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Control optimization through simulations of large scale solar plants for industrial heat applications

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Abstract

The European FP7 Project InSun; which started in April 2012; aims to demonstrate the reliability and efficiency of three different collector technologies suitable for heat production employed in diverse industrial processes in different climatic regions. These collectors are installed and will be monitored in detail over a period of almost two years.

One of the plants is installed at Fleischwaren Berger GmbH located in Sieghartskirchen, Austria, a company which produces meat and sausage products. The second solar plant is installed at the company Laterizi Gambettola SRL (SOLTIGUA) located in Gambettola, Italy, which produces highly insulating hollow brick blocks for external walls of buildings. The control optimization and commissioning of the two solar plants has been carried out as a part of the InSun project. Considering measurements and results of simulations developed with dynamic models, potential improvements of the low-level control algorithms are presented for the two solar plants.

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Keywords: Control optimization; solar thermal collectors, large scale solar plant; solar industrial heat applications

1. Introduction

The present work describes some improvements developed in the solar plants installed at Berger and SOLTIGUA as a part of the European FP7 Project InSun. The control optimization and commissioning of the two solar plants has been carried out considering measurements and results of simulations using the programs OptiCAd and Matlab.

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2. Control optimization of the flat plate collector field installed at BERGER in Austria

In the first part of the project a simplified model of the entire solar system is developed with the program Trnsys 16.1. This model considers technical information of the installed solar system and it includes the entire flat plate collector area of 1067.5 m² in one field as described in [1] and shown in Fig. 1.

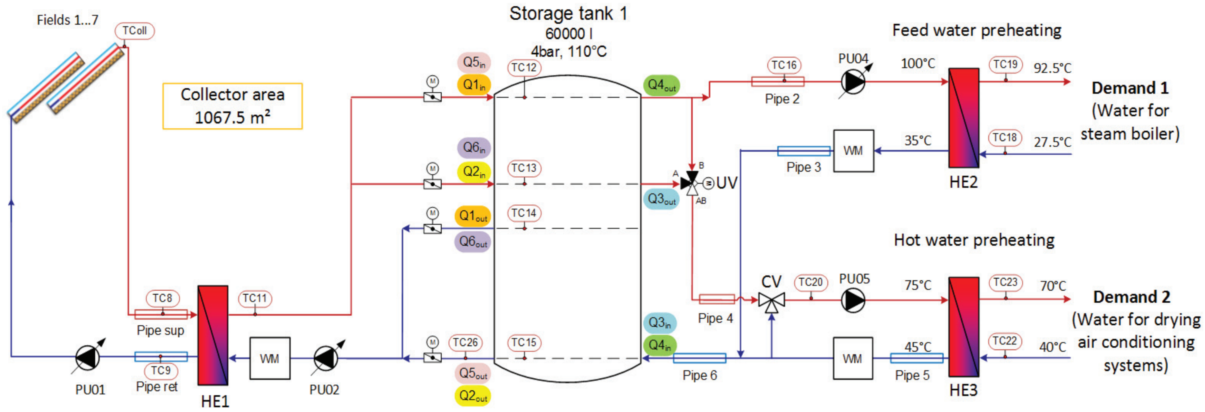


Fig. 1. Simplified hydraulic scheme of the solar system integration at the company Berger

The produced thermal energy is mainly used to preheat feed water for steam boiler and the surplus heat is used to increase the supply temperature within the heating water system up to 70°C. The feed water (HE2) of the steam vessel shall be preheated from approx. 27.5°C up to 92.5°C. The steam is internally required for process heating – specifically for ham cooking. The hot water (HE3) is required for several heat sinks within the plant (cleaning, ageing etc.).

To investigate the fluctuating temperature and flow rate values in the primary collector loop, a more detailed model was built using the program Matlab. In this second model, the collector field is divided into three sub fields. Also additional components and heat capacitances such as pipe diverters, heat capacity of pipe walls, dead time of pump and sensors are considered. This model was used to analyze and improve the implemented PI controller regulating the collector mass flow to reach a constant outlet temperature.

The following Fig. 2 shows a daily course of global irradiance, medium flow and supply temperature as measured in the solar field. The supply temperature is considerably fluctuating within the medium flow (e.g. medium irradiance) range due to the fluctuating pump flow in the collector field. The applied controller is obviously unable to cope with the changing dynamic of the field within this range.

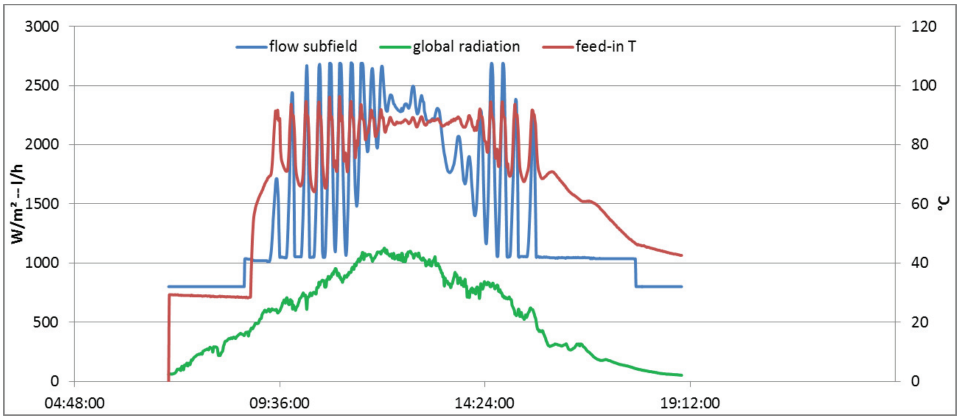


Fig. 2. Measurement data of the solar loop at the company Berger

The weather data of 23 August 2013 and the measured storage temperature at the load side were used as input values for a one day simulation. The flow and temperature courses of solar and load sides around the solar heat exchanger are presented in the Fig. 3. The figure shows a qualitatively similar behavior of temperature and flow as of measurement. The pump keeps oscillating between maximum and minimum frequency before the system reaches a certain settlement under high flow. On the load side the temperature oscillation amplitude reaches 20°C.

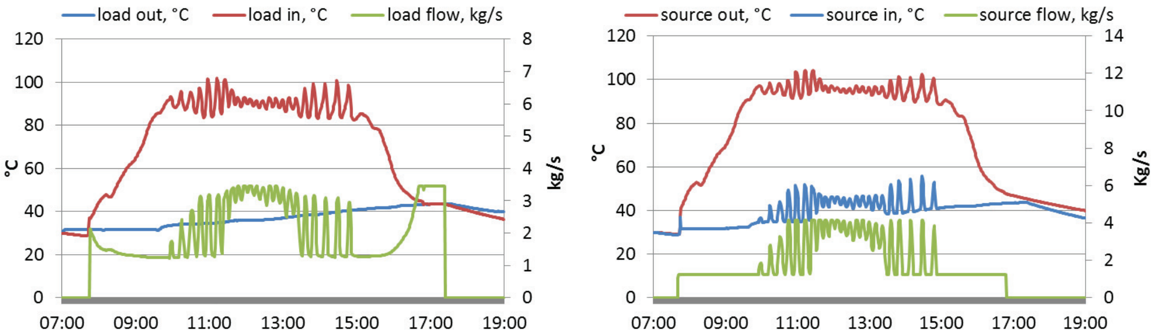


Fig. 3. Simulation data of initial state load side and source side around the heat exchanger of the solar system at the company Berger

Considering first results of the Matlab model, the following improvements are carried out:

(1) **Temperature sensor placement:** The compensation time of the existing field was determined to be around 7min. One of the first measures to enhance the controllability of the system is to decrease the dead time by moving the temperature sensor TC08 closer to the field. Assuming the T-sensor to be maximally shifted by 37m, which is the distance between the heat exchanger and the first mixer valve in the field, a better course in terms of temperature stability is obtained (Fig.4).

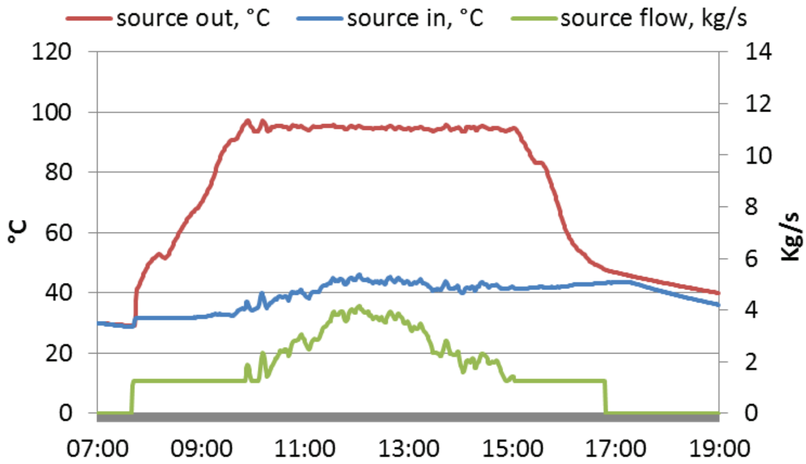


Fig. 4. Simulation data after moving the temperature sensor

(2) **Optimized PI parameters:** The PI controller was tuned for medium flow conditions using the rules of Chien, Hrones und Reswick [2]. The parameters obtained are shown in the Fig.5 (Kp = -0.042 %/K and Ti = 720s). Since the system gain at low flow is much higher, Kp should be half of the values for high flow. The corresponding results of simulations are shown in Fig.6.

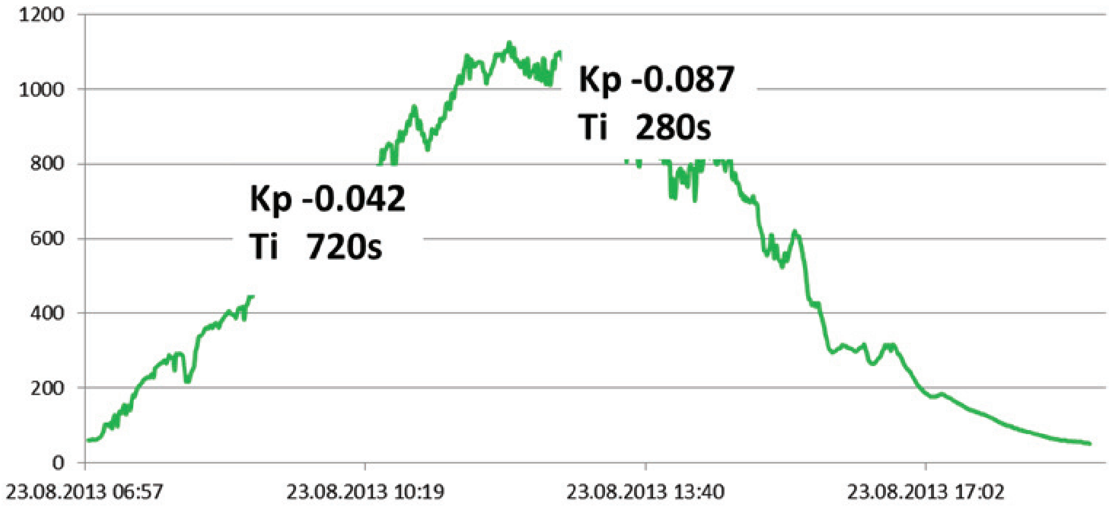


Fig. 5. Empirically tuned PI parameters depending on global rad. in W/m²

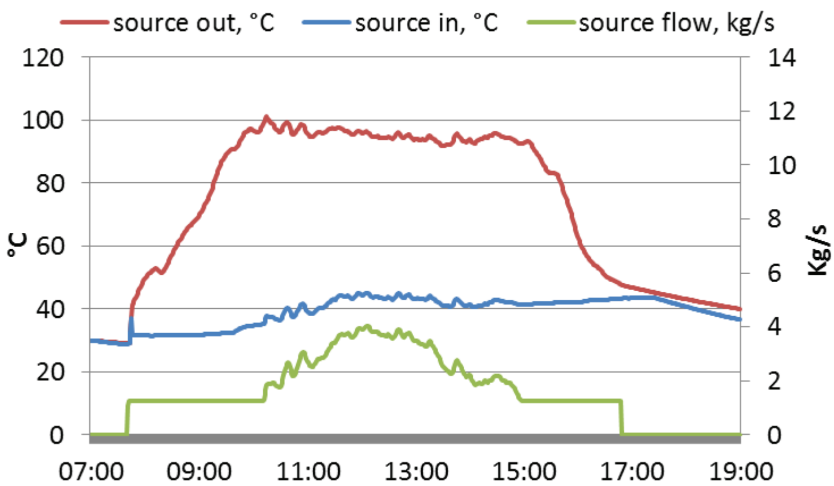


Fig. 6. Simulation data optimized PI

(3) **Constant set point:** Around 5:00PM the solar side fluid temperature decreases rapidly due to falling radiation while the storage side remains at relatively high temperature. The storage inlet flow is controlled at TC08-5K, which means that the secondary pump automatically increases its speed to maintain its loop temperature 5K below the falling primary temperature (see the measured load side flow in the following figure). The unnecessary storage side flow rise can be eliminated if a fixed set point tracking is implemented. Figure 8 shows the results obtained by applying Tset=90°C on load side.

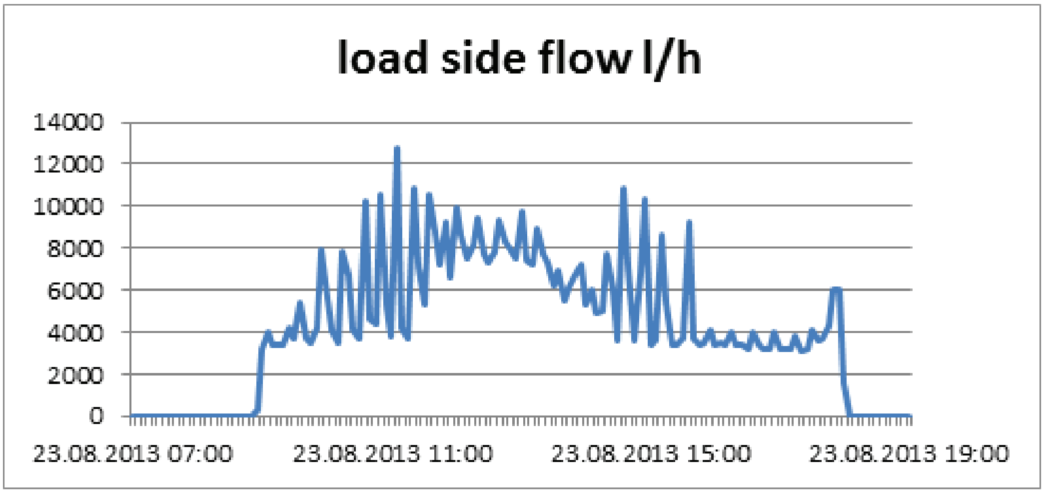


Fig. 7 Measurement data load flow

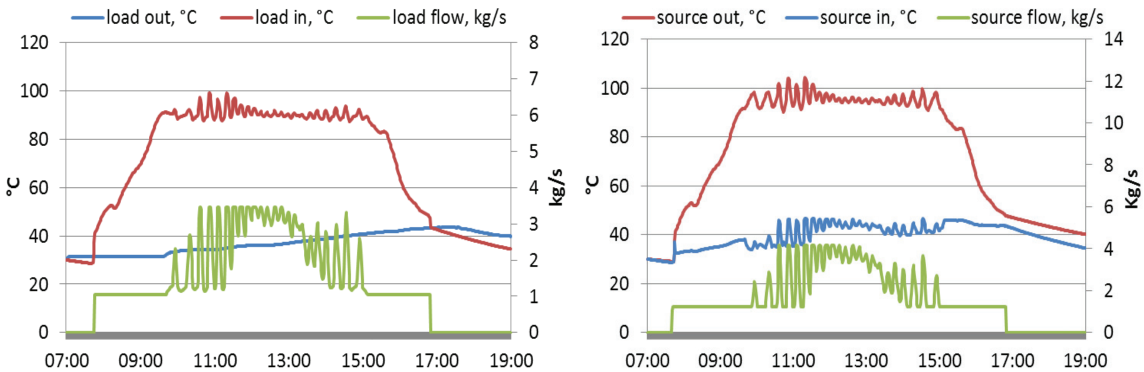


Fig. 8 Simulation data fixed set point

The load flow rise around 17:00 disappears. Additionally the amplitude of the fluctuations on the load side decreases to be less than 12°C. Further optimization of the pump speed controller is still needed.

(4) **Control at constant ΔT:** Considering a temperature difference (ΔT) between inlet and outlet at both sides of the heat exchanger; instead of temperature as a control variable; reduces the influence of fluctuating return temperature and offsets the sensor dead time and improve significantly the lifetime of pumps. According to the following conditions the results are shown in Fig.9.

Source pump PU01

- ON (max speed) if max. collector T > storage bottom T +hysteresis
- Speed control at constant ΔT between supply and return (between TC08 and TC09)
- Minimal speed 30%

Load pump PU02

- ON (max speed) if TC08 > storage bottom T +hysteresis
- Speed control at TC11=90°C
- Minimal speed 30%

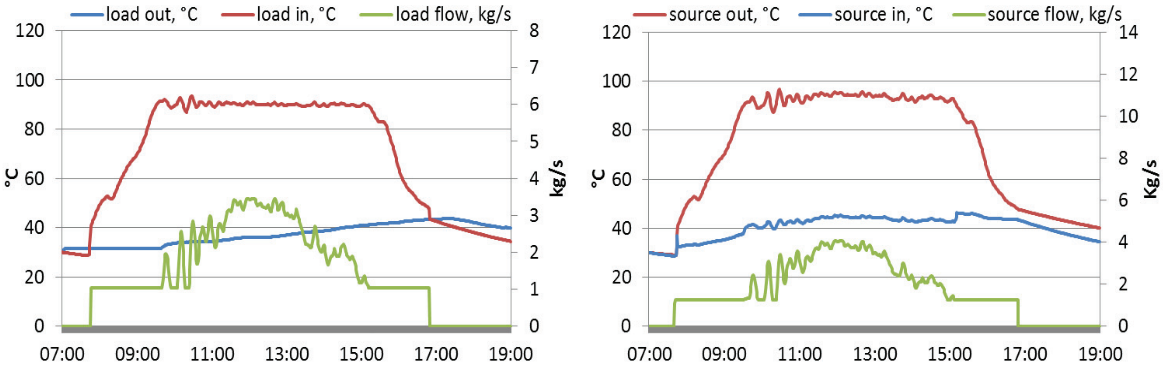


Fig. 9. Simulation data ΔT control

The improvements shown in this section enhance the temperature course on both heat exchanger sides. The pump speed signal is significantly dumped, which would lead to higher durability of the pump components (bearings and other moving parts). The electricity consumption may also be reduced due to longer nominal operation time. The useful energy transferred to the load side was calculated for each case. Moving the temperature sensor (in the same magnitude as indicated above) will enable approx. 2.4% more solar heat gains.

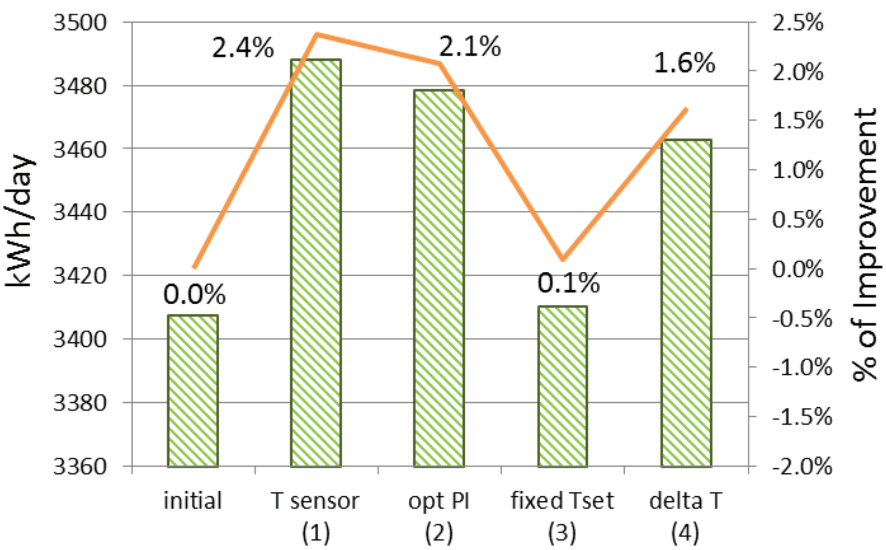


Fig. 10. Solar gains improvements for the 23rd of August 2013- Firma Berger

3. Control optimization of the Fresnel collector field installed at SOLTIGUA in Italy

The improvements presented for the SOLTIGUA plant concentrate on the control optimization of the 1056 m² Fresnel collector field operated with thermal oil as heat transfer medium and thermal oil to steam boiler.
Figure 11 shows the general layout of the HTF solar field. In the figure, the sensors labelled as $T_{HTF\ X}$ indicate temperature measurements, while those labelled $M_{HTF\ X}$ indicate mass flow measurements. The grey heat exchanger corresponds to the internal tubes of the steam boiler. Additional information can be found in [3].The solar field was modeled using the programs OptiCAd and MATLAB with the following considerations:

- A factorized IAM factor with a resolution of 3° on transversal and longitudinal plane
- Fixed η0 and a1-losses factor
- 8 distributed FTM36 subfields
- Dead times of sensors and actuators
- Temperature dependent HTF properties
- Collectors are totally defocused if the irradiance is below a certain threshold
- Weather data resolution of 1 min

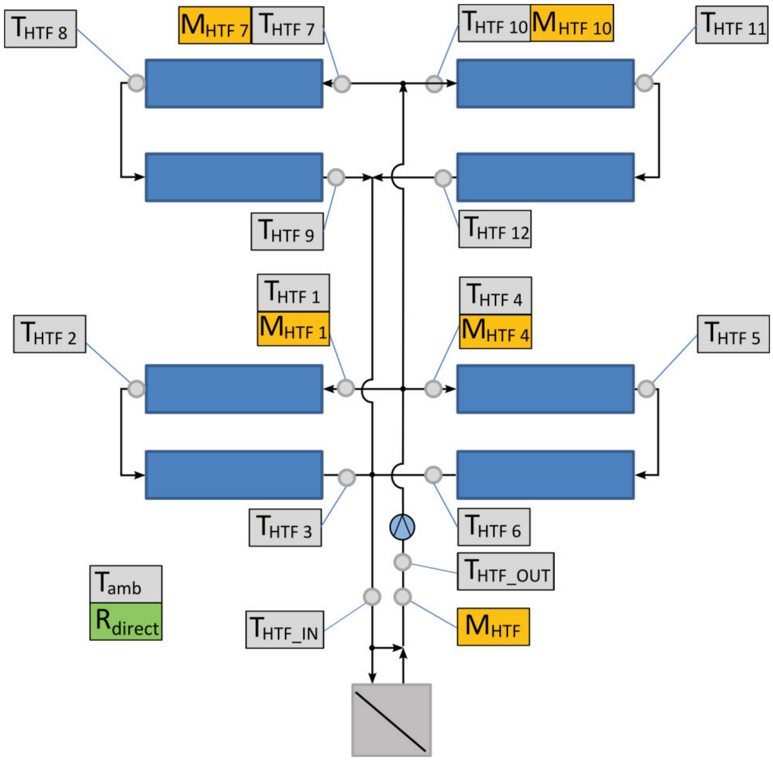
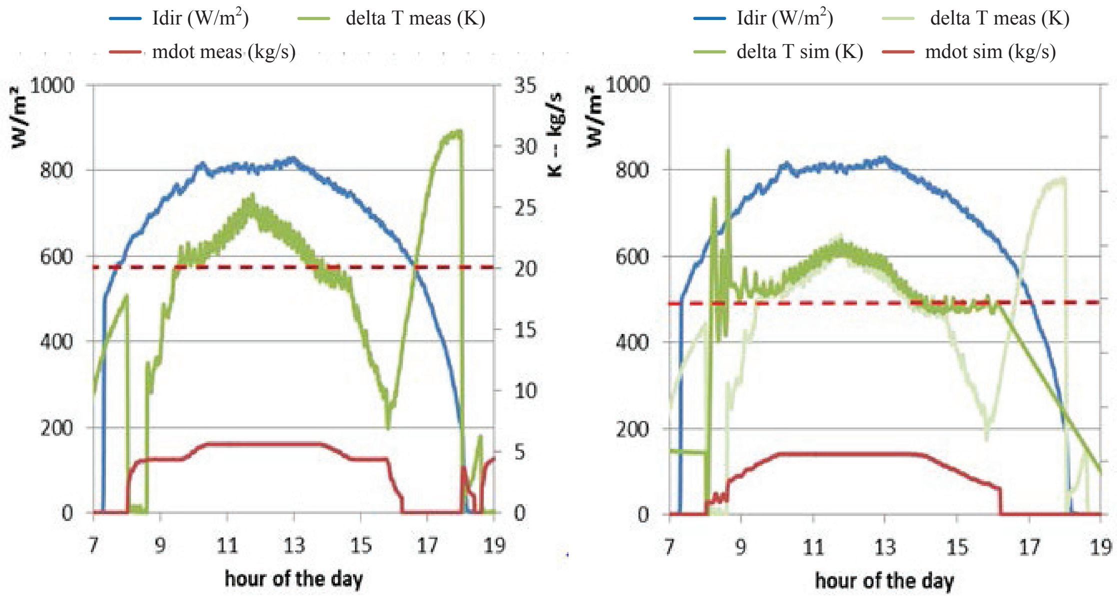


Fig. 11. HTF solar field layout at Soltigua [3]

Control optimization of the solar field

The solar field monitoring data show some control weaknesses in terms of set point tracking and disturbance dissipation. Figure 12 shows a daily course of direct irradiance, HTF flow and temperature drop as measured in the solar field on the 6th of September 2013. A minimum flow of app. 4.7 kg/s required for turbulent regime can be seen in the heating-up phase and after 3PM. The flow is controlled to maintain the temperature drop at 20K. Obviously the controller reaches saturation under high radiation values (>750W/m²) and the set point cannot be hold. When the pump is off, high temperature differences are recorded. This can be explained by the closeness of the sensors to the steam generator and by different heat losses characteristics of supply and return lines.

Different measures were developed through simulations to enhance the temperature course of the system. First, the flow velocity boundary was tightened by allowing a lower minimum value (up to 20% of the maximum flow). As illustrated in Fig.12, the pump control signal follows the irradiance course well during the day. The temperature drop remains 2.5 hours longer at the desired level than in the initial setup (grey curve). However, high fluctuations are observed in the heating-up phase due to the very high system gain. The collector efficiency dependency on the flow regime was not considered in this case.



Measured data of the solar loop | Simulation data lower flow boundary

Fig. 12. Control optimization of solar loop for the 6th of September 2013- Firma Soltigua. ("Idir": Irradiance, "delta T": temperature difference between inlet and outlet of the heat exchanger, "mdot": flow rate)

Second, the temperature course was observed during a cloudy day (see figure 14 for 9th September 2013). The pump starts several times during the day and the system is not able to maintain the set point of 30K. As can be clearly seen between 2 and 3PM, fluctuations in irradiance directly affect the temperature course and the controller is obviously unable to cope with fast weather disturbances. The flow velocity boundary was tightened. The system ability to keep the temperature drop in the desired range is enhanced, but also higher overshoots in the drop values can be seen (up to 70K). This is mainly caused by the controller inability to react on the fast disturbances mentioned above.

Finally, the shared control scheme was extended according to Fig.13: the upper half of the figure shows the conventional feedback loop containing the PID controller. The weather file is directly feed into the system model. In the bottom half a feed-forward block is added to adjust –out from the weather data- the mass flow to be circulated in order to keep the temperature drop at the desired level. In other word the feed-forward block tries to dissipate the effect caused by measurable weather disturbances. The integration of a feed-forward signal in the loop leads to the temperature and flow course of figure 14. The overshoots in temperature drop are clearly damped to be lower than 42K. The output signal fluctuations still observed cannot be totally eliminated due to several dead times taken into account (heat capacities, pump inertia etc.) which limit the system controllability.

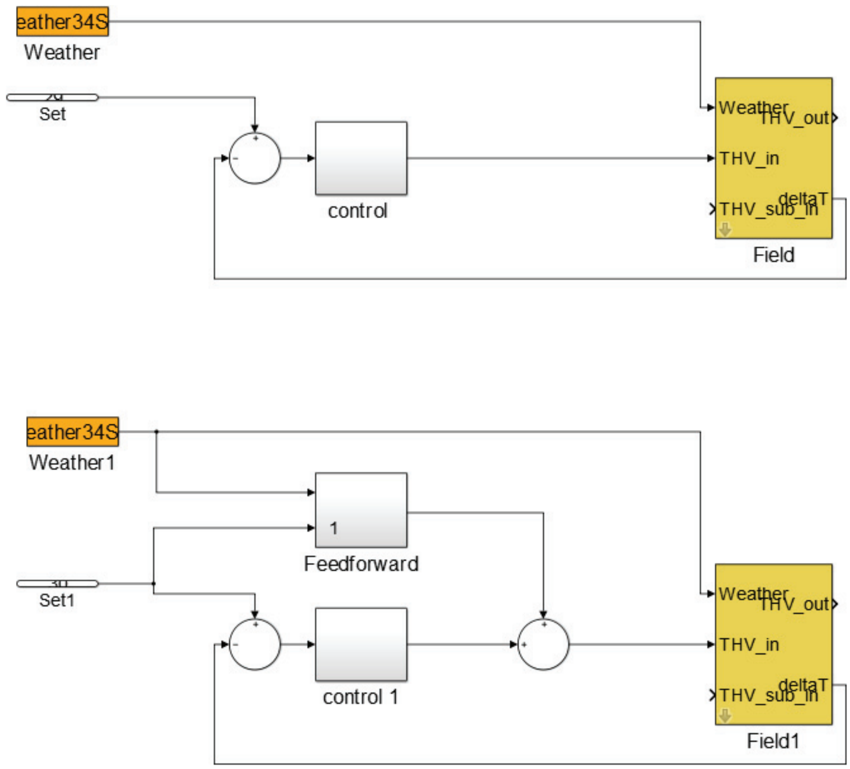
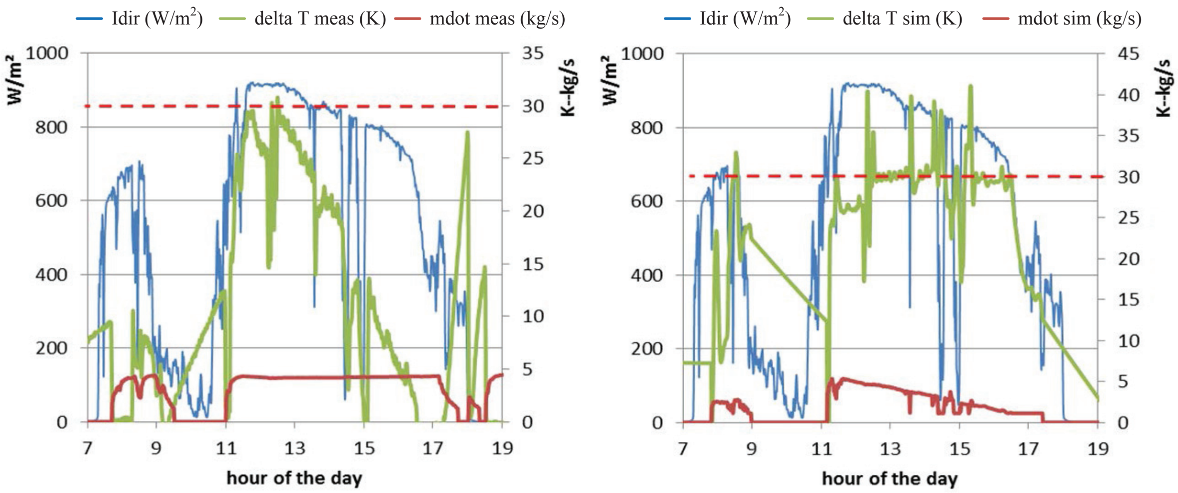


Fig. 13. Control extension



Measured data during a cloudy day

Simulation data feed-forward

Fig. 14. Control optimization for the 9th of September 2013- Firma Soltigua. (“Idir”: Irradiance, “delta T”: temperature difference between inlet and outlet of the heat exchanger, “mdot”: flow rate)

Conclusions

The Berger solar plant installed in the framework of the FP7 demonstration project InSun has been successfully commissioned in the summer 2013. The system is well equipped with different sensors and the monitoring data are automatically transferred to the project partners. The system utilization ratio reaches 37% in April 2014. Higher values are expected in the next operation period.
The analysis of the first monitoring data shows weaknesses of the collector loop controller. The system tends to oscillate in the medium flow range. This paper describes four measures to dump the temperature fluctuations and to enhance the pump life time. The calculated improvements are compared to the solar heat gains relative low. Further investigations of the heat streams through the whole system are still on going.
The SOLTIGUA solar field monitoring data also show some control weaknesses in terms of set point tracking and disturbance dissipation. A feed-forward extension of the originally described PID controller was proposed in order to cope with fast weather disturbances. Further investigations show that the steam supply continuity can be considerably enhanced if the boiler outlet valve is replaced by a smaller one. Once the demand side data are available, the impact of the proposed improvements on the solar gains can be determined.
In many cases the improvements were not quantified due to the fact, that control optimization is generally performed using the step response of the real system. The control quality can be measured in terms of rise time and overshoot. This kind of onsite measurements is necessary to quantify the enhancements. Furthermore, for accurate results the dependency of the Fresnel collector efficiency on the flow regime (Reynolds number) has to be considered prior to the calculation of the solar gains. Taking this dependency into account some numerical convergence troubles appear: if the collector coefficients change, the heat transfer is suddenly changed which has a direct effect on the fluid temperature and therefore on the fluid viscosity from which the Reynolds number directly depends.

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