SOME ASPECTS ON PARABOLIC TROUGH FIELD OPERATION WITH OIL AS A HEAT TRANSFER FLUID

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Abstract

Solar power plants of the SEGS-type gained enormous attention within the last years. A number of plants are already under construction or even close to grid operation. The bases for these developments are the experiences gained with the American plants in the past 20 years. This paper concentrates on two aspects concerning the operation of the plant which are, according to the authors experience, often not considered in the design phase of a new plant although their impact on the performance or component requirements of the plant is quite significant. The aspect of defocusing at over-load is analyzed by energy balances. The second field of oil temperature controllability is studied using a dynamic simulation tool.

Keywords: parabolic trough, oil, focusing, operation strategy, temperature control

1. Introduction

For parabolic trough solar power plants with oil as a heat transfer fluid a fix design field outlet temperature of about 393 °C is usually set when calculating efficiencies and annual electricity yields. The value is derived from the stability limit of the thermal oil. The mass flow through the field is adapted to exactly reach the predefined outlet temperature. This approach allows generation of simple and fast simulation tools. Nevertheless, for a detailed design of a plant it is mandatory to consider deviations from the constant outlet temperature. These can be caused by multiple effects. Two of them, de-focusing and transient behavior are addressed in this paper where the emphasis is laid on the illustration and sample calculations for oil based parabolic trough systems.

2. De-focusing strategy

2.1. Introduction

De-focusing has different objectives during operation of parabolic trough solar thermal power plants. First of all, the independent distributed control system prevents overheating of the heat transfer fluid in order to secure operation within in the thermal stability range of the thermal oil. Beside this local control for each collector an overlaying de-focusing strategy is necessary to deal with over-load situations.

Over-load situations occur due to the following reasons:

- The size of solar fields is economically optimized and, thus, a field with a solar multiple higher than 1 is normally realized. Accordingly, the energy yield of the solar fields exceeds the design yield at higher irradiance levels.
- Design of heat-exchangers for the steam generating system (SGS) and – if implemented – for the heat storage systems is orientated to design conditions.
- When the storage is completely charged the overall maximum heat-duty of both heat-exchanger systems escalates down to the maximum heat-duty of just the steam generating system.

In order to not to exceed the overall maximum heat-duty a certain number of collectors must be de-focused, see figure 1. The operator can decide which collectors should be defocused. The first differentiation is to defocus loop-wise (LWD) or collector-wise (CWD). LWD means that entire loops are defocused one-by-one in order to balance the energy yield with the overall maximum heat-duty. In contrast, a CWD will tilt one collector in each loop out of the sun until every loop is reduced by one collector. Then – if still not balanced with the overall maximum heat-duty – the next collector will be de-focused in each loop until equilibration is reached.

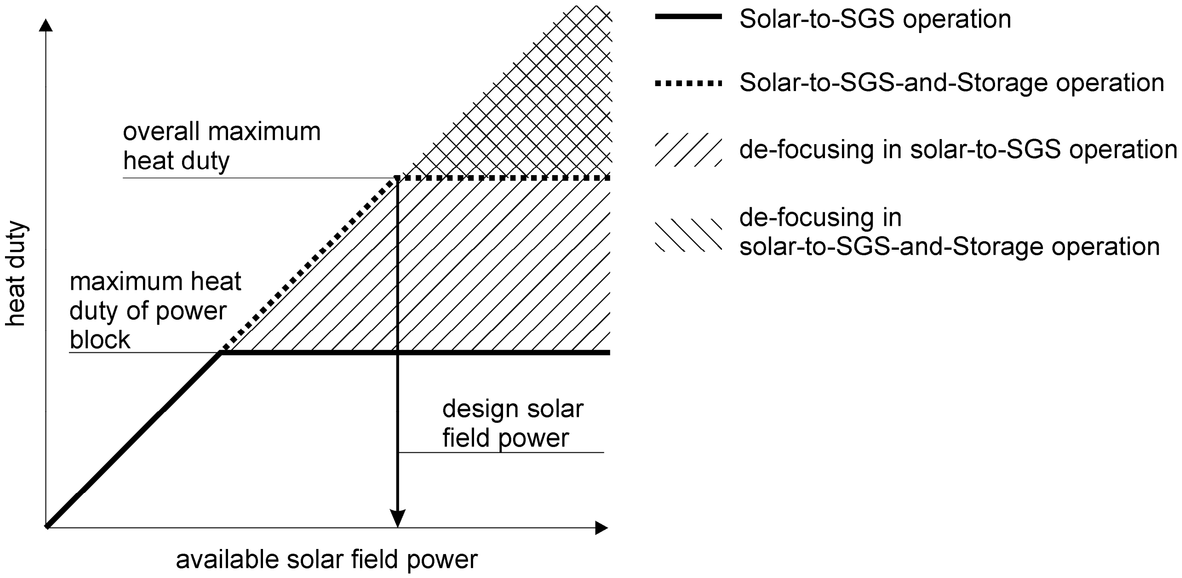

Fig. 1. De-focusing depending on available solar field power and operation mode

In design operation, the thermal oil temperature will be set close to the operating limits of the thermal oil. De-focusing will influence the oil temperature entering into the heat-exchanger systems. Both de-focusing strategies lead to different temperatures at the end of each loop depending on the number of de-focused collectors. The oil temperature will be close to design temperature in the loops with the fewest collectors de-focused. In the remaining loops the oil temperature will be lower and these streams will reduce the temperature entering into the heat exchangers by the mixing in the header pipes.

2.2 Modeling

In order to assess the influence of de-focusing strategies on the outlet temperature of the field, a simulation model was set up. Table 1 summarizes a selection of the overall field and collector parameters. The solar field is assumed to have its design heat production at ambient conditions of 850 W/m² direct normal irradiance (DNI), 25 °C air temperature and 60 % relative humidity at June, 21st solar noon, and a field availability of 95 %. The consumers of the energy are the storage and the power block, each with a maximum heat duty of approx. 132 MW_{th}.

Parameter	**Value**
Collector	Eurotrough 150
Collector Loops	156
Collectors per Loop	4
Design Heat Production	~264 MW_{th} @ 850 W/m²
Heat Transfer Fluid	Therminol VP-1
Inlet Temperature	293 °C

Table 1. Summary of field parameters

The mass flow distribution of the oil through the absorber pipes is determined by the momentum balance, i.e.

the pressure drop equations. The pressure drop equation

$$\Delta p = \lambda \frac{l}{d} \frac{\rho c^2}{2} \tag{1}$$

is influenced by temperature dependent variables. Temperature dependent parameters in equation 1 are the pressure drop coefficient λ, density ρ and fluid velocity c. Collector geometry is described by the length l and the inner absorber tube diameter d. When assuming constant irradiance to the complete solar field, temperature distribution and pressure drop are equal for each row in a completely focused field. During de-focusing of single collectors or even of entire loops, the temperature distribution will be different. Therefore, the temperature dependency must be considered for determining the mass flow distribution in the field. The pressure drop coefficient

$$\lambda = \frac{1.325}{\sqrt{\ln \frac{5.74}{\mathbf{Re}^{0.9} + 0.27 \frac{k_s}{d}}}} \tag{2}$$

is implemented using the explicit form of the Prandtl-Colebrook-Equation [1]. Where Re is the Reynolds number of the flowing oil and k_s is the roughness of the inner tube surface. The necessary properties, like viscosity and density of the heat transfer fluid are calculated according to the data sheet of VP-1 [2]. The fluid properties are calculated using the mean temperature

$$\bar{T} = 0.5\,(T_{\text{inlet}} + T_{\text{outlet}}) \tag{3}$$

of each collector. All components of the field are modeled stationary.

The control objective of the field is the outlet temperature which is intended to be 393 °C. The field pumps are used to reach the objective by altering the mass flow into the solar field, where the oil temperature may not exceed its maximum bulk temperature of 400 °C minus 7 K of security. There is no division of the solar field in sub-fields, so no additional control systems like valves are used.

2.3 Loop-wise De-focusing

One possibility of de-focusing is to defocus the collectors in one loop one after the other until the entire loop is de-focused. This is repeated with the next loops until the energy demand of power block and storage systems is exactly satisfied by the energy yield of the field. LWD always yields a temperature lower than 393 °C due to the fact that a hot stream is mixed with a cold stream in the header pipe.

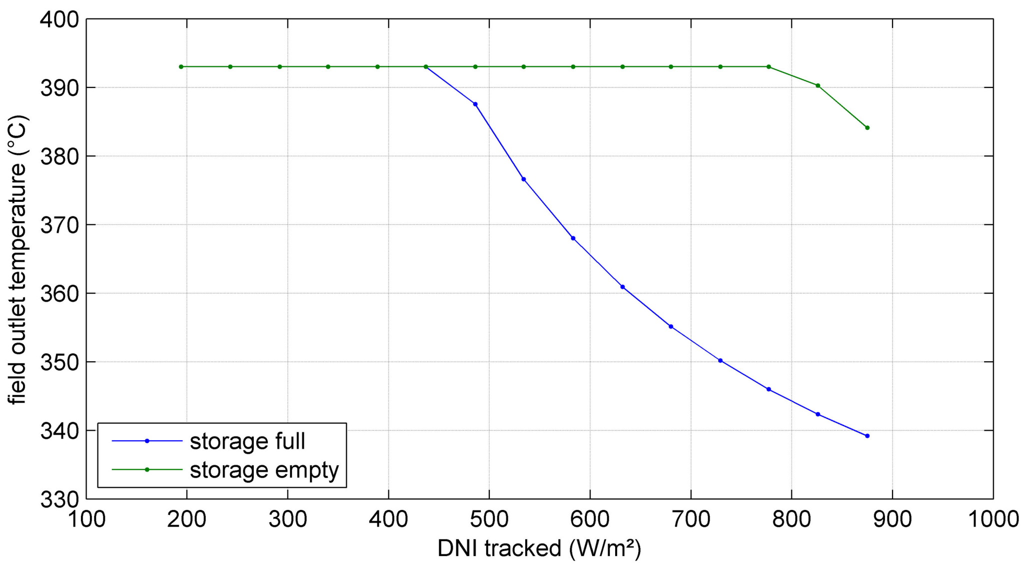

Fig. 2. Variation of outlet temperature of the solar field during LWD

Figure 2 illustrates the behavior of the temperature at different irradiances (DNI · cos φ). The green line indicates the outlet temperature dependency on the tracked DNI when power block and storage can consume the heat offer of the field. When the DNI exceeds the design DNI de-focusing takes place and therefore the temperature must fall. At a DNI of 900 W/m² (equiv. 875 W/m² tracked) the temperature is reduced to 384 °C. At lower irradiance than design irradiance no de-focusing is needed. Thus, the outlet temperature stays constant at 393 °C. When the storage is not able to consume heat anymore, the temperature is further decreased as shown by the blue curve. The temperature drop starts with de-focusing when solar field provides 132 MW_{th} (equiv. 472 W/m² DNI tracked) and drops by 54 K at a tracked DNI of 875 W/m².

2.4 Collector-wise De-focusing

Collector-wise de-focusing means that during de-focusing the last focused collector of a loop is turned out of focus-. The next collector which will be de-focused is the last focused collector of the neighboring loop. This is repeated until the solar field energy offer matches the demand of storage and power block. In figure 3 the CWD strategy is illustrated. It can be seen that the number of collectors between to different loops cannot be higher than 1. The loops with less de-focused collectors have a controlled outlet temperature of 393 °C. The others have a lower temperature. Thus, after the mixing, a lower temperature than the objective of 393 °C is reached. The temperature reduction is defined by the mass flow relation between the hot and the cold stream.

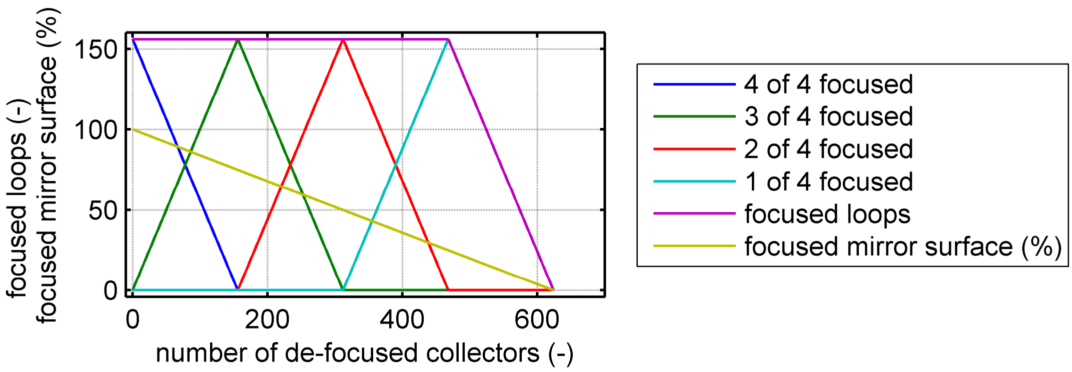

Fig. 3. De-focusing using the CWD strategy

The objective temperature is always reached when all loops have the same numbers of focused collectors. Figure 4 shows the temperature characteristics of CWD. Blue line indicates the temperature when the storage is chargeable. The objective of the temperature control can always be reached up to the design irradiance of 800 W/m². At higher irradiance, the outlet temperature will fall due to mixing. At irradiance levels of 1000 W/m² the field outlet temperature will be 380 °C. When the storage is completely filled, the maximum heat duty will be reduced to 132 MW. This means more de-focusing to match the solar field output and the demand of the power block. The magenta line indicates the outlet temperature dependency on the tracked irradiance on the field. The steepest temperature drop occurs at 925 W/m² DNI tracked and reaches a difference of 37 °C compared to its objective. The saw tooth similar behavior is explained due to two reasons. First, a decreased temperature is the result of mixing due to different numbers of focused collectors in the loops. Second, the reference temperature can be achieved when all loops have the same numbers of collectors focused. Up to a DNI of 480 W/m² no de-focusing is necessary. At 615 W/m² and 910 W/m², all loops have three or two collectors focused, respectively. At irradiances slightly lower than 615 W/m² or 910 W/m², an additional collector has to be focused resulting in one single loop which has one more collector in focus than all the others. In this situation, the mass flow has to be adapted based on this loop in order to avoid overheating. As a consequence, outlet temperature in all other loops significantly decreases.

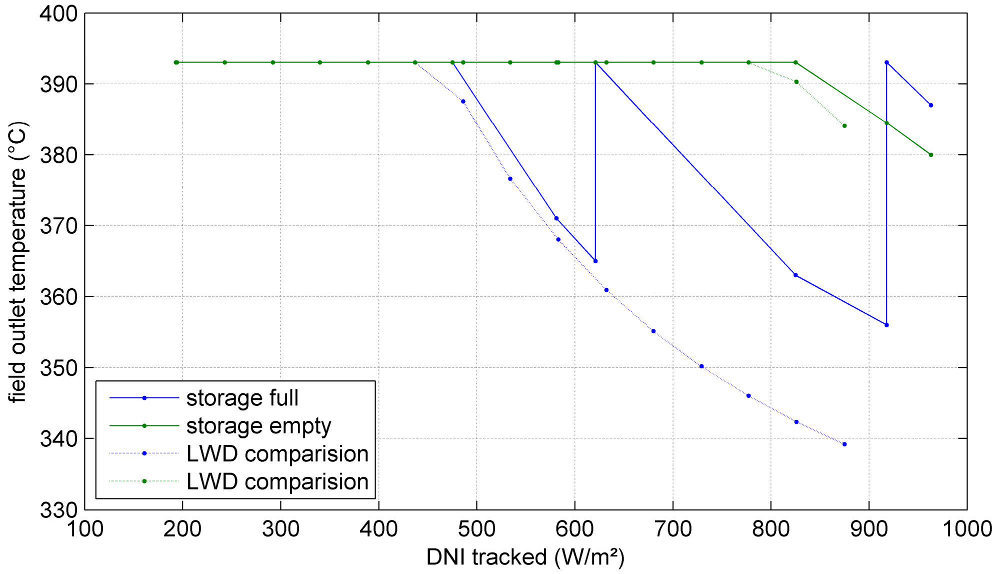

Fig. 4. Variation of outlet temperature of the solar field during CWD. Thin lines show results of LWD for comparison.

2.5 Mitigation possibilities

In order to mitigate or even eliminate the temperature drop different possibilities are thinkable. The maximum heat duty of the heat exchanger is the limiting parameter which makes de-focusing necessary. Thus, increasing the maximum possible heat duty to the storage allows at least during storage operation a non-defocused operation. Another idea is to remove the excess heat by transferring it to the condenser instead of de-focusing. In this case, no temperature drop is necessary in both operation modes, charging and solar-only.

During summer month, when most of the defocusing has to be done, some parts of the solar field can be decommissioned by simple valves. This leads to lower maximum solar field power and therefore to lower need of de-focusing. Another possibility how the temperature drops can be avoided is to use a different heat transfer medium. Since VP-1 is operated near its physical decomposition temperature and this is also the objective temperature, mixture always leads to a lower temperature. When using another heat transfer fluid with decomposition temperature significantly higher than its reference temperature, the control via the field pumps is able to maintain the temperature constant. This is due to the reason that the lower outlet temperature can be mixed with a hot stream that is hotter than the reference temperature. Thus, this mixture will be able to reach the reference temperature. As an example, it is shown that economical operation temperatures of direct steam generation, i.e. the objective temperatures of the field outlet can be significantly lower than the constraining maximum operation temperature of the absorber pipe [3].

In order to avoid the steepest temperature drops during CWD the de-focusing strategy could accept a lower heat yield of the solar field by not focusing additional collectors when the DNI is decreasing. A tradeoff between the yielded power and the temperature stabilization has to be done by the operator.

In this paper, the solar field outlet temperature was only controlled by the oil mass flow. The total mass flow of thermal oil was then distributed in the field due to its fluid properties. When adding additional control valves, i.e. sub-dividing the solar field into sectors, the deviations to the temperature reference can be decreased. They can even be eliminated when installing a control valve at the beginning of each loop. Another additional control actuator which helps to eliminate this problem is the use of collectors which can be stepwise defocused. This additionally control mechanism would mitigate the temperature drop if a discrete number of points between 0 and 100 % of illumination can be achieved. The temperature drop can even be eliminated if the entire spectrum can be set.

When comparing the temperature characteristics of LWD with CWD, see figure 4, it can be seen that the temperature of LWD is always below the temperature of CWD. Thus, a change from CWD to LWD is not favorable.

3. Oil temperature controllability

Steady-state modeling represents the current state of the art when designing solar thermal power plants. For an oil-based parabolic trough solar field this means that the field outlet temperature is assumed to be constant at its design value of about 393 °C. Such kind of modeling is valid as long as the system reacts fast to changes in the input variables and the mass flow can successfully be adapted to irradiance and ambient conditions. A parabolic trough collector loop with a length of about 600 m as realized today represents a significant thermal inertia.

As a first approximation, the difference between loop outlet and inlet temperature, ΔT, is proportional to the heat input into the loop if the mass flow is kept constant. Thus, a variation in irradiance leads to a proportional adaptation of the temperature profile and, with it, of the internal energy in the system. The time that is needed to reach the new stable state depends on the thermal inertia of the wall (W) and the fluid (Fl) volumes. A characteristic time constant t_{inertia} can be defined as the difference of internal energy between initial and final state divided by the change of heat input into the system,

$$t_{\mathrm{inertia}} = \frac{c_{\mathrm{W}}\rho_{\mathrm{W}}V_{\mathrm{W}} + c_{\mathrm{Fl}}\rho_{\mathrm{Fl}}V_{\mathrm{Fl}}}{c_{\mathrm{Fl}}\dot{m}} \frac{\Delta T}{2\Delta T} = \frac{1}{2}\frac{c_{\mathrm{W}}\rho_{\mathrm{W}}V_{\mathrm{W}} + c_{\mathrm{Fl}}\rho_{\mathrm{Fl}}V_{\mathrm{Fl}}}{c_{\mathrm{Fl}}\dot{m}} \quad . \quad (4)$$

To calculate the heat input, the full temperature rise of the loop has to be considered. For the thermal inertia only half of this value, representing the mean temperature rise, is used. Table 2 shows values for the inertia time constant for two typical operating conditions. A second time constant is defined by the throughput-time. That means the time a fluid particle needs to travel from the loop entrance to the exit. Values for the throughput-time are also given in the table.

	Winter day, 1000 W/m^2	Summer day, 1000 W/m^2
Temperature rise	110 K	110 K
Cosine of incident angle	0.69	0.97
Mass flow rate per loop	4.3 kg/s	7.7 kg/s
Throughput-time	5 min 52 s	3 min 17 s
Inertia time constant t_{inertia}	4 min 4 s	2 min 17 s

Table 2. Time constants of the collector loop for two operating conditions

Figure 5 shows transient simulations of the collector loop with three different artificial disturbances:

- drop in irradiance by 400 W/m^2 on all four collectors in the loop,
- drop in irradiance by 800 W/m^2 on only the first two collectors in the loop,
- drop in irradiance by 800 W/m^2 on only the last two collectors in the loop.

The effective power of the disturbance over the whole loop is the same for all three test cases. Simulations are performed with a transient simulation tool that solves unsteady balances of mass and energy in an axially discretized collector loop together with a steady-state pressure drop correlation and efficiency curves for the absorber pipe heat balance [4]. From the disturbance on collectors 1 and 2 half of the throughput-time can be identified as the time between the drop in irradiance and the first impact on the outlet temperature (the temperature signal has to travel half the collector loop length). The profile for the temperature drop results from inertia effects and the travel time. The corresponding time constants cannot simply be added, but it can be seen from the simulation results that the calculated time constants are quite suited to give a first estimate of the systems response. The transients in the winter case are less steep since the effective (cosine corrected) power disturbance is smaller and, at the same time, the throughput-time is larger.

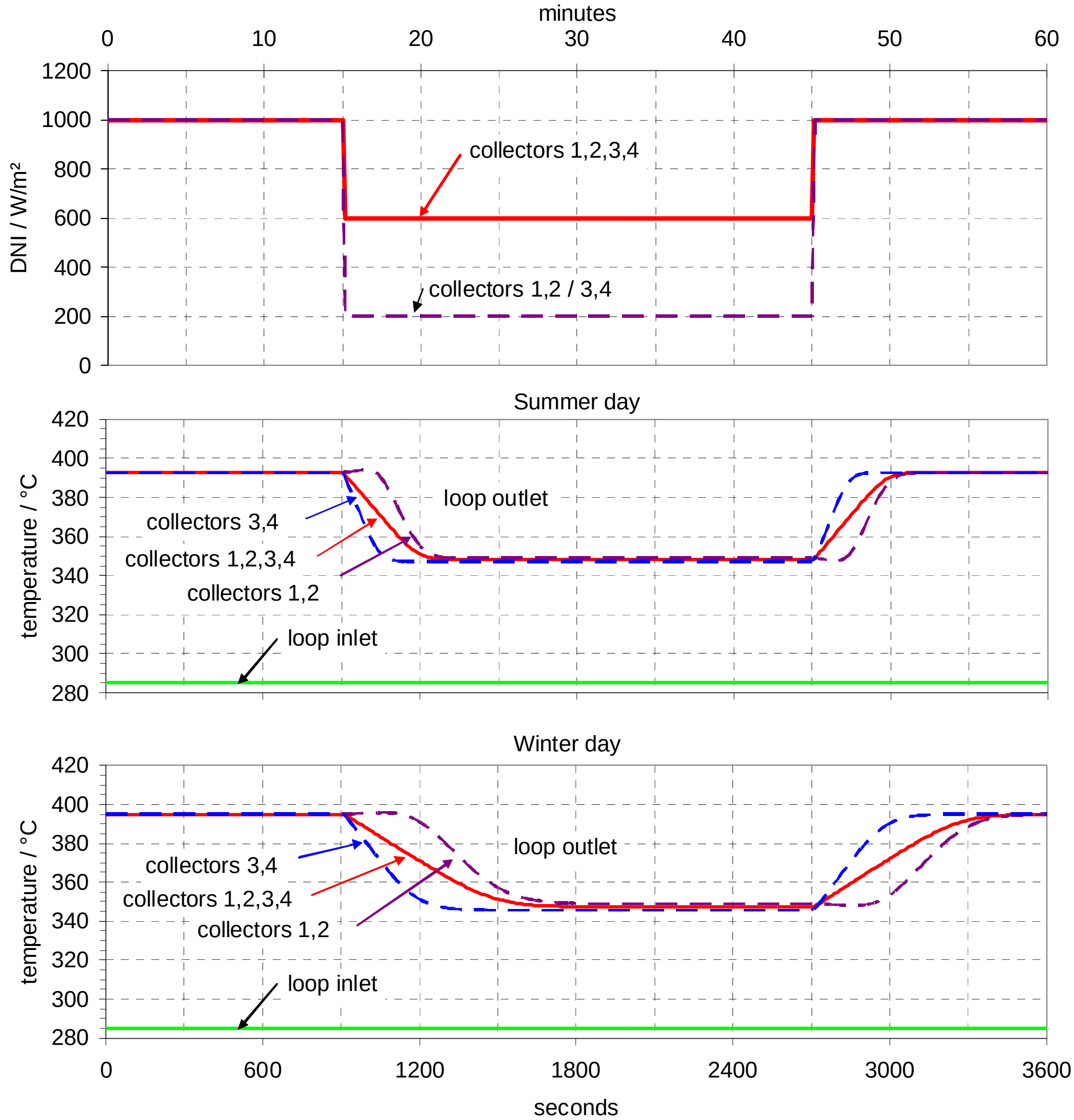

Fig. 5. Transient loop behavior under three artificial irradiance disturbances

Figure 6 shows a simulation for the winter day under measured irradiance disturbances (PSA, Feb 27th, 2002). It is assumed that the irradiance on the whole loop is homogeneous. The mass flow is kept constant during the simulation at a value of 4.4 kg/s. The loop inlet temperature is also set constant at 298 °C. The green temperature plot indicates the outlet temperature of one loop under this irradiance conditions. The large drop in irradiances results in outlet temperatures within a range of 30 K. The temperatures follow the DNI signal with a damping and a delay of several minutes. The blue line in the diagram indicates a field averaged outlet temperature. It is assumed that the irradiance signal is imposed on the most east and on the most west collector loop of the field. With a field extension of 1500 m and a signal speed of 4 m/s the time shift between east and west loop is 375 s. The simulation results for one loop are thus time shifted by 375 s and averaged with the original data to yield a field averaged value. The curve shows that the gradients become less steep and the overall range is reduced. A similar study for direct steam generation is described in [5]. Real signal speeds (speed of the traveling clouds) under normal weather conditions may reach much higher values in the region of 50 m/s. At 20 m/s, nearly no difference between the original and the time averaged curve can be seen (not plotted). This simple case study shows that the positive effects of field averaging on the oil temperature stability will only be small. Simulations for the summer day are not plotted here since the trends are similar.

The impact of oil temperature fluctuations on the plant performance can be summarized as follows. A decrease in oil temperature leads to modified operating points in the steam generator and the water-steam cycle with a reduction of the power block efficiency. A large impact may occur when the temperature drop reaches the operation limits of the power block. In this case, a temporary shut-down of the turbine would be required. The value of this limit strongly depends on the design of the power block. When using a thermal storage system the operational strategy has to define the tolerable temperatures for charging the storage. During a fluctuating irradiance period situations can occur where enough power for turbine operation and parallel charging of the storage is available. If the oil temperature does not reach the minimum value for storage charge some of the valuable energy has to be dumped or a fossil co-firing is required to stabilize the temperature. If irradiance goes up, the oil temperature may exceed the limit of about 395 °C. If the control system does not manage to keep the temperature below this limit, collectors have to be taken out of focus with a loss of energy.

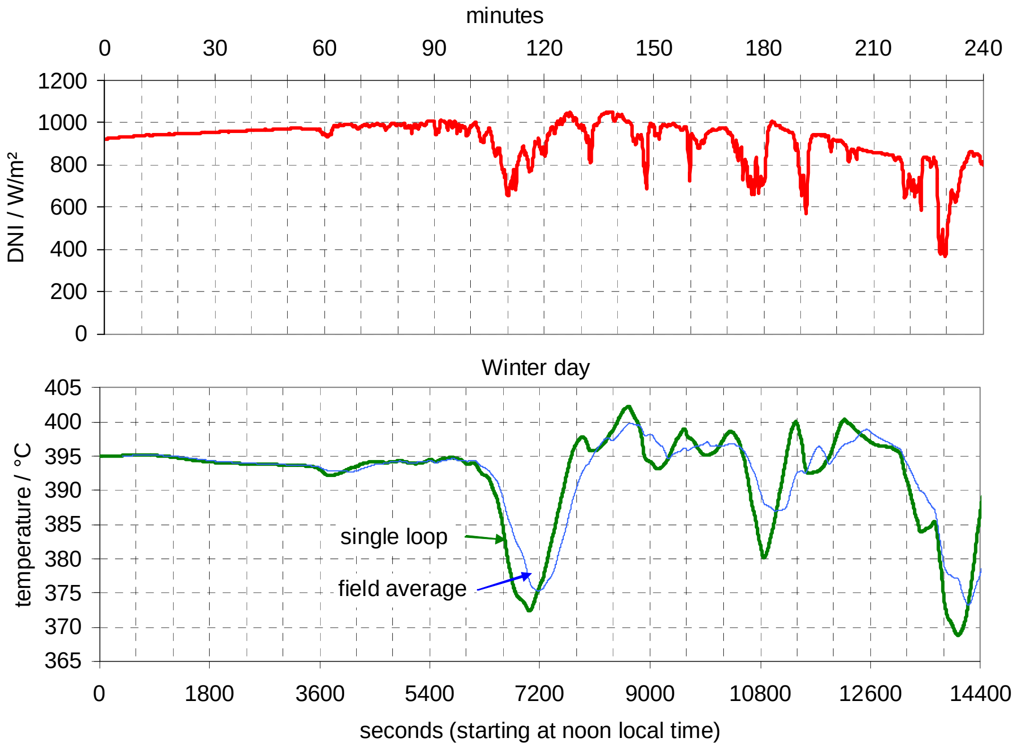

Fig. 6. Simulated loop and field outlet temperatures under a measured irradiance profile

Controlling the outlet temperature of an oil collector field is not a simple task due to the large delay times and a limited number of available actuators. The main control variable is the oil mass flow through the field. Figure 7 shows simulations with a constant mass flow as for the last two plots and with a controlled mass flow. The mass flow is controlled proportional to the irradiance with a dampening by a 1st order lag function with time constants 5 s and 120 s, respectively. The simulation results indicate a good performance of the fast adaptation of the mass flow with a time constant of 5 s. Transferred into practice, such a control would require full information of the irradiance along the collector and a very flexible pumping system that allows very large temporal gradients in mass flow. A second simulation with a less powerful pump (time constant of 120 s) reveals that a stabilizing effect is reached but with a quality worse than the one for the 5 s case.

Under this condition, the temperature fluctuations are in the range of 12 K. For the design of the collector field, these temperature fluctuations under normal operation have to be considered especially to define the operating points with a sufficient distance to temperature limits. It might be useful to define operating points (field outlet temperature) in dependence of the weather conditions. During clear sky periods, the temperature set point can be defined close to the defocusing limit while more safety margin should be considered for days with high variability in solar irradiance. Also the design of heat exchangers and power block should always consider that the oil outlet temperature does not remain on the nominal value. The higher the power block flexibility in this point, the less effort is needed in controlling the field temperature. As discussed above the short-term temperature fluctuations become important for the electricity yield as soon as strong non-linear effects like de-focusing or dumping occur. A systematic evaluation of the impact on the annual yield is analyzed in the German research project SESK [6].

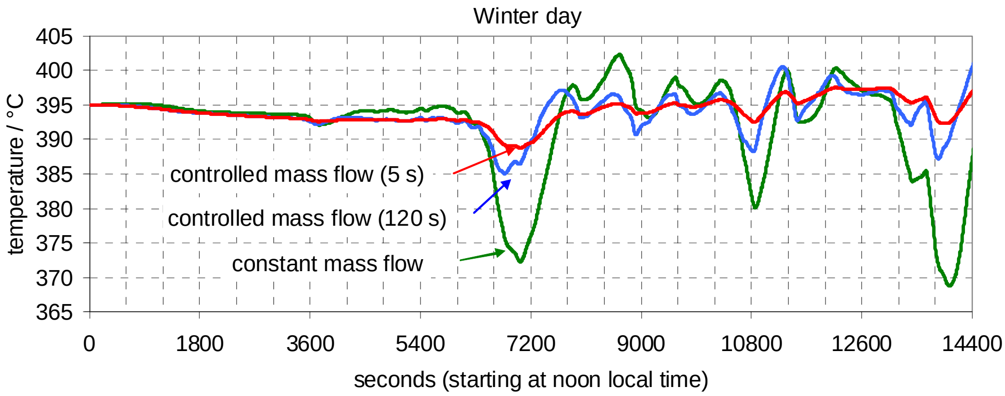

Fig. 7. Loop outlet temperatures with constant or controlled mass flow

4. Conclusions and Outlook

The paper illustrates two physical effects in oil based parabolic trough collector fields that have to be considered during the design of such a plant. Firstly, it is shown that the discrete nature of the focus state will lead to a temperature drop at the field outlet for overload situations. Measures to be taken may be to introduce a collector system with a continuous focus state or to equip a certain number of collector loops with control valves. While this overload performance is a steady-state effect, the oil temperature at the loop or field outlet will change as a result of fluctuations in direct irradiance. It is demonstrated, that significant temperature fluctuations have to be expected. This boundary condition has to be considered when designing the plant.

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