PRESSURE DROP ANALYSIS OF STEAM GENERATION PARABOLIC TROUGH PLANTS

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Abstract

Direct steam generation (DSG) in parabolic trough plants has the potential to be more cost-effective than oil based systems. The produced steam can directly be used for process heat applications. Within the P3 project such a DSG plant of 108 m^2 of Solitem's PTC1800 has been installed on the roof of the building of the company Alanod.

In the present paper, a two-phase pressure drop analysis of typical steam generation plants with different layouts is presented. A static model has been developed for this purpose. Parametric studies have shown that, due to the elevated pressure drops, the length of a collector loop within a DSG plant is limited. Consequently, in bigger plants collector loops need to be installed in parallel.

In each collector loop so-called Ledinegg instabilities occur. When collector loops are installed in parallel, there are additional flow instabilities. Those parallel flow instabilities occure due to shading of one or several collector loops. Changing pressure drops lead to an unfavourable reallocation of mass flows. In the worst case, steam is superheated and the collectors get damaged due to high temperatures. Ledinegg and parallel flow instabilities can both be reduced by installing an additional flow resistor at the collector loop's inlet.

1. Introduction

Direct steam generation (DSG) in parabolic trough plants represents a cost-effective alternative to conventional oil based or pressurized water based systems. The produced steam can either be used directly in industrial processes or to generate electricity. The present study concentrates on process heat applications.

Within the German project SOLDI the feasibility of direct process steam generation was demonstrated in the SOPRAN test facility at DLR Cologne [1]. Currently, in the project P3, a parabolic trough collector field is installed on the roof of a building of the German company Alanod, [2]. The field consists of 108 m² of PTC 1800 collectors developed and produced by Solitem. Saturated steam is produced and fed into a steam network.

Recent works by various authors show that flow instability problems will be faced also in solar applications. On the one hand, the typical Ledinegg instability in a single loop might occur, but also parallel flow distribution problems may occur [1, 3]. This paper presents stability analyzes for a process heat application in the pressure range of 5 to 15 bar.

2. Static modelling of the system

In order to examine pressure drops occurring in direct steam generation plants, a Matlab® model has been developed. The model is able to calculate two-phase pressure drops under steady-state conditions. In the following sections the layout of the model is described.

2.1 Model of the direct steam generation plant

An exemplary steam generation installation is shown in fig. 1. This installation is similar to the layout of the P3 project. Saturated steam at a pressure of 5 bar (T_{sat} = 151.8 °C) is produced. Liquid water enters the solar field (0) getting evaporated by the concentrated solar irradiation. Wet steam with the steam mass fraction x_n

leaves the solar field. In the steam drum water and steam get separated. Saturated steam leaves the steam drum, supplying the steam network, position s. The outlet pressure p_s is predetermined by the network. Separated water leaving the steam drum is mixed with feed water (f) and recirculated to the solar field via a pump, position z. The steam mass fraction at the outlet of the field is controlled by means of the recirculation mass flow.

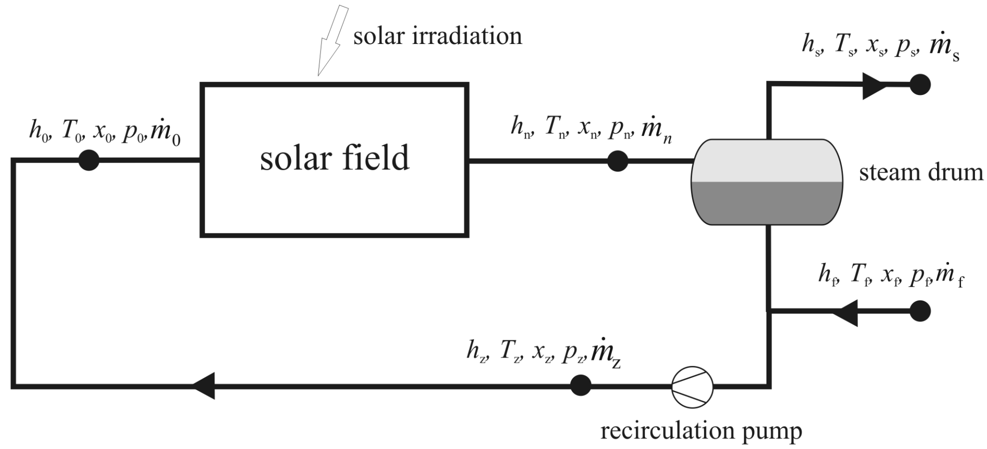

Fig. 1. Exemplary direct steam generation plant

2.2 Model of the collector loop

The solar field consists of 1 or more loops of several of Solitem's PTC 1800 collectors. One module has an aperture length of 5 meters and an aperture width of 1.8 m. Usually, 6 collector modules with a total length of 30 m are mounted on one tracking system. Parameters of the PTC 1800 collectors are given in table1.

aperture width	module length	absorber tube inner diameter d
1.8 m	5 m	0.0356 m
focal length	temperature range	optical peak efficiency η_0
0.78 m	150 - 250 °C	68 %

Table 1. Collector specifications

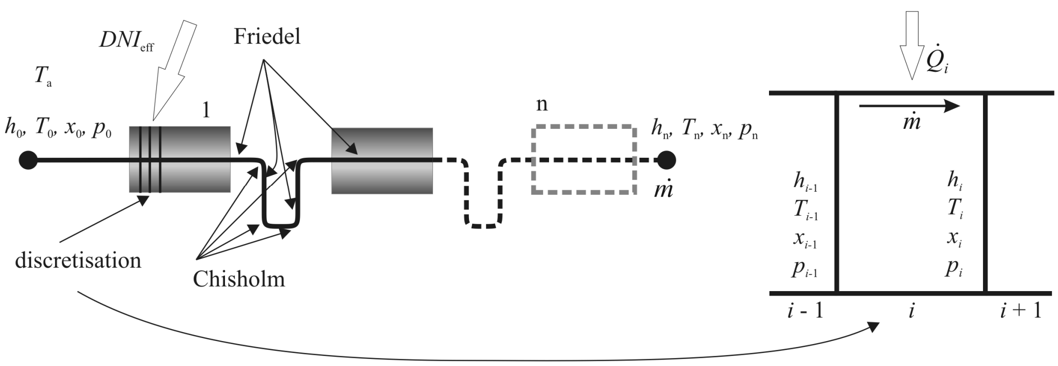

Fig. 2. Collector loop model

Fig. 2 shows a scheme of the collector loop model. There are n collectors with a length of 30 m. When several collectors are mounted in series ($n > 1$), flexible pipes are in between two collectors. In the model, these are represented as four 90 °-elbows with 5 straight pipes in between.

Pressure drops in the elbows are calculated with a correlation, proposed by Chisholm [4]. This pressure drop depends on the fluid's properties, mass flow and the ratio of radius of the bend and inner pipe diameter, *R/d*,

$$\Delta p = f(\dot{m}, d, R, p, x) \quad .$$

In the model, straight pipes are subdivided axially into control volumes. For the collector model, a discretisation of 15 elements in a 30 m collector has been used. The accuracy of the results cannot be significantly increased with a finer discretisation. Fig. 2 on the right shows element *i* of the discretisation. The fluid enters the element with the properties of element *i*-1. The fluid in the element has properties *i*.

The pressure drop in one control volume is calculated with a correlation proposed by Friedel [5]:

$$\frac{dp}{dz} = \frac{p_i - p_{i-1}}{dz} = f(\dot{m}, d_i, x_i, p_i)$$

where d_i represents the tube diameter of the element *i*. One has to acknowledge that the Friedel correlation was developed for smooth pipes. Hence, pressure drops tend to underestimate, since absorber tubes can get incrusted. For the dimensioning of a collector loop, pressure losses should be multiplied with an appropriate safety factor. By observing the control volume an equation for the fluid's enthalpies and the heat transferred into the element can be written as follows:

$$\dot{Q}_i = \dot{m}(h_i - h_{i-1}) = f(DNI_{\text{eff}}, IAM, \eta_0, T_i, T_{\text{a}}, A_i)$$

,where DNI_{eff} represents the effective direct normal irradiation, *IAM* the incident angle modifier, η_0 the optical peak efficiency, and A_i the aperture area of the element.. Heat losses of the absorber tube depend on the difference between fluid and ambient temperature (T_i and T_{a}). Optical efficiency and thermal losses are calculated with empirical correlations which are based on measurements in the DLR in Cologne [6]. Steam mass fractions at the inlet and the outlet depend on the fluid's enthalpy and pressure:

$$x_{i-1} = f(p_{i-1}, h_{i-1}) \qquad\qquad x_i = f(p_i, h_i)$$

3. Pressure drop as a function of a single collector loop's length and its outlet pressure

In the P3 project, a total of 60 m absorber tube is mounted in series. Possible layouts for further projects where more steam is to be produced have to be investigated. Hence, a first step is to investigate the impact of the loop length on the performance. For this purpose, the layout shown in fig. 1 is examined. For the simulations in this section the following hypotheses are applied

- Effective solar irradiance, pressure and steam mass fraction at the solar field outlet are parameters
- The saturated steam mass flow leaving the steam drum is always compensated by the feed water mass flow.

The solar field consists of one collector loop, composed of several collectors with 30 m length each. The number of collectors in the loop is varied in order to investigate the pressure losses and the maximal temperatures in the absorber tube. Table shows 2 the input values for the parameter study. Three different outlet pressures, 5, 10, and 15 bar are examined. Furthermore, for each pressure level three representative steam mass fractions are taken into account.

p_{n}	T_{a}	T_{f}	DNI_{eff}	x_{n}
5 bar, 10 bar, 15 bar	20 °C	100 °C	1000 W/m²	0.1, 0.15, 0.2

Table 2. Parameters for the maximal absorber tube length study

Results are shown in fig. 3. In the left diagram total pressure losses as a function of the collector loop's length are plotted. The diagram on the right gives the maximum temperature in the absorber tube. One can observe that, in this constellation, generally a lower steam mass fraction leads to higher pressure losses, since the recirculation mass flow is increased. A further conclusion is that higher outlet pressures reduce the absolute pressure drop. Obviously, higher outlet pressures entail higher saturation temperatures

As a third conclusion, the one might remark that with 5 bar outlet pressure the maximal temperature in the collector increases extremely with the collector length. The outlet temperature is always 151,8 °C due to the saturation pressure of 5 bar. However, with an absorber tube length of 210 m the maximum temperature would 175 °C, occurring near the collector loop's inlet where the saturation temperature is higher. This leads to higher heat losses. By increasing the absorber tube diameter pressure losses could be reduced but, on the other hand, heat losses rise due to larger heat transfer area. As a consequence, it is favourable not to exceed a certain collector length, but to mount several loops in parallel.

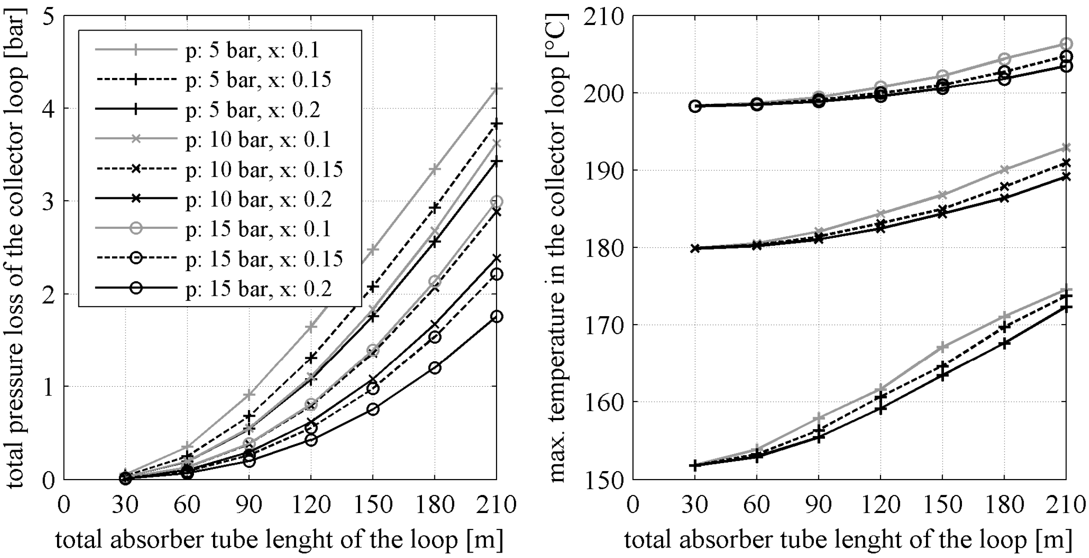

Fig. 3. Pressure drop and max. temperature as a function of the absorber tube length

4. Instable pressure drop behaviour

4.1 Ledinegg instabilities in a single collector loop

A flow instability in a single collector loop occurs if an increase of mass flow leads to a decrease in pressure drop. The normally continuously rising pressure-drop-mass-flow curve then shows a local maximum and an imposed pressure drop on a pipe system may yield two different mass flows. Under certain circumstances, the system can jump between these two states. This so-called Ledinegg instability [7] occurs especially in two-phase flow conditions, where the pressure drop is significantly influenced by the steam fraction. Also the solar steam generation can suffer from this problem as shown in the following.

The Ledinegg instability is analyzed using a single reference collector loop extracted from the solar field system. It consists of 2 collectors of 30 m each mounted in series. Under constant ambient conditions the inlet mass flow and the water inlet temperatures are varied resulting in a wide range of outlet steam conditions. Outlet pressure p_n remains constant. Input parameters are listed in table 3.

T_0	p_n	T_n	T_a	DNI_{eff}	solar field layout
10-150 °C	5 bar	151.8 (Tsat)	20 °C	1000 W/m²	1 loop of 2*30 m

Table 3. Parameters of the single loop pressure drop instability study

The results of the simulation are shown in fig 4 on the left side. With an inlet temperature T_0 of 150 °C, pressure drops increase with the augmenting mass flow. Lower inlet water temperatures lead to an unsteady pressure drop curve. From the left diagram in fig. 4, one reckons that 2 flows correspond to the same pressure drop. In combination with the fluid pumps characteristic the mass flow may turn out to be not controllable.

This is the case when a plus in pump power does not lead to an increase in mass flow. If the system falls into a configuration with small mass flow the steam is superheated in the collectors. When a certain temperature is exceeded collectors could be damaged. It can be clearly seen that critical situations occur at low inlet temperatures (at the given pressure). In a real system like the one in fig. 1 these temperatures can be reached if a small recirculation rate goes along with low feed water temperatures entering the system. Special attention has to be paid for the morning hours where the temperatures in the solar system are still low. The design and control system of the plant have to consider this aspect.

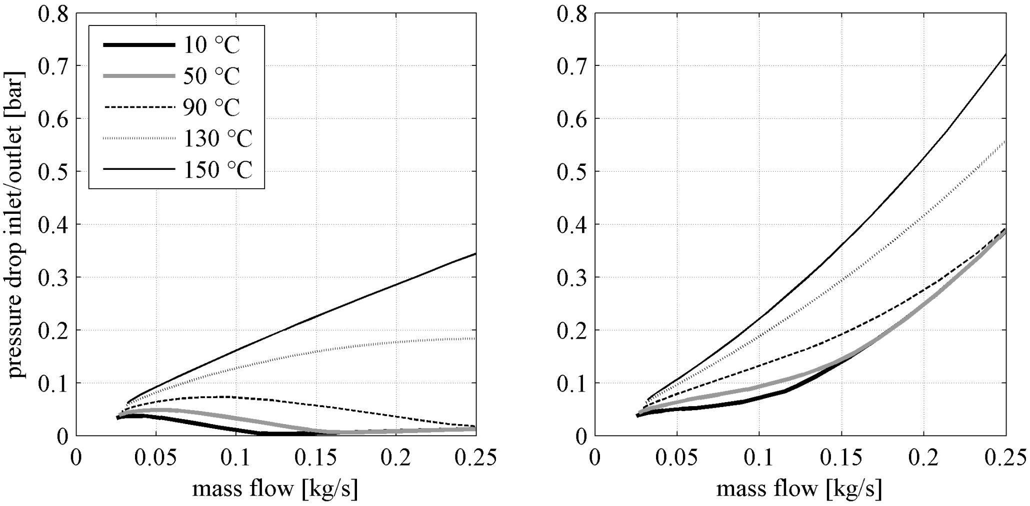

Fig. 4. Impact of a flow resistance on the pressure drop characteristics left: without flow resistance – right: with flow resistance of *j*=6

In once-through boilers of coal fired plants similar problems occur. For this reason, during start up mass flows and heat are controlled in such a manner, that instable pressure drops are avoided, [8]. In solar thermal power plants, boundary conditions such as ambient temperature and irradiation are not stable and cannot be influenced. An appropriate method to avoid pressure drop fluctuations is the installation of an additional flow resistor at the inlet (single phase flow) of the collector loop, as proposed in [1] and [9]. The pressure drop of the flow resistor is added to the pressure drop of the collector loop. Thus, a steadily increasing pressure drop characteristics is obtained. Flow resistors show a nearly parabolic pressure drop characteristics described with the equation.

$$\Delta p = \zeta * \frac{\rho}{2} * u_2^2$$

where ρ describes the density of the fluid. u_2 refers to the velocity of flow in m/s at the outlet and ζ describes the resistance coefficient. The flow resistor is installed at the collector loop's inlet where water is liquid. Its density is considered as constant and its flow velocity at the outlet equals the one at the inlet of the flow resistor, $u_2 = u_1 = u$. Pressure drops can also be expressed as a function of the mass flow rate multiplied with the resistance coefficient j.

$$\Delta p = j * \dot{m}^2 \qquad \text{mit} \qquad j = \zeta * \frac{8}{\rho * d^4 * \pi^2}$$

A parametric study has shown that for the considered installation values, pressure drop curves of the collector loop are strictly increasing for $j > 6$, see fig. 4.

4.2 Pressure drop instabilities in two parallel collector loops

As already outlined in section 3 a certain loop length should not be exceeded. Therefore, in this section a system of parallel collector loops is modelled, see fig. 5. These collectors are mounted in parallel. They are supplied by one common pump.

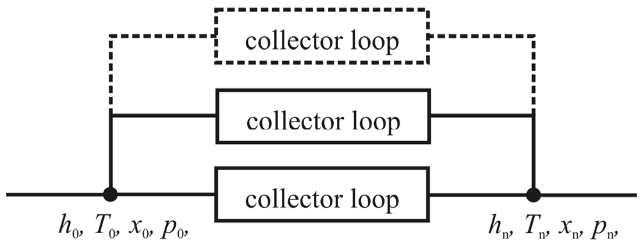

Fig. 5. Parallel collector loops

In the first study, a system of 2 parallel collector loops without hydraulic resistance at the inlet is examined. As in the previous section input parameters can be chosen independently. Inlet temperature T_0, total mass flow rate (sum for the two loops) and outlet pressure p_n is held constant. Since both loops are supplied with one pump their pressure drops have to be equal. The same mass flow will circulated through both loops provided that ambient conditions are exactly the same for both. However, it occurs that one collector is shaded while the other still is irradiated. Different steam mass fractions influence pressure drops and the mass flows gets redistributed. Fig. 6 shows such a scenario. In the upper diagram, pressure losses of a single collector loop and pressure losses of two collector loops in parallel are shown (double mass flow for the same pressure drop). The pressure drop curve of one single shaded collector is plotted, as well. As a third configuration, the pressure drop of two loops in parallel with one of them shaded is plotted. Parameters are listed in table 4.

The pressure drop of the two-loop system with one loop shaded is very low compared to the two-loop system with both loops irradiated. This indicates a strong mass flow maldistribution with a high mass flow in the shaded and a small mass flow in the heated loop. The mass flow distribution can be derived from the diagram in the following way. We suppose that the effective *DNI* is 1000 W/m² for both loops (a and b) and the initial mass flow is 0.3 kg/s for each collector and hence 0.6 kg/s for both (c). A steam mass fraction of 0.1 is obtained. If one collector is shaded and the mass flow is held constant pressure drops decrease from almost 0.4 bar to 0.06 bar (d). We obtain the new mass flow of the irradiated collector in point e, 0.03 kg/s. The mass flow of the shaded collector is thus 0.57 kg/s. In the diagram below the new steam mass fraction of the irradiated collector of 0.98 can be read.

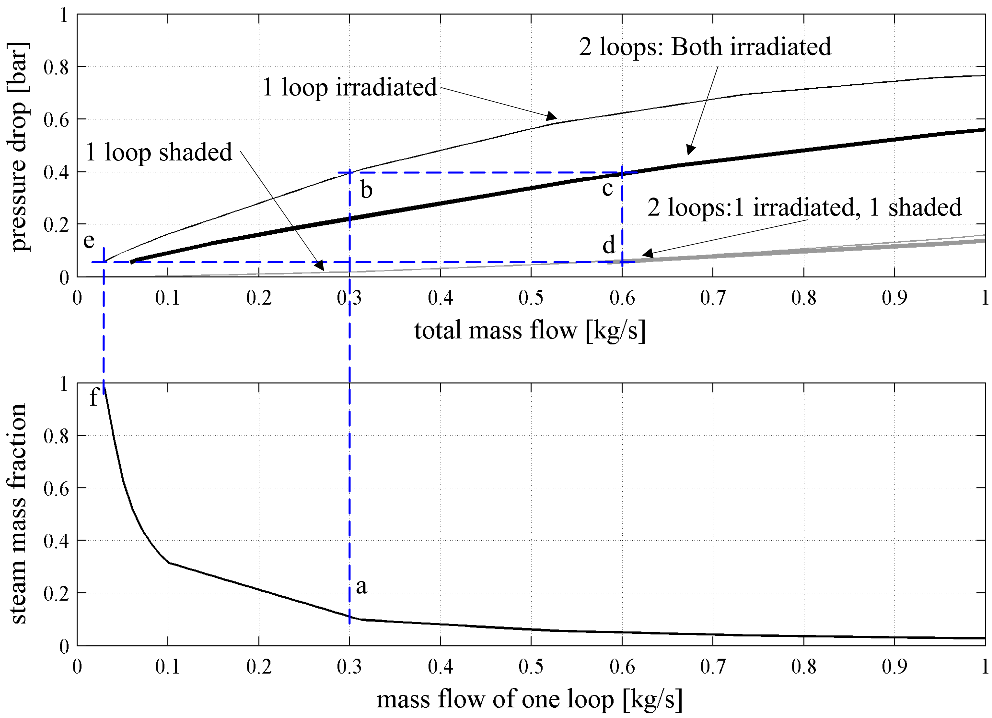

Fig. 6. Parallel flow instabilities: 2 parallel loops without flow resistor at the inlet

It gets obvious that in this constellation the solar field is not optimally designed. Shaded collectors are flown through by more water than irradiated ones. Due to the low mass flow in the irradiated collectors, the steam mass fraction is close to 1. In the above example, if the original mass flow was slightly lower than 0.6 kg, superheated steam would be produced in the irradiated loop. In the worst case, the collector could be damaged when the maximum temperature is exceeded. The inhomogeneous mass flow repartition would be exacerbated if 3 or more collectors were installed in parallel.

T_n	X_0	p_n	T_a	DNI_{eff} irradiated	DNI_{eff} shaded
150 °C	0	5 bar	20 °C	1000 W/m²	0 W/m²

Table 4. Parameters for the parallel flow study

In order to cope with the unfavourable mass flow repartition, the simplest solution is to add a flow resistor at the inlet of each loop. The pressure drop difference between an irradiated and a shaded collector is then lower. The two-phase pressure losses then only account for a part of the pressure losses of one loop. In a second parameter study 10 loops of 2 x 30 m are mounted in parallel in the collector field. At each row inlet, a flow resistance with the resistance parameter $j = 6$ is installed. On all accounts such a flow restrictor is required in order to cope with Ledinegg instabilities as discussed in the last section. Boundary conditions are the same as in the study above, see table 4. In order to choose an extremely unfavourable case, initial steam mass fraction shall be 0.2 which leads to a mass flow of 0.21 kg/s for each loop, see fig. 7. If 9 out of 10 collectors are shaded (bold grey line), applying the same method as in fig. 6, we obtain a new mass flow of 0.14 kg in the irradiated collector loop. The steam mass fraction is 0.27 which is acceptable. Superheating of steam will not occur.

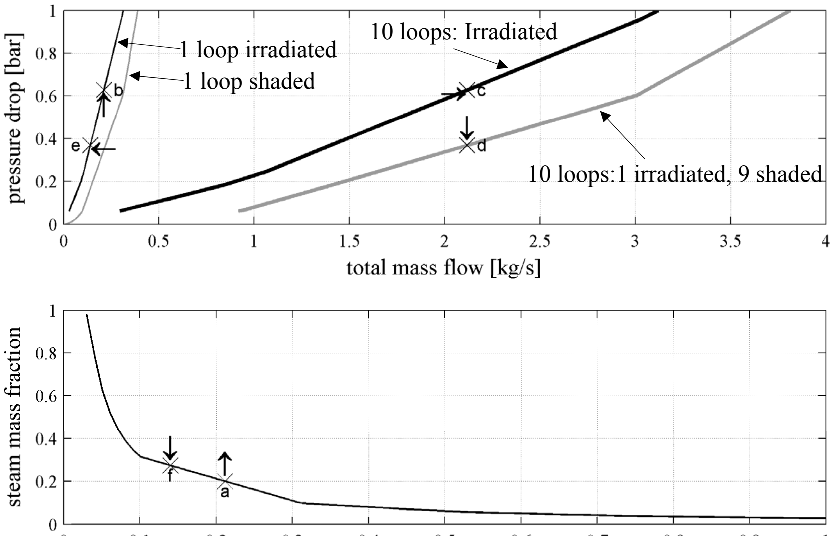

Fig. 7. Parallel flow instabilities: 10 parallel loops with flow resistor at each inlet

The study above shows, that with the installation of a simple flow resistor at the loops' inlet the impact of parallel flow instabilities can be reduced. Even if several collectors are shaded, steam will not be superheated in irradiated loops. With the simulation tool developed the necessary resistance value of the flow restrictor can be determined.

Nevertheless, the mass flow repartition in the collector loops is not optimal. When collectors are fully shaded, water is still circulated. Heat and pressure losses occur, reducing the overall performance of the solar field. In order to cope with this problem, controlled valves could be installed at the inlet of each loop. When collectors are shaded, water mass flow could be reduced in the respective loops. Due to lower pressure losses the circulation pump's electricity consumption is reduced. Continuative economic studies have to show if such an installation of controlled valves is justified from an economic point of view.

5. Conclusion

A static Matlab model of a direct steam generating parabolic trough plant has been developed. The main purpose of the model is to represent two-phase pressure losses.

A simulation of a typical solar plant for process heat applications has shown that the length of a single collector loop is limited due to pressure losses. Saturation pressure at the loop's inlet is higher than the pressure at the outlet. As a result, the maximum steam temperature is attained near the inlet of the loop. This behaviour entails more elevated heat losses and hence a lower collector efficiency. Therefore, it is wise to install collector loops in a hydraulically parallel alignment.

More detailed examinations of single collector loops reveal that with low inlet temperatures, so-called Ledinegg instabilities occur. These can be avoided by installing a flow resistor with a parabolic pressure drop characteristics at the loop's inlet. The pressure drop of the flow resistor is added to the two-phase pressure drop in the absorber tubes and a steadily increasing pressure drop characteristics curve can be obtained.

Simulations of parallel collector loops show that, due to shading, parallel flow instabilities occur. The redistribution is counterproductive since irradiated loops turn out with less mass flow. Flow resistors required for Ledinegg compensation help to reduce this effect to a tolerable extend. Though, an ideal flow distribution can only be obtained by installing flow control valves at the entrance to each collector loop.

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