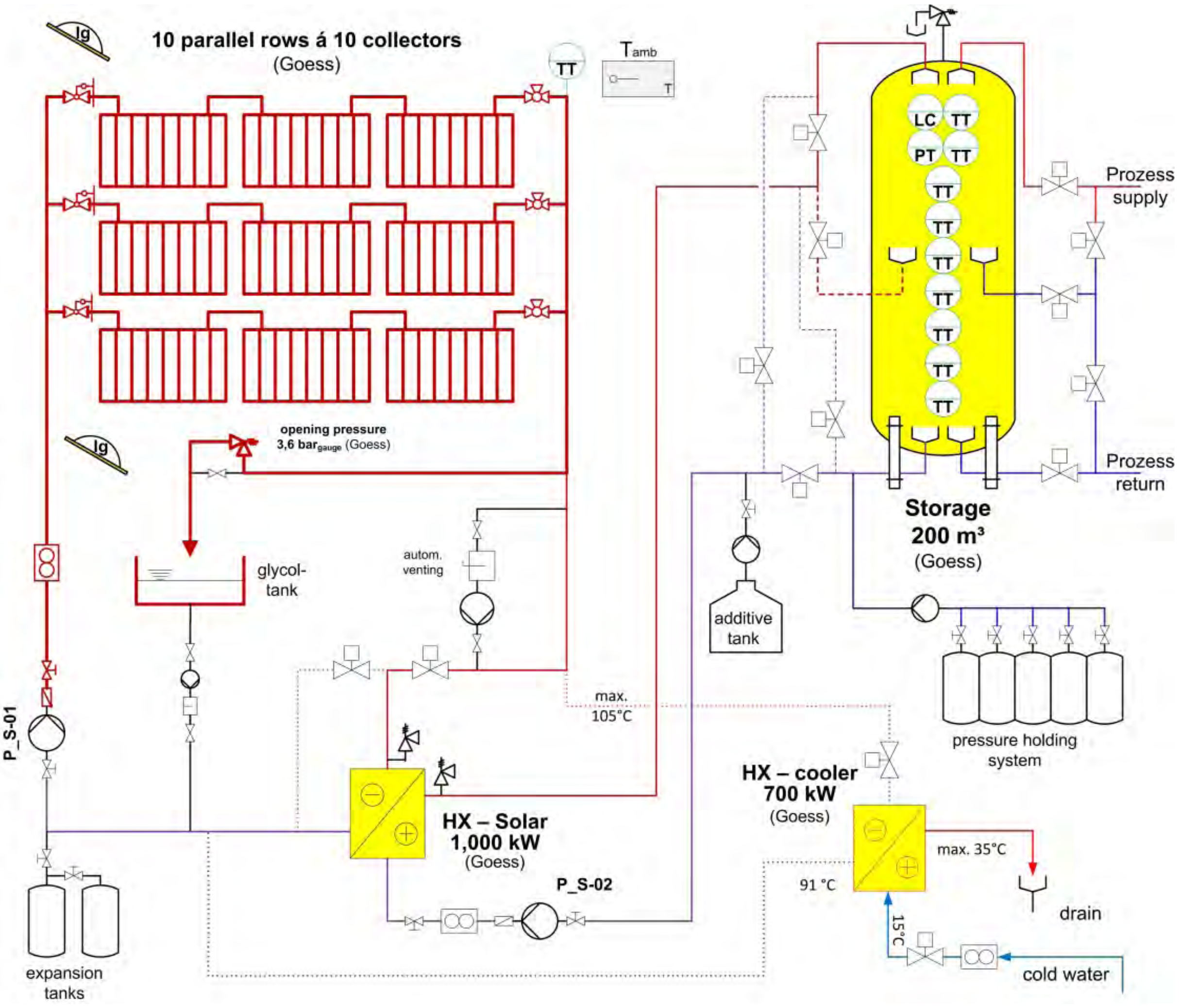

Figure 14: Active cooling strategy (water cooler in solar primary loop) designed for the brewery in Goess (similar for all three sites).

Functional description “pressure-controlled safety valve”

In case of a complete standstill of the system (all pumps off) and the system overheats then the heat transfer medium expands up to the opening pressure of the safety valve, which was designed to be 3.6 bar_{gauge} for the system at the brewery Goess. Since the system is filled with a water/propylene-glycol mixture (40 vol%) as frost protection this pressure corresponds to an evaporation temperature of around 153 °C (see also Table 3).

This means that for a system with a good emptying behaviour no higher temperatures than 153 °C would occur outside the collectors in the case of stagnation, and that shortly after the safety valves opens the fluid content of the solar primary loop would be released to the glycol tank. Since the collectors in this case show poor emptying behaviour and the actual maximum stagnation temperature of the collectors used is around 200 °C, overheating occurs in the collectors and in the collector field piping highlighted in red in Figure 14 (depending on steam power).

As soon as stagnation is over and the system is cooled down refilling is done manually via the filling pump. Since the glycol tank is open to the atmosphere refilling of the system also causes the need for a proper bleeding of the system.

5.1.2 Textile manufacturer Carl Meiser GmbH&Co.KG, Germany

For the textile manufacturer Carl Meiser GmbH&Co.KG in Albstadt Tailfingen (Germany), a thermal heat application was commissioned by the company Smirro through the DBU (German Federal Foundation for the Environment) to implement a hybrid system between fossil energy heating and solar thermal heating.

A 100 m² parabolic trough collector (PTC) field was installed on the roof of the manufacturer combined with a water heat storage with a variable volume between 10 and 70 m³. Preheated water is used to feed the steam process running at 190 °C, which is used for the different manufacturing processes.

The heat produced from the collectors is transferred to the storage tank by an external heat exchanger where the liquid from the primary loop (thermal oil) exchanges with the liquid from the second loop (water). The circulation of both loops are regulated by two pumps, see Figure 15.

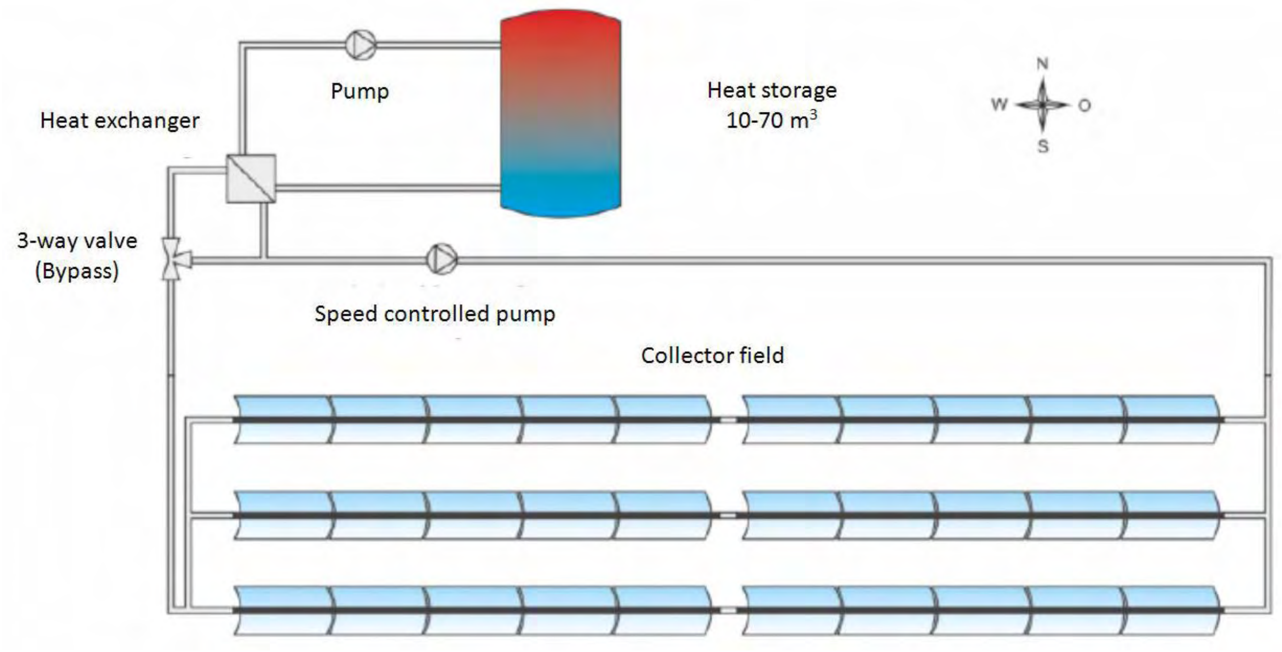

Figure 15: Exchange Primary and Secondary Loop 1 (Source: Smirro GmbH/ITW).

For this system different criteria have been established to control the collector field.

Criteria to activate the primary loop:

- Wind speed: < 50km/h
- Hemispheric Irradiance: 380W/m² for 10 min
- Fluid temperature at the outlet of the absorber tube: <120 °C

Criteria to deactivate the primary loop:

- Wind speed: > 50km/h for 30s
- Hemispheric Irradiance:< 340W/m² for more than 10 min
- Fluid temperature at the outlet of the absorber tube: >120 °C

Criteria to activate the secondary loop:

- Collectors outlet temperature:> 65 °C

Criteria to activate the defocussing (overheating prevention):

- Temperature at the outlet of the absorber tube: >130 °C

Criteria for the volume flow in the collector circuit:

- Minimum Volume flow (1800 l/h) for temperature at the outlet of the absorber tube <30 °C
- Maximum Volume flow (2400 l/h) for temperature at the outlet of the absorber tube >120 °C

The parabolic trough collector field heats up the heat storage, which was already implemented in the manufacturer’s heating system. This heat storage exchanges heat with the steam system (see figure below).

The PTCs are controlled through a PLC device with the criteria listed above to manage the defocussing and control the temperature in the system.

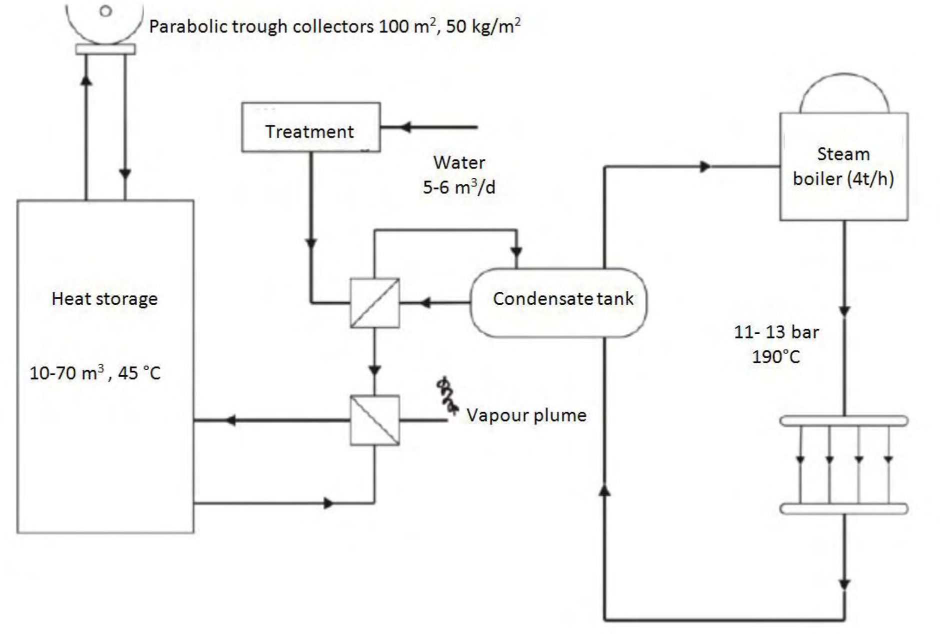

Figure 16: Carl Meiser GmbH&Co.KG hydraulic system schema (Source: Smirro GmbH/ITW).

This heat system provides steam at 190 °C for the different manufacturing procedures. Thanks to this system the company can save up to 44.3 MWh/year.

5.1.3 Drain-back systems in the Netherlands: The “van Melle” system

In the Netherlands about half of the total installed SDHW’s are drain-back systems. The market share of drain-back systems has fluctuated around 50% starting from 1978 when the market started from almost zero. Around 1980 a few small start-up companies concluded that to be cost-effective a solar water heater for a typical Dutch single family home with hot water demand of 100 l/day should have the following characteristics:

1. Small sized: preheater of +/- 2.5 m2 with 100l storage targeting for a hot water demand of 80 l/day of 60 °C. for solar fractions of max 50%, and gas savings of approximately 200 m3/year. Extra costs for a larger collector area or larger tank would not be cost effective.
2. Long lifetime so customers have a product that pays for itself during its lifetime.
3. No yearly or periodic maintenance requirements because the associated costs of yearly maintenance would be almost as high as the yearly financial yield of the energy savings.

In a few years time, most of the design issues and technical details were solved and the typical Dutch small “water-filled closed drain-back” solar water heaters had most of the market, and remain popular in the Netherlands: equipped with flat-plate collectors with serpentine absorbers (e.g. ZEN, ITHO Daalderop) or header+riser absorbers (e.g., Luigjes/ATAG) and mostly with a stainless steel storage tank with integrated closed drain-back tank. They have closed collector circuits filled at atmospheric pressure at ambient temperature and are equipped with 3 bar safety valves.

For larger systems, especially for multi-family houses, agricultural buildings, etc. drain-back concepts have also been used and are still being planned and built. System size is mostly below 100 m^2 with a few larger (around 300 m^2).

Worth describing is by far the largest system, which is installed on the flat roof of the Perfetti van Melle in Breda factory (a large production plant for the well-known Mentos and Fruitella products). This solar system has 2400 m^2 collector area, 8 rows of 32 collectors of each 10 m^2 and a 95 m^3 storage tank combining heat storage and drain-back. The solar heat is used for preheating hot water and generating process heat.

The system was designed and delivered turn-key by ZEN-Solar in 1998. At the time, ZEN had considerable experience with drain-back sytems, but ones with much smaller collector fields (<200 m^2) as a simple 10-fold up-scaling was considered risky. So first a special design principle for sizing the pipework (return, manifolds, supply), for better and faster drainage, was developed and tested (and later patented). This design method was successfully implemented in the design of the 2400 m^2 collector field and since then in general many large drain-back systems supplied by ZEN (like on the Bewleys hotel in Dublin) and by ITHO-Daalderop.

Drainage and filling of the circuit is excellent and no frost problems have been encountered. However, serious, and until then never experienced, problems developed one year after installation caused by the clogging of most absorber pipes (d_i = 8 mm) by deposits of magnetite particles released from the corroding inner surface of the pipes and storage tank, which in this case are made of plain carbon steel. The corrosion was caused by the leaking in of atmospheric air through some small leaks that could not be located and repaired. The inflow of air happens when the circuit breathes slightly in and out during daily temperature cycling.

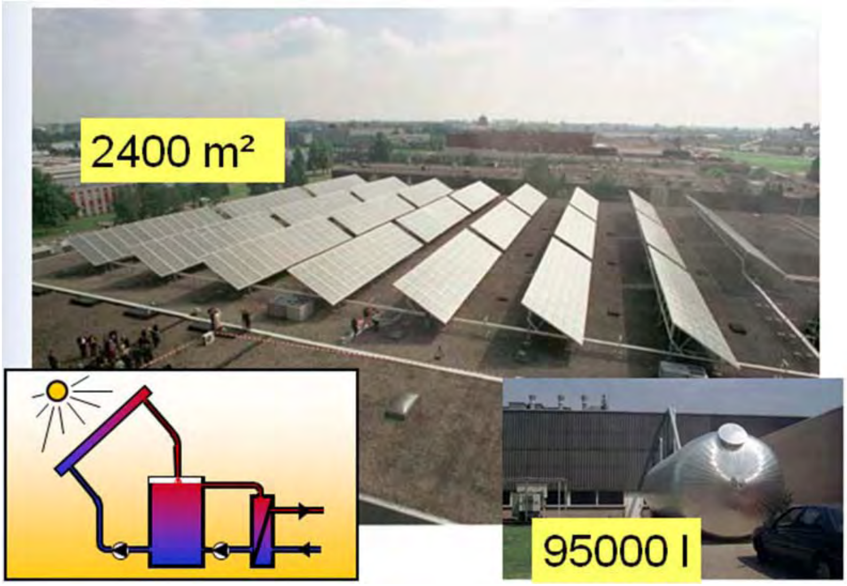

Figure 17: Van Melle system with 2400 m^2 collector area: collector field on roof, circuit diagram, storage /drain-back tank on ground level.

At first filtering was tried to keep the water clean, but a solution was found in adding a nitrogen-injection system, which prevents breathing in of air by maintaining overpressure (injecting nitrogen when the internal pressure drops under 50 mbar).

6 Other relevant and related topics

6.1.1 Night cooling

The need for re-cooling energy and resources (e.g., cooling water) can be significantly reduced in large flat plate collector fields if, in addition to the active cooling device, the possibility for night cooling is foreseen.

Night cooling can be implemented using a hydraulic concept that enables unloading the solar energy storage tank during night hours (in Chapter 5.1.1 a best practice example of a solar process heat application in an Austrian brewery is explained). In case the energy storage is fully loaded and no heat demand is projected for the upcoming day(s) solar thermal generated heat during the daytime can be dissipated over the collector field during the night. In this case, hot water from the top of the solar energy storage is circulated through the entire solar thermal collector field, which operates like a large radiator in the cold night hours.

Night cooling efficiency in general is highly dependent upon the thermal efficiency of the solar collectors used[2], the temperature level of the fluid circulated through the collectors and the ambient conditions (outside air temperature, cloudiness, wind speed) while night cooling. Hence the heat quantities that might be dissipated in night hours need to be determined for each project separately. Once the night cooling efficiency is determined for unfavourable framework conditions (e.g., cloudy night, sultry weather conditions, no wind) this information can also be used to optimize the energy storage volume (e.g., for a five day production week the solar energy storage need not be designed for 100% storage over the weekend, but less because of the night cooling).

From measurements in the Austrian brewery Goess mentioned in Chapter 5.1.1, it is known that up to 80% of the energy gained during the day can be dissipated in clear night hours. Considering very unfavourable conditions as mentioned above at least 20 - 25% of the heat gained during the day can be dissipated during the night /16/.

6.1.2 Pressure Equipment Directive (PED)

The Pressure Equipment Directive (97/23/EC) was adopted by the European Parliament and the European Council in May 1997. It initially come into force on 29 November 1999. From that date until 29 May 2002 manufacturers had a choice between applying the pressure equipment directive or continuing with the application of the existing national legislation. From 30 May 2002 the pressure equipment directive is obligatory throughout the EU.

The directive provides, together with the directives related to simple pressure vessels (2009/105/EC), transportable pressure equipment (99/36/EC) and Aerosol Dispensers (75/324/EEC), for an adequate legislative framework on European level for equipment subject to a pressure hazard.

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[2] Night cooling can be implemented for flat plate collector fields only. In evacuated tube or evacuated flat plate collectors heat dissipation during night hours by means of heat convection and heat conduction is avoided by the vacuum.

The PED Directive 97/23/EC arises from the European Community's Programme for the elimination of technical barriers to trade and is formulated under the "New Approach to Technical Harmonisation and Standards." Its purpose is to harmonise national laws of Member States regarding the design, manufacture, testing and conformity assessment of pressure equipment and assemblies of pressure equipment. It therefore aims to ensure the free placing on the market and putting into service of the equipment within the European Union and the European Economic Area. Formulated under the New Approach the directive provides for a flexible regulatory environment that does not impose any detailed technical solution. This approach allows European industry to develop new techniques thereby increasing international competitiveness. The pressure equipment directive is one of a series of technical harmonisation directives for machinery, electrical equipment, medical devices, simple pressure vessels, gas appliances, etc.

The Directive concerns items such as vessels, pressurised storage containers, heat exchangers, steam generators, boilers, industrial piping, safety devices and pressure accessories. Such pressure equipment is widely used in the process industries (oil & gas, chemical, pharmaceutical, plastics and rubber and the food and beverage industry), high temperature process industry (glass, paper and board), energy production and in the supply of utilities, heating, air conditioning and gas storage and transportation.

Under the Community regime of the Directive, pressure equipment and assemblies above specified pressure and/or volume thresholds must:

- be safe;
- meet essential safety requirements covering design, manufacture and testing;
- satisfy appropriate conformity assessment procedures; and
- carry the CE marking and other information.

Pressure equipment and assemblies below the specified pressure/volume thresholds must:

- be safe;
- be designed and manufactured in accordance with the sound engineering practice of a Member State; and
- bear specified markings (but not the CE marking).

Source:

http://ec.europa.eu/enterprise/sectors/pressure-and-gas/documents/ped/index_en.htm

Whether a solar thermal collector or collector array falls under the PED depends on different aspects, for example design temperature, design pressure and water content. Further information is given here:

http://ec.europa.eu/enterprise/sectors/pressure-and-gas/documents/ped/index_en.htm

7 Literature References

/1/	EN ISO 9806:2013: Solar energy - Solar thermal collectors - Test methods, CEN-CENELEC Management Centre: Avenue Marnix 17, B-1000 Brussels
/2/	Mauthner, F., Hausner R.: SolarBrew, Deliverable 2.2, Solutions for unproblematic stagnation behavior, Gleisdorf, May 2013
/3/	Fink, C., Hausner, R.: Stagnation Technology for Thermal Solar Systems; European Commission, GDXII, CRAFT-JOULE Programme Task B1 – B8; Austria, Gleisdorf 2001; available at: http://www.aee-intec.at/0uploads/dateien119.pdf
/4/	Hausner, R., Fink, C., Wagner, W., Riva, R., Hillerns, F.: Entwicklung von thermischen Solarsystemen mit unproblematischem Stagnationsverhalten. Endbericht. Projekt im Rahmen der Programmlinie Haus der Zukunft, Impulsprogramm Nachhaltig wirtschaften, im Auftrag des BMVIT, AEE INTEC Gleisdorf 2003
/5/	Scheuren, J., Eisenmann, W.: Stagnationsuntersuchungen in den Kollektorkreisen hochdimensionierter großer Solaranlagen, Abschlussbericht zum BMU-Vorhaben 0329268A, ISFH Hameln/Emmerthal 2007
/6/	Rommel, M., Siems, T., Schüle, K., Mehnert, S., Thoma, C.: Verbundprojekt: Systemuntersuchungen großer solarthermischer Solaranlagen, Schlussbericht zum Teilprojekt: Entwicklung von Techniken zur Beherrschung des Stillstandsbetriebes. BMU-Vorhaben 0329268C, FHG ISE Freiburg 2007
/7/	EN 13831-2007: Closed expansion vessels with built in diaphragm for installation in water; ON Österreichisches Normungsinstitut, Austrian Standards Institute, Heinestraße 38, 1020 Wien
/8/	Stagnation resistance of hydraulic connectors for solar thermal applications, http://www.solarenergy.ch/index.php?id=279&L=6
/9/	ÖNRM M 7777-1/2013: Solar thermal systems — Part 1: Requirements and planning — Complementary provisions to ÖNRM EN 12977 (all parts)
/10/	ÖNRM M 7777-2/2013: Solar thermal systems — Part 2: Standstill performance and hydraulic circuit modules — Complementary provisions to ÖNRM EN 12977 (all parts)
/11/	Weiss, W.: Solar Heating Systems for Houses, A Design Handbook for Solar Combisystems, IEA SHC Task 26, James & James Ltd, 2003
/12/	Harrison, S.J., Lin, Q. & Mesquita, L.C.S. (2005). Limiting Stagnation Temperatures in Flat-Plate Solar Collectors. Proc. ASME/ISEC2005, Orlando, FL.
/13/	Stephen Harrison, Cynthia A. Cruickshank, A review of strategies for the control of high temperature stagnation in solar collectors and systems, Energy Procedia 30 (2012) 793 – 804
/14/	R. Hausner, C. Fink: Stagnation behaviour of solar thermal systems. Technical report of IEA SHC Task 26, November 2002, http://www.aee-intec.at/0uploads/dateien48.pdf
/15/	J. Glembin, D. Eggert, G. Rockendorf, J. Scheuren: Evaporation in Solar Thermal Collectors During Operation - Reasons and Effects of Partial Stagnation. J. Sol. Energy Eng. 133(4), 2011. doi:10.1115/1.4004384
/16/	Mauthner, F.: Beschreibung und Analyse der Systemtechnik und des Anlagenbetriebes am Beispiel der solaren Prozesswärmeanlage in der Brauerei Goess; Proceedings 24. Symposium Thermische Solarenergie, Bad Staffelstein,

	Deutschland, Mai 2014
/17/	S. Brunold et.al., 2007: Beurteilung der Möglichkeiten von thermochromen Schichten als potenzielle Überhitzungsschutzmassnahme für solarthermische Kollektoren; Schlussbericht BFE Projekt Nr. 43729,
/18/	S. Brunold, 2010: Entwicklung von Kunststoffkollektoren: Grundlegende Fragestellungen und Ergebnisse eines Forschungsprojektes; Proceedings of 20. OTTI Symposium Thermische Solarenergie, Bad Staffelstein, Mai 2010.
/19/	S. Jack et al., 2013: Flat plate aluminum heat pipe collector with inherently limited stagnation temperature. Energy Procedia 48 (2014), pp. 105 – 113.
/20/	Stiglbrunner et al., 2010: Endbericht „PROMISE APPLICATION - Senkung des CO2 Ausstoßes durch Energieeffizienz und thermische Solarenergie für Industriebetriebe – Werkzeuge, Methoden und Umsetzung”, Programmlinie „Neue Energien 2020 – 1. Ausschreibung“, Österreichische Forschungsförderungsgesellschaft mbH (FFG), Gleisdorf.

Annex: Stagnation behavior of solar thermal systems

(Excerpt from /14/ with additions from /2/)

Processes encountered during stagnation

On the basis of a simplified collector model the sequence of events during stagnation can be divided into five different phases:

- **Phase 1 – expansion of liquid.** The collector temperature rises until evaporation starts in the upper part of the collector array (somewhere in an absorber). The increase of system pressure is small.
- **Phase 2 – pushing the liquid out of the collector.** Most of the liquid media in the collector is pushed into the expansion vessel due to the first formation of saturated steam[3]. As a result, the system pressure as well as the corresponding boiling temperature in the pipe sections filled with saturated steam rises rapidly and liquid, which is almost at the boiling temperature, puts a high temperature stress on the affected system components. This phase lasts for only a few minutes and ends when there is a continuous path for steam from the collector inlet to the outlet. Residual liquid remains in the collector.
- **Phase 3 – emptying of collector by boiling.** The residual liquid in the collector evaporates at further increasing pressures and temperatures. As a consequence, steam penetrates further into the system as long as the energy transported via steam condensates at “cold” sections within the solar loop. The affected system components are heated up to the local boiling temperature which again is determined by the system pressure and the local composition of the heat transfer medium[4]. At the end of phase 3 the steam volume and the system pressure reaches their maximum values (cf. Figure 18).
- **Phase 4 – emptying of collector by superheated steam.** The collector becomes increasingly dry and the steam in the dry sections is superheated resulting in a decreasing efficiency of the solar thermal collector. Due to that the steam volume decreases again and the solar loop is slowly filled with liquid heat transfer media again although there is still solar irradiation. As a consequence, the superheating phase can take a few hours on cloudless days and ends when irradiance is on the decline.
- **Phase 5 – refilling of collector.** The collector begins to refill as soon as the collector temperature falls below the boiling temperature and condensation begins as a result of a reduction in the solar irradiation.

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[3] E.g.: one litre of liquid water equals to 1,673 litres of saturated steam @ STP and to 693 litres of saturated steam @ 1.5 bar(g) / 127 °C and to 397 litres of saturated steam @ 3.5 bar(g) / 148 °C.

[4] E.g.: System pressures of between 1.5 to 3.5 bar(g) lead to boiling temperatures of water of between 127 °C to a maximum of 148 °C and to boiling temperatures of between 134 °C and 154 °C in case of a 40 Vol.% water / ethylene-glycol mixture

Critical phases while stagnation

The hot liquid pushed out of the collector over the course of Phase 2 can put a critical temperature strain on components other than the collector. The most critical aspect is the heat transport by saturated steam produced in the collector and condensed at high temperatures at all “cold” locations in the loop, with potential degradations of components even though they are located far away from the collector, such as the expansion vessel installed near the heat storage tank.

Further on the liquid remaining in the collector at the end of Phase 2 determines the length and intensity (maximum system temperature and pressure) of Phase 3. This is because evaporation of the remaining liquid keeps most of the collector at the boiling temperature while heat is further produced by the collectors with the corresponding efficiency at boiling temperature[5]. This leads to large steam volumes or steam penetrates far into the system reaching a maximum level at the end of Phase 3.

Once the evaporation of the liquid has been completed (around the middle of Phase 4) the whole collector dries out and reaches its equilibrium temperature and no more heat is gained from the collector (collector efficiency = 0).

Obviously, Phases 2 and 3 are highly dependent on the emptying behaviour of the collectors used as well as of the hydraulic design of the entire collector field. Figure 18 next illustrates the five phases of stagnation as explained before for three different collectors with different emptying behaviours (from poor to very good).

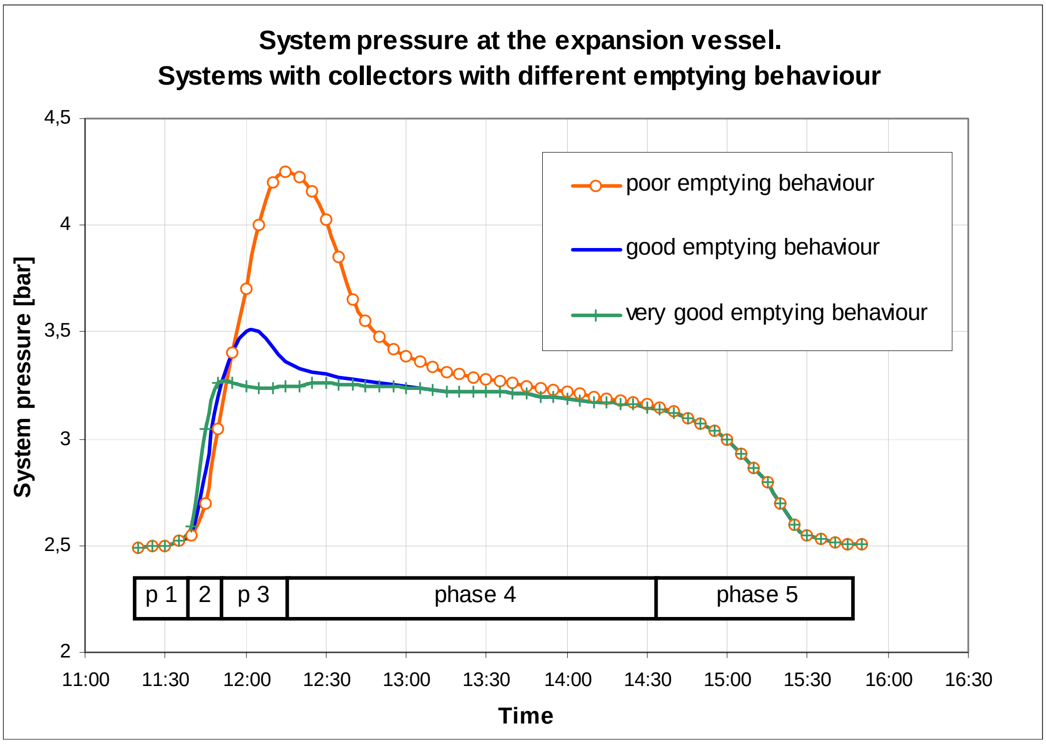

Figure 18: System pressure versus time for three collectors with different emptying behaviour.

For collectors with very good emptying behaviour (see also Figure 20) liquid is pushed out

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[5] E.g.: At a temperature of 150 °C the efficiencies of advanced flat plate and evacuated tube collectors are still in the range of 50 %

of the collector very quickly in the event of stagnation as soon as first steam formation occurs (end of Phase 1). Little or no liquid remains trapped in the absorber and hence the collector soon dries out and system pressure does not increase further due to additional steam formation.

By contrast, the remaining liquid in collectors with poor emptying behaviour (see **Figure 19**) also lead to higher system pressures. This also means that steam penetrates further into the system and may stress system components also in some distance from the collector.

Emptying behaviour of collectors

The emptying behaviour of collectors determines the frequency, area, magnitude and duration of the maximum temperature of the system and of its components and hence is an important characteristic for the design of solar thermal systems.

Collector examples with poor emptying behaviour are shown schematically in **Figure 19**.. Within such hydraulic configurations liquid heat transfer medium is trapped in parts of the collector and can only be removed by evaporation in the course of stagnation. While stagnation this leads to large amounts of energy that is transported as steam throughout the system. In addition the probability of condensation pressure shocks increases.

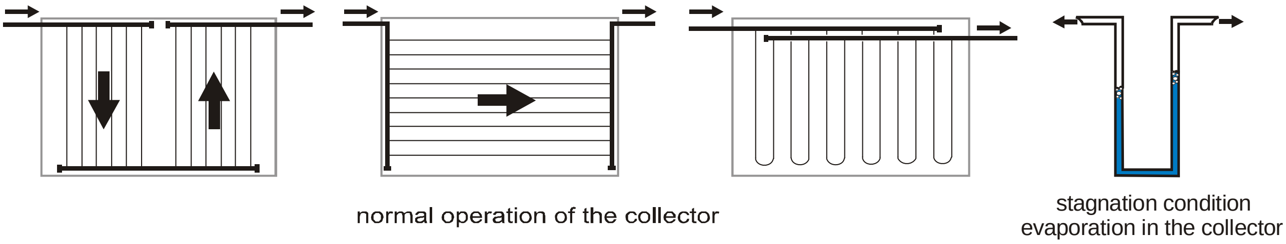

Figure 19: Schematic examples of common collector circuits with poor emptying behaviour.

By contrast, hydraulic configurations of the collector absorbers drawn in Figure 20 show good emptying behaviour because the return line (and/or flow line) of the collector is located at the bottom of the collector. With this, or similar arrangements, the liquid is quickly pushed out of the collector in Phase 2. Consequently, the duration and extent of the critical stagnation in Phase 3 is reduced and the areas affected by saturated steam only reach to just below the bottom of the collector (see Figure 18 –good emptying behaviour).

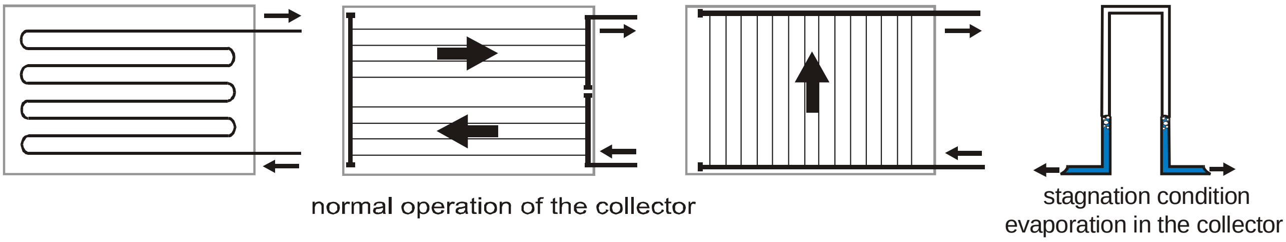

Figure 20: Schematic examples of common collector circuits with good emptying behaviour /2/.

Emptying behaviour of collector fields

Good emptying behaviour in individual collectors does not guarantee good emptying behaviour of collector fields. The basic principles that are valid for individual collectors also have to be observed for collector fields. If the connecting lines of the collectors are not arranged in a favourable manner, good emptying behaviour for a collector can become poor emptying behaviour for a collector field.

In the example shown on the left-hand side of Figure 21, the return line connection is arranged in a way that liquid is being trapped in case of stagnation. At the end of phase 2 this arrangement leads to one of the two collectors becoming filled with steam as a result of slight individual differences. The resulting steam-liquid circuit, which can last for a long time, supplies liquid to the collector not yet fully emptied by condensing the steam in the condensation stretch of pipe. This process also leads to a larger volume of steam in the remaining system. A simple solution to the problem is to ensure that the system will drain as shown on the right-hand side of Figure 21.

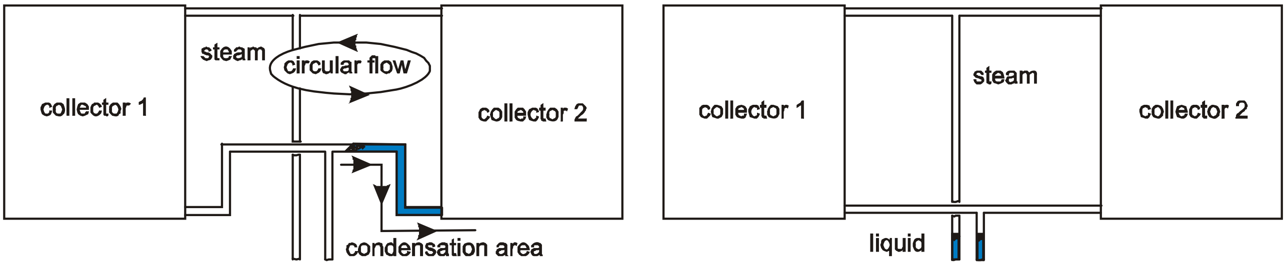

Figure 21: Example of the hydraulic connection of two collectors with good emptying behaviour in an unfavourable way leading to a poor emptying behaviour of the entire system (left figure) as well as in an favourable way leading to a good emptying behaviour of the entire system (right figure).

Influence of system hydraulics on the emptying behaviour

The emptying behaviour of collectors is influenced considerably by the position of the check valve in relation to the expansion vessel.

If the check valve is positioned as shown in Figure 22 (right picture) then the system can only be emptied via the solar loop supply line while the path to the expansion vessel over the return line is blocked. This arrangement results in a lot of residual liquid in the collector field, which again leads to large steam volumes that may penetrate very far into the system.

By simply re-arranging the position of the expansion vessel as shown in Figure 22 (left picture) it can be ensured that the entire system can be emptied via both the solar return and the solar supply line.

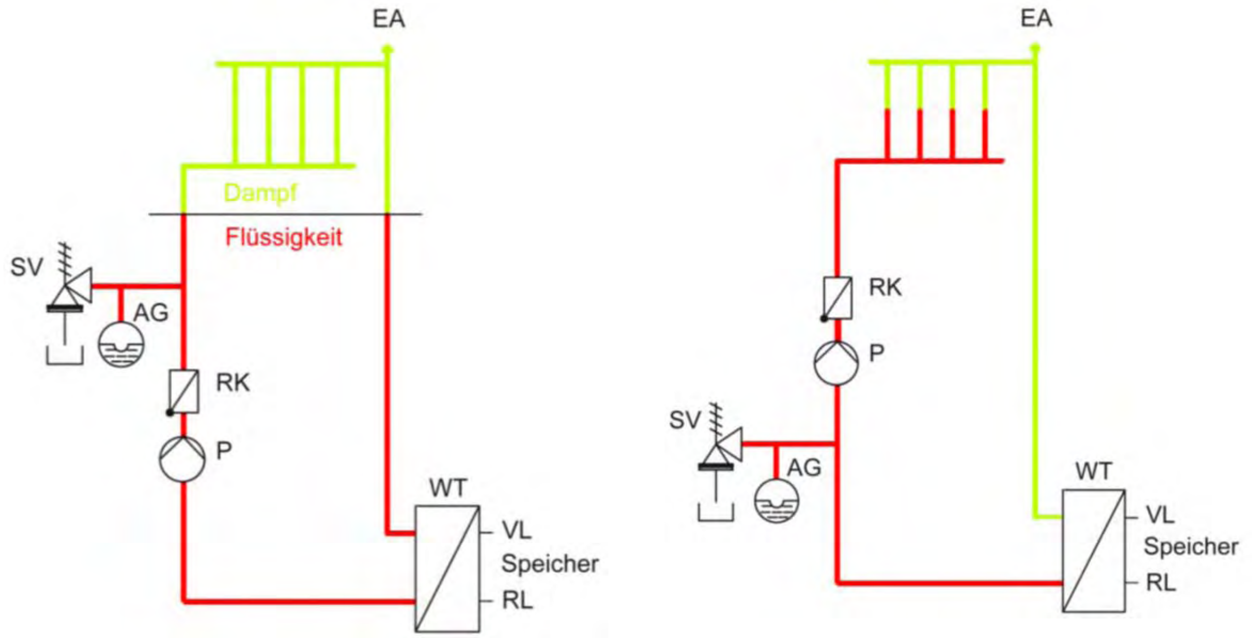

Figure 22: Good and poor arrangement of the components in the solar primary loop /10/

Dimensioning of the expansion vessels in solar thermal systems

Due to the formation of steam in the solar loop while stagnation the volume of the expansion vessel needs to be dimensioned quite differently from conventional heating installations.

In conventional hot water loops steam formation normally never occurs and hence expansion vessels need to be designed to absorb liquid expansion only (e.g, dimensioning according to /7/).

For solar thermal systems the common procedure to calculate the nominal volume of the expansion vessel needs to be modified in a way that besides liquid expansion additional volume due to steam formation in the event of stagnation can be absorbed (e.g., dimensioning according /9/, /10/ or other national standards).

Examples for the calculation of expansion vessels considering the steam volume in residential applications (domestic hot water and combi-systems) are provided in /11/.

However, in the case of an emergency a safety valve is mandatory for both conventional heating systems and solar thermal systems and prevents hydraulically closed systems from severe system damage caused by overpressure.

Specific steam power, steam range and steam volume

It is important to mention here that the steam volume, which determines the volume of the expansion vessel in solar thermal applications, is dependant from the maximum specific steam power in W/m^2_{coll} that might occur in case of stagnation.

The values for the specific steam power range from < 50 W/m² for good emptying collectors and > 130 W/m² (up to 200 W/m²) for collectors with poor emptying behaviour /2/, /3/, /4/, /5/.

Considering specific heat losses for insulated piping in W/m it can be calculated how far steam penetrates into a system (maximum steam range) and if temperature-sensitive components might be harmed and hence need to be protected. From the maximum steam range the maximum steam volume and further on the necessary expansion vessel volume can be calculated.

IEA Solar Heating and Cooling Programme

The Solar Heating and Cooling Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency. Its mission is

*To enhance **collective knowledge** and **application** of solar heating and cooling through **international collaboration.***

The members of the Programme collaborate on projects (referred to as “Tasks”) in the field of research, development, demonstration (RD&D), and test methods for solar thermal energy and solar buildings.

A total of 53 such projects have been initiated to-date, 39 of which have been completed. Research topics include:

- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44)
- Solar Cooling (Tasks 25, 38, 48, 53)
- Solar Heat or Industrial or Agricultural Processes (Tasks 29, 33, 49)
- Solar District Heating (Tasks 7, 45)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52)
- Solar Thermal & PV (Tasks 16, 35)
- Daylighting/Lighting (Tasks 21, 31, 50)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- Standards, Certification, and Test Methods (Tasks 14, 24, 34, 43)
- Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46)
- Storage of Solar Heat (Tasks 7, 32, 42)

In addition to the project work, there are a number of special activities:

- SHC International Conference on Solar Heating and Cooling for Buildings and Industry
- Solar Heat Worldwide – annual statistics publication
- Memorandum of Understanding with solar thermal trade organizations

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