Task 55 Towards the Integration of Large SHC Systems into DHC Networks

B-D3.1 Control of large-scale solar thermal plants

IEA SHC FACT SHEET 55.B-D3.1

Subject:	Control of large-scale solar thermal plants
Description:	Overview on the control of large-scale thermal plants, limited to plants feeding into DH networks as well as their key components, i.e. the actual collector circuit and the heat exchanger between primary and secondary circuit.
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Introduction

The control of large-scale solar thermal systems and heating grids - respectively hybrid energy systems - in which they are embedded, goes along with several control tasks, which are carried out in different control layers. At a higher level, supervisory controllers, often referred to as energy management systems, decide on the operating mode of the different plants and components, and provide the reference signals for their controllers. These modes of operation of the different plants and components are then carried out by the respective controllers at plant and component level, and by those responsible for the operation of the district heating network. The control of large-scale solar thermal systems thus can be divided into the following 3 main categories:

1. Supervisory control (energy management systems), which is the focus of IEA SHC FACT SHEET 55.A-D4.1.
2. Control of heat distribution networks, which is one focus of the IEA SHC FACT SHEET 55.A-D4.2.
3. Control strategies for the integrated plants and components, i.e. the actual solar plant but possibly also heat pumping systems or other plants and components. **The control of large-scale solar plants is the focus of this IEA SHC FACT SHEET 55.B-D3.1.**

Among all solar thermal plants, flat-plate collectors are by far the most used technology. In Europe about 70% of all solar thermal systems installed contain flat-plate collectors [1]. This ratio is even much higher for large-scale solar thermal plants at least partly feeding into DH networks. For this reason, the focus of this fact sheet will be on the control of large-scale solar thermal plants consisting of flat-plate collectors connected in series to so-called collector arrays and with several collector arrays connected in parallel. However, a brief outlook on possible additional or different control tasks for special plants is given in the final chapter.

Independent of the exact type of integration, the availability of on-site consumers or buffer storages, etc., the actual solar thermal plant usually consists of a primary circuit (collector circuit) and a secondary circuit connected by a plate heat exchanger. The control of these solar thermal plants must fulfil the following two tasks, see also Figure 1:

1. Control of the feed temperature (collector outlet temperature) in the primary circuit.
2. Control of the secondary circuit, i.e. the operation of the pump at the heat exchanger.

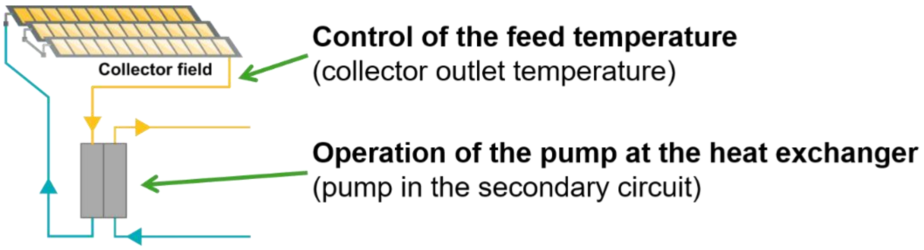

Figure 1: Control tasks at large-scale solar thermal plants

Both control tasks will be discussed in detail in two chapters followed by a final outlook on possible additional or different control tasks for special plants.

For sure, the start-up and the shut-down must be carried out by the control as well. However, this is done by simple step chain controls starting respectively stopping the actuators as soon as certain threshold levels are achieved. Therefore, this is not further investigated here, but can be found for example in [2].

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Control of the feed temperature in the primary circuit

The feed temperature (collector outlet temperature) in the primary circuit is controlled by adjusting the rotational speed of the pump. In rare cases an additional 3-way valve could get used for very low mass flows, however, since this is rare, and it does not make a methodological difference, it is not considered in the following.

In the easiest way, this is carried out by simple PID controllers. However, this generally goes along with poor control performance since the controller’s behavior needs to be chosen very slowly to avoid instable behavior because of the long and varying dwelling times from inlet to outlet, in particular at low mass flows, i.e. low global radiation.

Among most technology providers respectively operators a strategy which is rather common is the use of a static feed forward control in combination with an integrating controller, e.g. [3, 4, 5], what will be explained in more detail in the next section.

State of the art – Static feed forward control with integrating controller

The static feed forward control calculates the mass flow $\dot{m}_{\mathrm{P}}^*$ needed to achieve the desired feed temperature T_{feed}^* in steady state for the current return temperature T_{ret} , the current global radiation I_{g} and ambient temperature T_{amb}. According to the ISO 9806 [6], the corresponding heat flow $\dot{Q}$ can be calculated by

$$\dot{Q}(t) = A_{\mathrm{coll}} K(\theta) \eta_0 I_{\mathrm{g}}(t) - A_{\mathrm{coll}} c_1 \Delta T(t) - A_{\mathrm{coll}} c_2 \Delta T(t)^2 \tag{1}$$

with the temperature difference

$$\Delta T(t) = \bar{T}_{\mathrm{fl}}(t) - T_{\mathrm{amb}}(t) \tag{2}$$

where A_{coll} denotes the gross collector area, I_{g} the global radiation received by the collector surface, $\bar{T}_{\mathrm{fl}}$ the arithmetic mean fluid temperature between the inlet and the outlet of the collector, i.e. the return temperature T_{ret} and the desired feed temperature T_{feed}^* , and T_{amb} the ambient temperature. The coefficients represent the optical efficiency η_0 , the heat loss coefficients c_1 and c_2 . The function $K(\theta)$ represents the incident angle modifier (IAM) which describes the dependency of the optical efficiency η_0 on the angle of incidence θ of the global solar radiation I_{g}, which varies from collector to collector and is typically estimated through experiments [7] and given in the data sheet.

By using the average isobaric heat capacity c_p the the mass flow $\dot{m}_{\mathrm{P}}^*$ needed to achieve the desired feed temperature T_{feed}^* in steady state can thus be calculated by the following equation, where some plants do not directly use the current measurement of the global solar radiation I_{g}, but filter the signal with low pass filter:

$$\dot{m}_{\mathrm{P}}{}^* = \frac{A_{\mathrm{coll}} \left[K(\theta) \eta_0 I_{\mathrm{g}} - c_1 \left(\left(\frac{T_{\mathrm{feed}}{}^* + T_{\mathrm{ret}}}{2} \right) - T_{\mathrm{amb}} \right) - c_2 \left(\left(\frac{T_{\mathrm{feed}}{}^* + T_{\mathrm{ret}}}{2} \right) - \mathrm{T}_{\mathrm{amb}} \right)^2 \right]}{c_{\mathrm{p}} \left(T_{\mathrm{feed}}{}^* - T_{\mathrm{ret}} \right)} \tag{3}$$

To achieve stationary accuracy the feed forward control is additionally combined with an integrating controller, however, in many cases the output signal of the controller is not added to the control signal calculated by the integrating controller but multiplied with this signal. For long return and supply pipes special care about the positions of the temperature sensors, and possibly the effect of the heat losses in the pipes, must be taken. The desired mass flow $\dot{m}_{\mathrm{P}}^{*}$, which must not be below a certain lower limit, is finally maintained by a lower-level flow controller, which must be parametrized so that it reacts reasonably faster than the temperature controller. A schematic overview of this control strategy, with the controller's output signal being added to the control signal calculated with the feed forward control, is given in Figure 2.

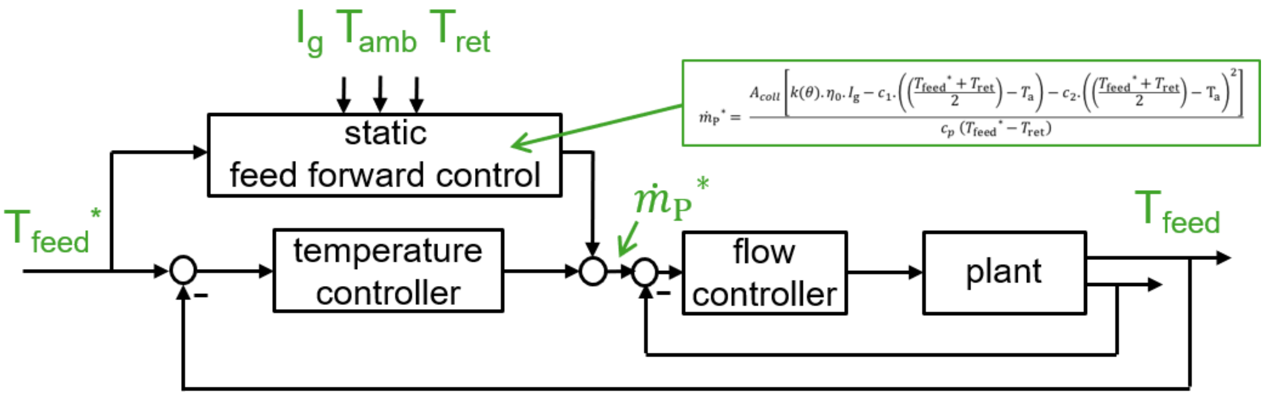

Figure 2: Static feed forward control with integrating controller

Operation of the heat exchanger – Control of the pump in the secondary circuit

The operating strategy of the heat exchanger aims at maximizing the efficiency of the heat exchanger, i.e. to minimize the sum of the terminal temperature differences on the cold side ΔT_c and on the hot side ΔT_h, see Figure 3.

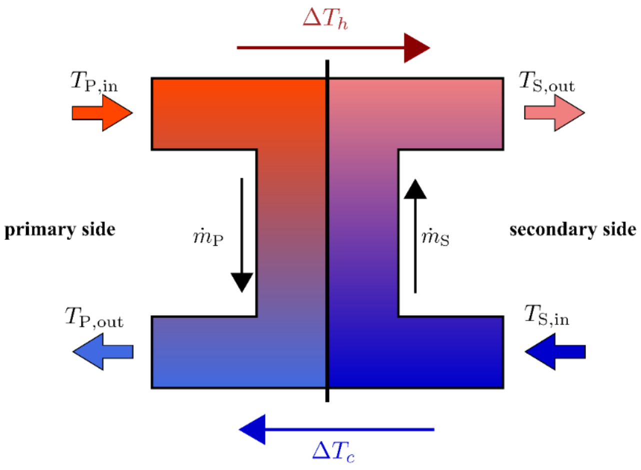

Figure 3: Heat exchanger connecting the primary (collector) circuit and the secondary circuit

This is simply achieved by keeping the heat capacity flows the same at the primary (P) and the secondary (S) side of the heat exchanger, i.e. the products of the respective mass flows $\dot{m}_i$ and heat capacities$c_{\mathrm{p},i}$:

$$\dot{m}_{\mathrm{P}} c_{\mathrm{p,P}} = \dot{m}_{\mathrm{S}} c_{\mathrm{p,S}} \tag{3}$$

Finally, the feed temperature in the secondary circuit, i.e. the outlet temperature of the heat exchanger on the secondary side $T_{\mathrm{S,out}}$, must be at a certain level. This is typically achieved by applying a simple cascadic control structure, where the outer slower controller adjusts the set point for the feed temperature in the primary (solar) circuit T_{feed}^{*}, i.e. $T_{\mathrm{P,in}}$, so that the feed temperature in the secondary circuit $T_{\mathrm{S,out}}$ achieves the desired value. In some cases, the feed temperature in the secondary circuit is not really controlled, but only the feed temperature in the primary circuit is controlled, with the set point being a certain offset above the feed temperature required in the secondary circuit.

Outlook on possible additional or different control tasks for special plants

In this chapter a short outlook on possible additional control tasks for large-scale solar thermal plants serving a special purpose or tasks which can be highly different from plant to plant is given.

Temperature and flow control in distribution networks

The distribution network, i.e. the hydraulic network connecting the thermal storage with the consumers (heat sinks), highly depends on the applications and can be very different from plant to plant. In some cases, only a simple hydraulic circuit connects the storage with on-site consumers while in other cases the hydraulic circuits can be very complex connecting several consumers in parallel or serial where each of the consumers have different needs regarding mass flows, temperatures and consequently heat flows. For this reason, it is not possible to propose a common strategy for these tasks. However, for example in [8] a method aiming for a decoupled control of mass flow and temperature is described, which could get adapted to different specific configurations.

Decoupled control of the flow in parallel collector arrays

In case of large subfields which are differently oriented and/or differently sized it can make sense to install motor driven balancing valves which allow a dynamic balancing of the fields in order to achieve the same feed temperature, see e.g. [9]. In doing so, special care of the hydraulic correlations needs to be taken, e.g. the influence of a single valve on the remaining arrays and consequently the overall mass. A possible strategy to do this is outlined in [10]. However, the availability of motor driven balancing valves for large subfields is very rare.

Control of tracking devices

Although tracking devices are used primarily for concentrating collectors they also gain relevance for flat-plate collectors due to their decreasing prices as a result of their increased use in the PV sector, see e.g. [11], [12]. For this purpose, typically one-axis tracking devices are used to rotate the entire collector arrays. This leads on the one hand to a higher solar share and provides on the other hand the possibility to stop the heat production of the plant by turning the collectors out of the sun. The second aspect allows to decrease the size of the heat storage, eliminates the problem of overheating, and is especially of interest when the heat is provided to an industrial process, where the heat demand can be highly fluctuating, e.g. on the weekends. The control of these devices is rather simple with the goal to follow the path of the sun as it is already known in advance. This is typically accomplished by PID controllers. More problematic could it be in regions where strong wind disturbs the tracking control, however, since these applications are rather new there are no issues known yet. Besides the tracking, the main control goal in these applications is still the control of the outlet temperature which is done in the same way as described in the previous chapter.

Control of concentrating collector technologies

Concentrating collector technologies, e.g. Linear Fresnel or parabolic through, are typically built only in a small scale up to now, and only rarely used in large-scale solar thermal plants. These collector technologies allow to efficiently produce heat at high temperatures, also in regions with moderate climate [13].

Even though this technology is continuously gaining relevance, no standard strategy for its control has yet been established. It is rather the case that the control strategies applied strongly depend on the used technology, its integration and the final utilization of the heat. However, the control strategies previously described for flat-plate collectors serve as a good starting point. An overview on the control for these systems typically used for process heat or electrical power generation is for example given in [14].

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