Operation Analysis and Experiences of a Solar-thermal System Assisting the Air Conditioning of an Office Building in Esslingen Germany

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1. Introduction

Since July 2006, Offenburg University of Applied Sciences, in collaboration with the Fraunhofer Institute for Solar Energy Systems in Freiburg and Stuttgart University of Applied Sciences, has been monitoring the solar-assisted air conditioning of Festo AG & Co. KG in Esslingen. The system was funded by the German Federal Environment Ministry in the scope of the research project Solarthermie2000plus. The existing adsorption chillers, previously powered by waste heat from compressors and by gas boilers, was retrofitted with a solar-thermal system as a third heat supply.

The solar-thermal system comprises a field of CPC vacuum tube collectors manufactured by Paradigma, covering 1330 m² gross collector area, and two buffer storage tanks of 8.5 m³ storage volume each. The collector circuit is filled only with water and connected to the buffer storage without a heat exchanger. The system is prevented against freezing with an innovative thermal freezing protection in the controller unit. The cooling power is produced by three adsorption chillers rated at 353 kW each. The solar system and cooling system are connected via the heating system and various distributors. The solar system has also been connected to the thermo-active building system of a new building in order to exploit the solar heat optimally at low return temperatures for space heating while the chillers are not in operation.

Prior to and during system operation, Stuttgart University of Applied Sciences and the collector manufacturer Paradigma GmbH performed dynamic simulations in order to dimension and evaluate the system.

81 additional sensors allow detailed monitoring of the solar and cooling system operation [Huber et all. 2008, 2009, 2010, Bollin et all. 2009].

In this paper monitoring results of three years of system operation will be shown and discussed. Furthermore the performed optimizations will be shown and rated.

Figure 1.1: Foto of the Collector array of the solar air conditioning at Festo AG & Co. KG in Esslingen.

2. History and motives behind the construction of the system

At the factory premises of Festo AG & Co. KG in Esslingen, a large amount of waste heat is produced by compressors, at temperatures between 65°C and 75°C. In order to exploit this energy even during the summer, when no space heating is required, and thereby save on primary energy and CO2 emissions, Festo considered installing thermal chillers. The mean driving temperature of approximately 70 °C was too low for conventional absorption cooling machines, which is why three adsorption chillers, manufactured by Mayekawa and rated 353 kW each, were purchased and commissioned in 2001.

In addition to the compressor waste heat, these chillers also required heat from gas boilers to operate. In order to reduce the proportion of heat from gas boilers, Festo decided to install a solar-thermal system as a third source of heat. The saw-tooth roof of a factory hall was practically ideal for this, given its pitch (30°) and orientation (south +18°). In order to achieve high yields, and to guarantee the required temperature level of 80°C, Festo decided to install vacuum tube collectors.

3. Monitoring and equipment

The additional measuring system was to measure all energy fluxes within the system boundary (solar system/main distributor and adsorption chiller) and beyond the system limits. In particular, the volume flow of heat fed from the collector field into the storage tanks and delivered to the heating system was to be measured as well as the heat from the boilers and compressors. Given the “water-only system” and its freeze protection circuit, the heat pumped from the heating system to the collector field via the buffer storage tanks had to be measured separately. In the adsorption chillers, the heat flow volume was to be measured at all three circuits of each machine.

Elaborate measurement of the electricity consumption of the adsorption chiller, its peripheral pumps and the cooling towers was to shed light on the electrical energy requirements of the machines, and allow this to be determined for each individual consumer. Furthermore, the solar incidence and outdoor and collector temperatures were also to be measured.

This elaborate measuring system allowed a comprehensive evaluation of the plant operation. In addition to this analysis of the optimization potential, it should also be possible to analyze malfunctions and to determine plant characteristics for comparing plants (benchmarking) such as solar gain, efficiency, solar fraction and useful solar heating costs. Figure 3.1 shows the system schematic with measuring and control sensors in the solar system.

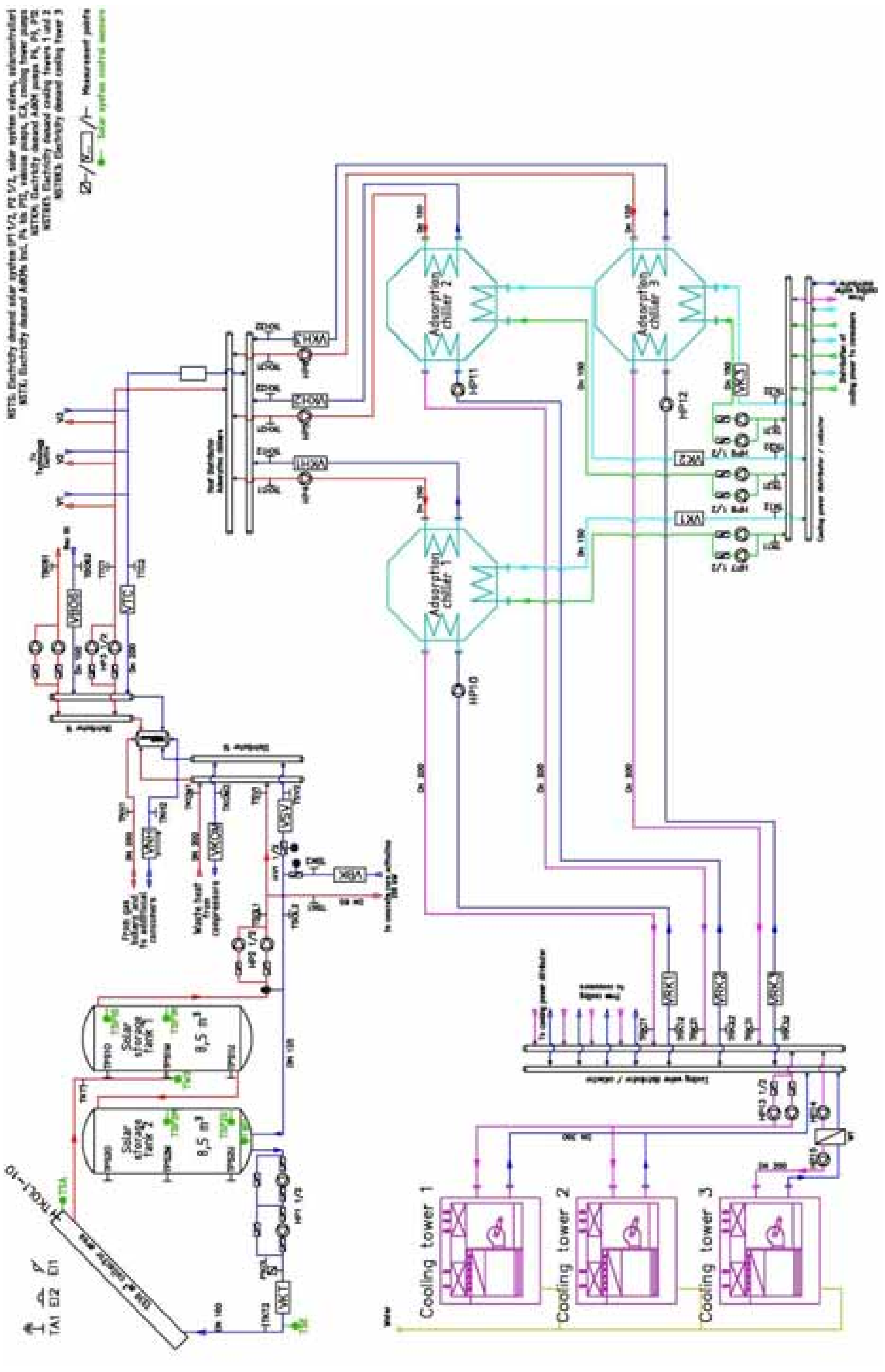

Figure 3.1: Schematic of the solar air conditioning at Festo AG & Co. KG in Esslingen with the measuring and control sensors of the solar system.

4. Operation results and experiences

4.1. Measurement results for the solar system

The intensive measurement phase of the Solarthermie2000plus project Solar Cooling has been running at FESTO AG & CO. KG since 01 August 2008. Readings from 81 sensors are recorded at five-minute intervals and called up daily by Offenburg University of Applied Sciences. All parties involved in the project also have access to the scientific measurements. Except for a few disturbances, complete readings exist for three years of intensive measurement from 01/08/2008 to 31/07/2011. The measured data is summarized in Table 4.1 below, and partially graphed in Figure 4.1.

The sensor failure at the discharge flow rate measurement point (VSV), which occurred between 15 September and 06 October 2008, has been taken into account in the analysis in Table 4.1 and Figure 4.1, in that the same percent heat loss in the store was assumed for this period as for the two weeks before and after the sensor failure. The failure of a valve on the discharge side (06–15 Aug.), which led to a significant reduction of the volumetric discharge flow and thereby the yield, has not been factored in.

During the first year of measurement, from a solar incidence on the aperture area (1218 m^2) of 1563 MWh (1283 kWh/m^2) on the collector field, 543 MWh (445 kWh/m^2) (efficiency 35 %) of heat was fed into the solar storage tanks. The heat volume flow due to start-up and freeze protection losses (in total 66 MWh or 54 kWh/m^2) has already been subtracted from this value. On the discharge side, 481 MWh (395 kWh/m^2) of heat was taken from the storage tanks (efficiency 31 %). Again, the start-up and freeze protection losses have already been subtracted. The solar fraction of 6.3 % for the observed period appears very low. The limiting factor in the design of the collector field was the area of the only suitable roof available, which did not allow for a larger collector field. Until the last period of measurement from august 2010 to july 2011, the solare fraction increased up to 9.8 %. One reason for this, among others, is the change in operation mode of the adsorption chillers since august 2008, where the gas boilers are used less often. The reasons for the increasing solar yield are described below.

Tab. 4.1: Results of the last three years of intensive measurement of the solar air conditioning at Festo AG & Co. KG in Esslingen from June 2008 to May 2011.

	08/2008-07/2009	**08/2009-07/2010**	**08/2010-07/2011**
Solar incidence on the entire collector field in MWh	1563	1586	1621
Net yield from the collector circuit in MWh	543	574	594
Net useful solar heat yield in MWh	481	528	538
System efficiency as % of net useful heat yield	31	33	33
Total heat loss at collector field in MWh	66	50	51
Heat from gas boilers in MWh	4227	2009	1598
Waste heat from air compressors	2914	3537	3335
Solar fraction as %	6.3	8.7	9.8
Fraction of sustainable heat as %	45	67	71
Heat consumption of adsorption chillers in MWh	3577	No results	No results
Cooling energy produced by the adsorption chillers in MWh	1665	879	478
COP_{th}	0.47	No results	No results

The fraction of sustainably produced heat, calculated from the useful heat from the solar system and waste heat from the compressors in relation to total heat consumption, is 45 %. This was significantly increased after February 2009 as a result of increased operations of the compressors and consequently greater waste heat production. The solar fraction also increases here due to the change in mode of operation of the adsorption chillers and other optimizations (see 4.2). Operation of the adsorption chillers required 3577 MWh of heat from the Festo AG & Co. KG heating network to produce 1665 MWh of cooling energy. That gives an average COP_{th} (thermal Coefficient of Performance – quotient of useful cooling energy and driving heat) in the first year of measurement of 0.47. In the other years of measurement the COP_{th} can't be calculated because of an error in the measurement system.

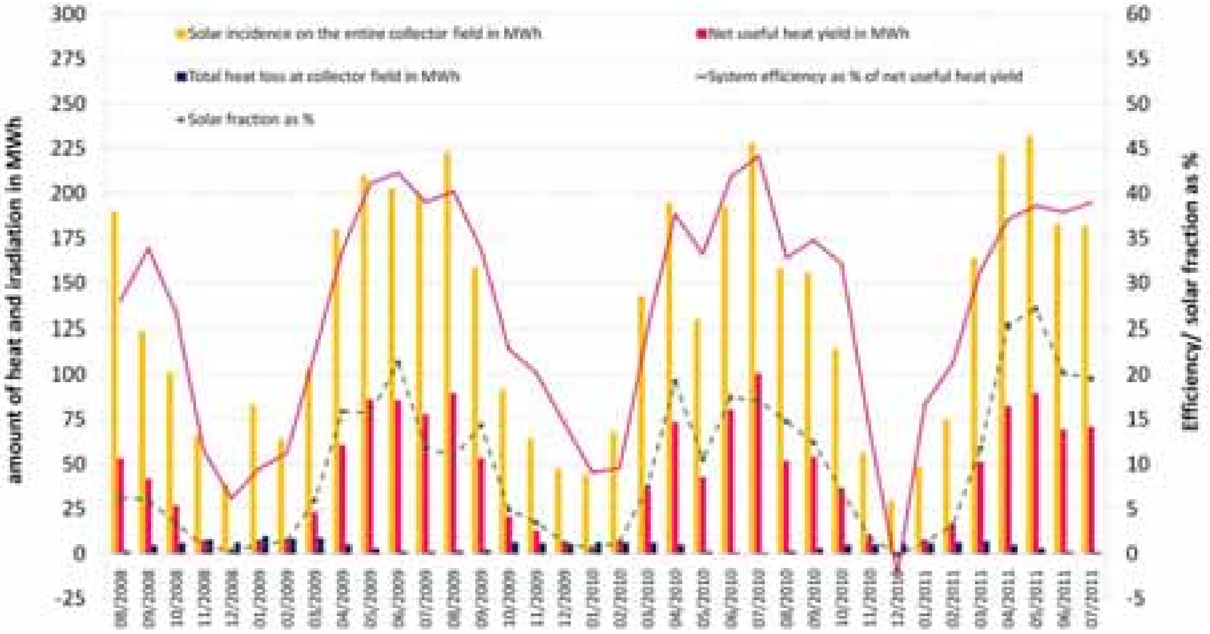

Figure 4.1: Results of the first year of intensive measurement of the solar air conditioning at Festo AG & Co. KG in Esslingen from June 2008 to June 2011. (essential data from Table 4.1 in monthly resolution)

4.2. Mode of operation and optimization measures

i. Weak valve in the collector circuit

At the beginning, improper flow was discovered in the collector circuit at night time, caused by the high temperature of the storage tanks compared to the collectors. This led to high heat losses across the collector field. The cause of this was an anti-siphon valve with too little spring force to prevent the improper flow. After changing the anti-siphon valve at the end of April 2008, almost no improper flow was detected (Figure 4.2).

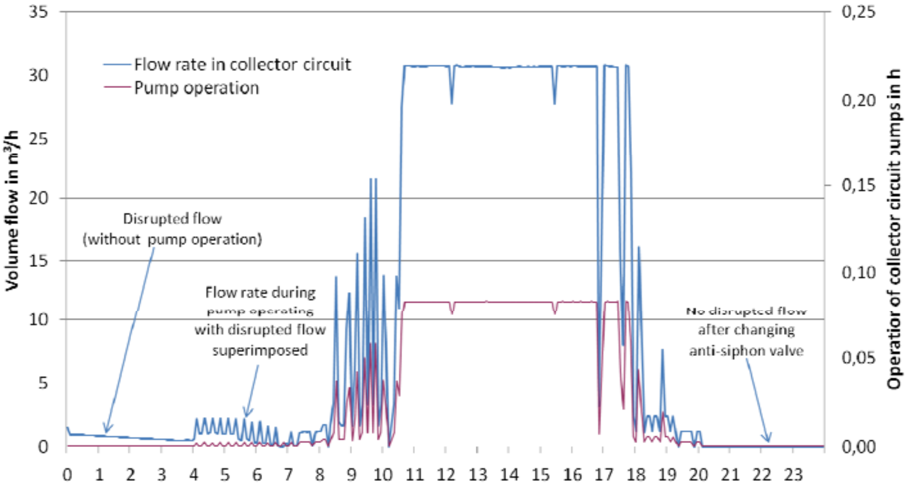

Figure 4.2: Volumetric flow through collector circuit and operation time of the collector circuit pump during a 5-minute interval on 29 April 2008.

ii. Optimization of switching to a direct branch to the thermo active building system of a new building

The solar system is connected to the adsorption chillers by a central distributor, to which the other heat consumers are connected (see Figure 3.1). When heat is fed into this central distributor, the return temperatures are mostly above 60 °C. The nominal temperature for storage tank discharge is 80 °C. For this reason, a direct branch was installed to a thermo-active building system in a new building. The storage tanks are discharged to the thermo-active building system at 35 °C and above. This makes return temperatures of 25 °C and lower possible. Since only maximum 200 kW of heating power can be dissipated in this fashion, the predicted sunshine duration of the next day was added as a control parameter to prevent frequent switching between the thermo-active building system and main distributor. As soon as the forecast sunshine duration exceeded a certain value, it would switch permanently to the main distributor for the entire following day. This control rule prevented feed into the low-temperature thermo-active building system on many days. Given the high supply and return temperature upon discharge to the main distributor, the temperature in the storage tanks rose significantly, with detrimental effects on the solar yield and the heat loss over the freeze protection circuit (Figure 4.3). The forecast sunshine duration was therefore deleted as a control parameter. Now, during heating operation, it is only the storage tank temperature that decides whether to discharge to the thermo-active building system. Since this change was made only shortly before switching to cooling operation, no concrete statements can be made as to the success of this improvement measure. It already appears, however, that there is significantly more frequent discharging to the thermo-active building system.

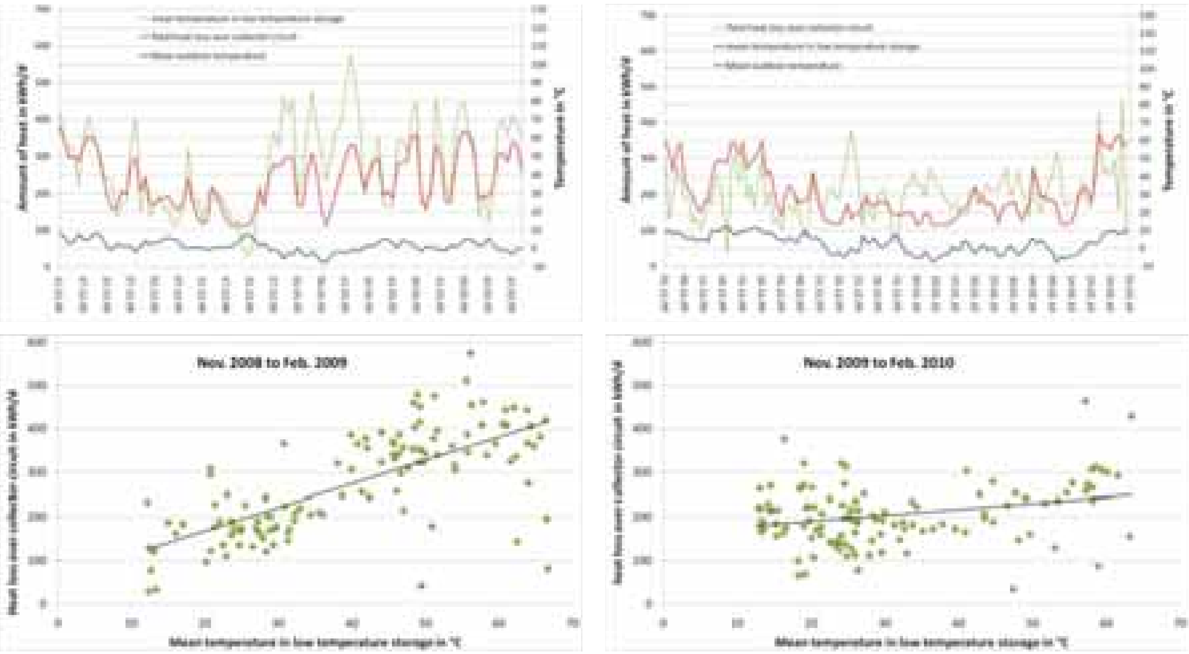

Figure 4.3: Correlation between mean daily storage tank temperature and heat loss to the collector field during freeze protection operation mode before (left) and after (right) optimization of control of discharge of storages.

Losses due to freeze protection cannot be recorded separately from losses at start-up, which add up to totally 66 MWh/a in first year of measurement. It must be noted at this point, however, that given the high storage tanks mentioned above, the losses due to freeze protection were significantly higher than at lower storage tank temperatures, and that the collector field with active freeze protection does not cool as much as without.

iii. Optimize the operation of the adsorption chillers

At the beginning of April 2009, the mode of operation of the adsorption chillers was changed such that they would only become operational if a sustained minimum heating power from the solar system and the compressors was available over a certain period. The individual machines are then connected or disconnected depending on the available heating power. This largely prevents the need for additional heating from the gas boilers. The additionally required cooling power is produced by electric motor-driven compression chillers. As can be seen from table 4.1, this significantly increased the solar and sustainable fraction of the total heat consumption during the summer months. In April and September 2009, were several times stagnations of the solar system due to little heat consumption (Figure 4.4). The resulting shutdown of the collector circuit pump due to exceeding the maximum temperature in the solar storage tanks led to a reduction of the solar yield. This problem was overcome by a step-wise reduction of the above mentioned sustained minimum power for the operation of an adsorption chiller from approximately 500 kW to 350 kW.

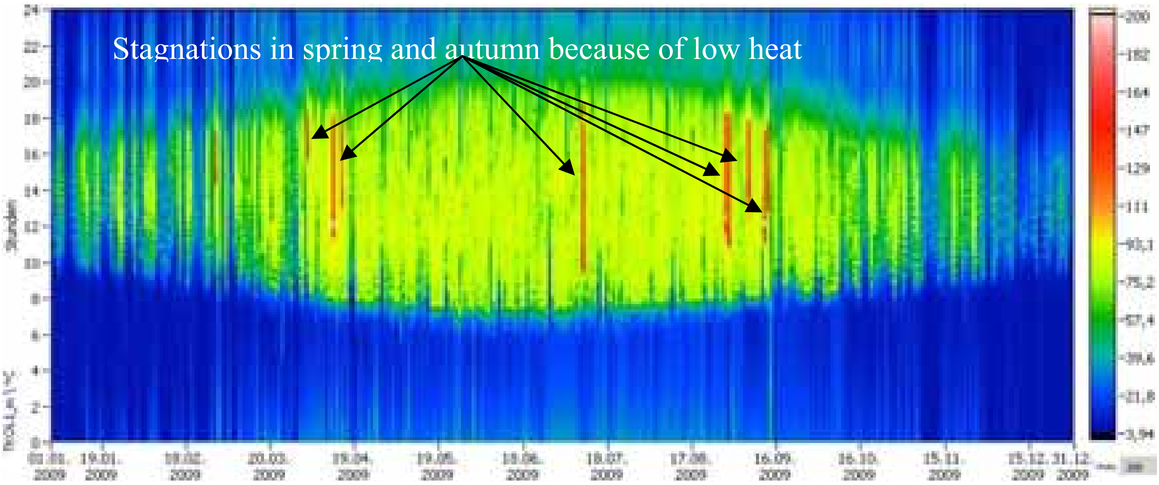

Figure 4.4: Carpetplot of collector temperature of the FESTO system: The shown temperature in collector increases up to 200 °C. It can be seen with the red lines where the temperature is much higher than 100 °C.

iv. Behavior of the solar system during stagnation

In the event of stagnation, the following behaviour was observed (Figure 4.5). The collector temperature rose as high as 200 °C (superheated steam). The temperature in the collector circuit supply line rose as high as 143 °C, which equates to a saturated steam pressure of approx. 3.9 bar. It can therefore be assumed that steam existed in the pipe. The given pressure at the storage tank level was measured at the level of the supply line temperature. A temperature rise was also observed in the storage.

Accordingly, it can be assumed that the liquid water was being pressed entirely out of the collectors, through the supply line and into the first storage tank, and steam was being fed in, which condensed there. For this case, the supply line was attached to the storage tank at half height, so that the steam would cool down and condense as it rose through the water in the tank.

In the event of stagnation under full solar incidence, the solar system is able to take in the superheated steam and, after condensation of the steam, to resume regular operation automatically.

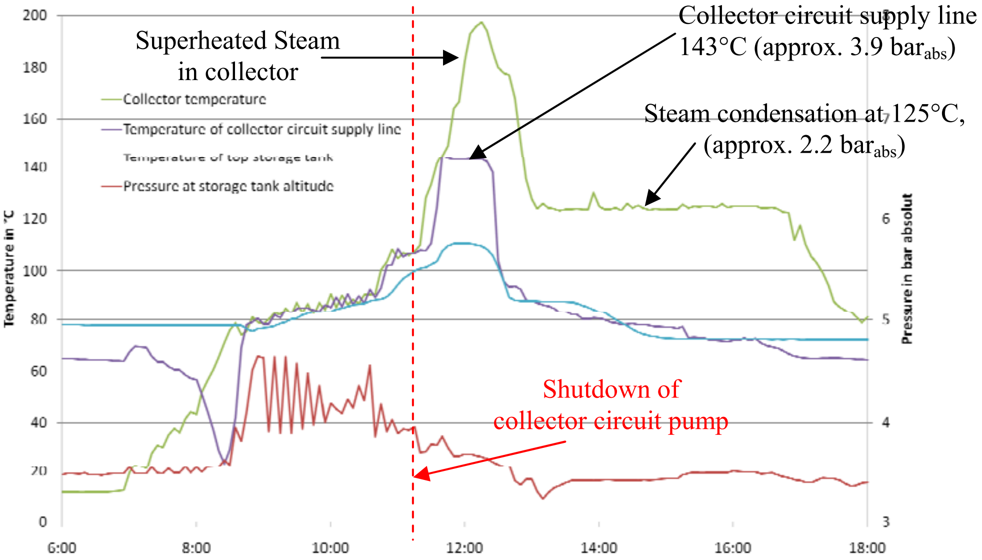

Figure 4.5: Behaviour at stagnation of the solar system for the solar air conditioning at Festo AG & Co. KG in Esslingen on 17 August 2008

5. Conclusions

The results of three years of detailed system monitoring of the solar-thermal system assisting the air conditioning of the Festo office building in Esslingen Germany shows that a large-scale solar thermal adsorption cooling system could be operated under Central Europe climate conditions successfully.

The solar yield of 500 MWh and system efficiency of 33.4 %, guaranteed by the collector manufacturer, was fulfilled. The required values were even exceeded with 543 MWh and 34.8 %. The control of the discharge at the buffer storage cycle and the operational mode of the adsorption chillers have been optimized. Therefore, lower heat losses concerning the freeze protection control and less system stagnations are expected and therewith higher solar yields could be achieved. With an annual mean COP of 0,47 the adsorption chillers operated below the expected 0.6, while a COP of 0,6 could be achieved punctually under best conditions [Huber et all. 2010].

As a quality management tool, system monitoring is the base of system optimization. In the given case false flows through the collector during night can be indicated and stopped as well stagnations due to malfunction of the system control. The behavior of the collector field under stagnation conditions could be analyzed and validated as well.

6. References

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