Investigation of the Reduced Performance of a Collector Array with Direct-Flow Vacuum Tubes

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Abstract

TU Berlin and ISFH investigated the reduced performance of a collector array with direct flow vacuum tubes and an aperture area of 258 m². A transient simulation of the collector loop has been performed using the TRNSYS software package. The simulation showed that the measured daily energy gain is only 60% of the gain indicated by the simulation. Measurements showed partial stagnation in several collectors of the array where the outlet temperature of single vacuum tubes fluctuates between the collector loop temperature and the boiling temperature of the fluid.

The process of partial stagnation was investigated in detail at the ISFH. The results indicate no significant reduction in collector efficiency under partial stagnation. The main cause of partial stagnation is the reduced volume flow, thus indicating hydraulic problems in the investigated collector array. A reduction in the volume flow can reduce the collector efficiency due to an internal thermal coupling in the coaxial absorber pipes.

Infrared photography indicated problems with the vacuum of several tubes as well as damage in the pipe insulation. By integrating the detected reduction factors in the simulation model, the measured collector gain shows good accordance to the simulated collector gain. The results point out the importance of a purge system in vacuum tubes as well as the need to improve the hydraulic layout of the whole collector system.

1. Introduction

In a project funded by the German Federal Ministry for Environment, Nature Protection and Reactor Safety (FKZ0329283A) the performance reduction of a solar collector array consisting of direct flow vacuum tubes with a total aperture area of 258 m² is examined. The collector array is installed on the roof of an office building of the Federal Press Office in Berlin (BPA). Its primary task is to generate the heat for two absorption chillers each with a heating load of 44 kW with a driving temperature of the generator of about 80°C. Previous work showed that the outlet temperature of several tubes can reach high levels, so that boiling has to be assumed in the tubes, although the collector loop temperature is far below the boiling temperature [1]. Since the evaporation is only temporary and localized, it is called partial stagnation.

Partial stagnation indicates problems in the hydraulics of the collector array. Theoretical calculations have shown that the hydraulic layout of the collector groups as well as the one-sided connection of two collectors cause an uneven flow distribution [2]. However this theoretically determined non-uniform flow distribution is not enough to cause partial stagnation. Further investigations with regard to the hydraulics, as well as the influence of a reduced volume flow on the collector performance, were examined.

2. Investigations

2.1. Transient simulation of the collector array performance

In order to evaluate the performance of the collector array, it is necessary to fulfil certain criteria while comparing the measured and expected collector loop heat gain against each other. Normally, the measured heat gain is only valid after a certain steady state condition is reached. Especially in large systems, the thermal inertia of the system components (collector, pipes, heat transfer fluid between the temperature sensors) has major effect on the measured collector loop heat gain. Thus, the reason for the transient simulation of the system performance was to consider also the dynamic processes in the collector loop.

The thermal capacities of the collectors and pipes were modelled by using a capacity node. The time period a single fluid element needs to go through the collector loop once was taken into account by the PIPE type. Heat loss of parallel pipes in the collector array were modelled by a heat loss node [3] which was characterized by a specific heat transfer coefficient UA in W/K.

For the simulation, the weather data, as well as the collector loop input temperature (t_c) and the volume flow rate (V_K) are given to the simulation model from measurement data. Figure 1 shows the simplified deck file of the TRNSYS simulation model.

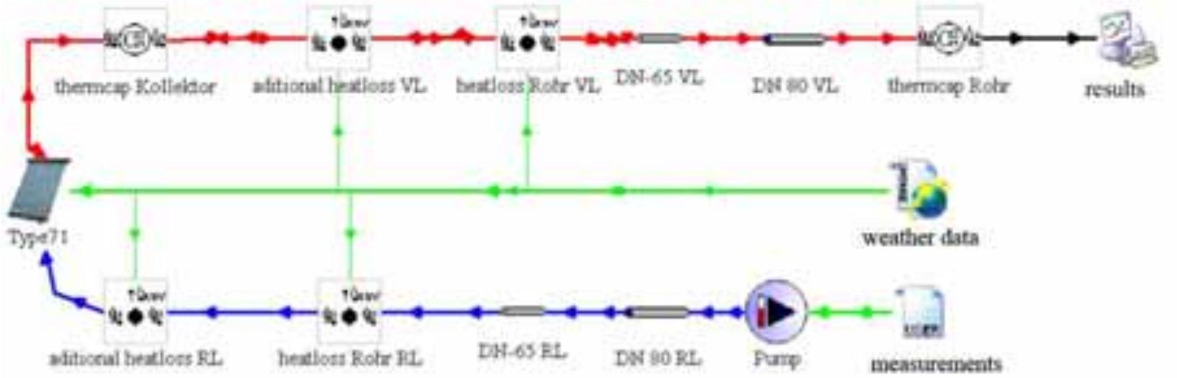

Fig. 1. Simplified deck file of the TRNSYS simulation model.

Output of the simulation is the fluid temperature exiting the collector loop (t_h). With this temperature, the simulated collector loop heat flux can be calculated.

Figure 2 shows the diurnal profile of a typical clear summer day. After the warming-up period, the first absorption chiller was turned on at around 11:20 and the second absorption chiller at around 12:00. Each time a chiller was started, a plug of cold fluid started to flow through the solar loop causing the temperature t_{Kc} to drop sharply. While this plug of cold fluid was running through the collector loop, the value of the measured heat gain had high amplitudes.

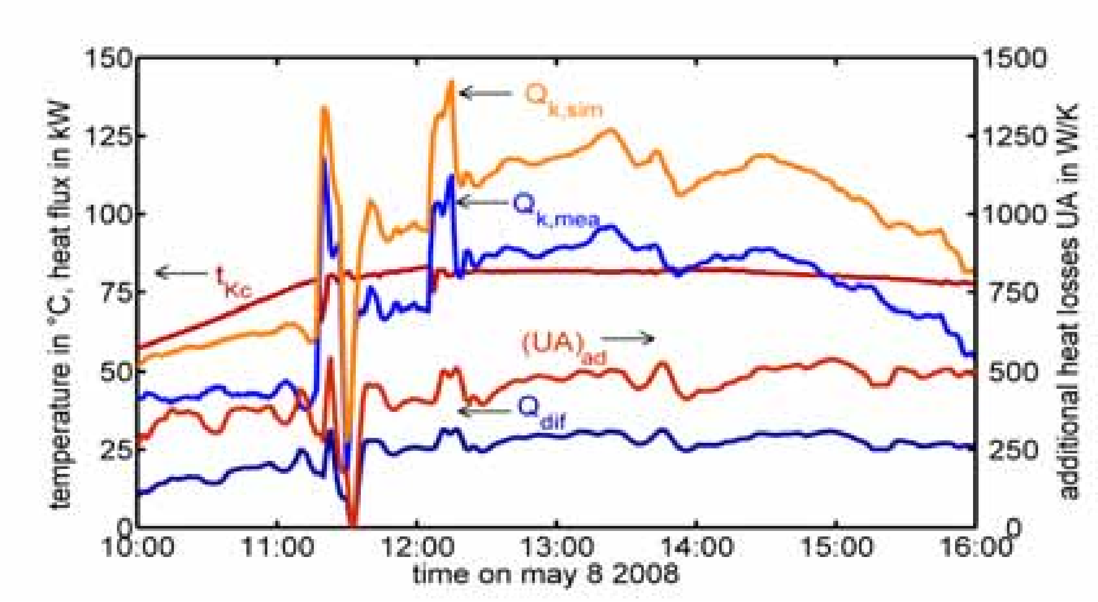

Fig. 2. Diurnal profile of the heat flux simulated ($Q_{k,sim}$) and measured ($Q_{k,mea}$) , heat flux difference (Q_{dif}) and the derived additional heat loss coefficient $(UA)_{ad,}$

The value of the simulated heat gain shows these amplitudes with the same magnitude. The difference between the measured and the simulated heat gain (Q_{dif}) indicates additional heat loss in the collector loop. Assuming that this heat loss is caused by transmission over a constant area, an additional loss factor is developed, as expressed by the following equation:

$$(\mathrm{UA})_{\mathrm{ad}} = \frac{\mathrm{Q_{dif}}}{\mathrm{T_K} - \mathrm{T_A}} = \frac{\mathrm{m.\,c_{PLS}}\left(\mathrm{t_{K,out\_sim}} - \mathrm{t_{K,out\_mes}}\right)}{\mathrm{T_K} - \mathrm{T_A}} \tag{1}$$

Where T_K is the mean collector loop temperature, T_A the ambient temperature, m the mass flow rate, c_{pLS} the heat capacity of the fluid, t_{K,out_sim} the simulated outlet temperature and t_{K,out_mes} the measured outlet temperature of the collector loop.

This loss factor reaches values of up to 500 W/K.

2.2. Investigation of partial stagnation in a test collector and in the collector array.

Since the causes for the occurrence of partial stagnation in the collector array as well as their influence on the efficiency were not known, detailed experiments were carried out with an outdoor test collector at the ISFH.

Partial stagnation occurs when the absorbed heat in the collector cannot be discharged sufficiently by the collector loop fluid so that the fluid temperature reaches the boiling point. Thus the main causes for reaching the boiling condition are a low volume flow rate, a high temperature level and high solar irradiance.

Furthermore, it can be provoked by a non-uniform flow distribution in the collector since tubes with a decreased volume flow rate reach a higher temperature level. High gas contents in the fluid might lead to desorption in the collector. Desorbed gas bubbles in the small cross sections of the pipes in the vacuum tubes lead to further hydraulic losses. In this case, the horizontal position of the vacuum tube is important for stagnation behaviour. If the tubes have a negative inclination (header lower than the tubes) desorbed gas bubbles would accumulate at the top end of the collector tube, which results in a blockage of fluid flow. This blockage leads to an efficiency reduction since the affected tubes cannot generate any collector yield.

At horizontal collector slope (orientation at the BPA) the measurements show no efficiency reduction during partial stagnation. Only at very high inlet temperatures (around 120°C) and low mass flow rates (around 200 kg/h) the partial stagnation might pass over into full stagnation and thus provide any heat generation in the whole collector. However, these extreme conditions are very unlikely for the BPA system. A detailed presentation of these investigations can be found in another paper of these proceedings [4].

Neither the measured temperature and pressure level or the gas content in the collector loop at the BPA can cause partial stagnation. Since the effects of partial stagnation (collector tube outlet temperatures close to the boiling temperature) can still be measured, the volume flow rate in parts of the collector array must have been reduced dramatically.

2.3. Reduction of the collector efficiency due to a reduced volume flow

A reduction in efficiency due to a reduced volume flow in direct flow vacuum pipes with a coaxial tube is caused by a coupling effect. The coaxial design causes a heat transfer from the outer to the inner tube which preheats the incoming fluid and cools down the fluid in the outer tube. Therefore, the highest fluid temperature can be reached before the outlet of the collector tube. The mean temperature of the absorber is higher than the average temperature between inlet and outlet of the collector. Higher temperatures inside of the collector tube cause higher heat loss to the environment than predicted by the average in- and outlet temperature. This difference increases with lower volume flow rates. At a flow rate of 31 kg/m²h, the efficiency is reduced by about 10%. A model to calculate this coaxial effect as well as the experimental validation of this model is presented in [5].

2.4 Hydraulic investigation of the collector array

The occurrence of partial stagnation indicates problems in the hydraulic system which is caused by a reduced volume flow in parts of the collector array. Possible causes for such a volume flow reduction could be:

- Uneven flow distribution of collector groups due to a bad hydraulic layout
- Uneven flow distribution in the collector due to a one-sided connection
- Local pressure drops due to plugging of pipes with gas or sludge

The uneven flow distribution of the 20 collector groups had previously been a problem of this system. Although the parallel collector groups had been connected according to the “Tichelmann” principle, an equal flow distribution could not be realized, and balancing valves had to be installed. Fig. 3 shows the measured group volume flow in the current system. With a total flow rate of 20 m³/h, groups 1 to 19 should have a flow rate of 1000 l/h. The last group (20) is split in two equal sub groups and the balanced flow rate here should be 500 l/h. Except for collector group 13 the deviation from the mean group flow rate is in an acceptable range of less than 10 %.

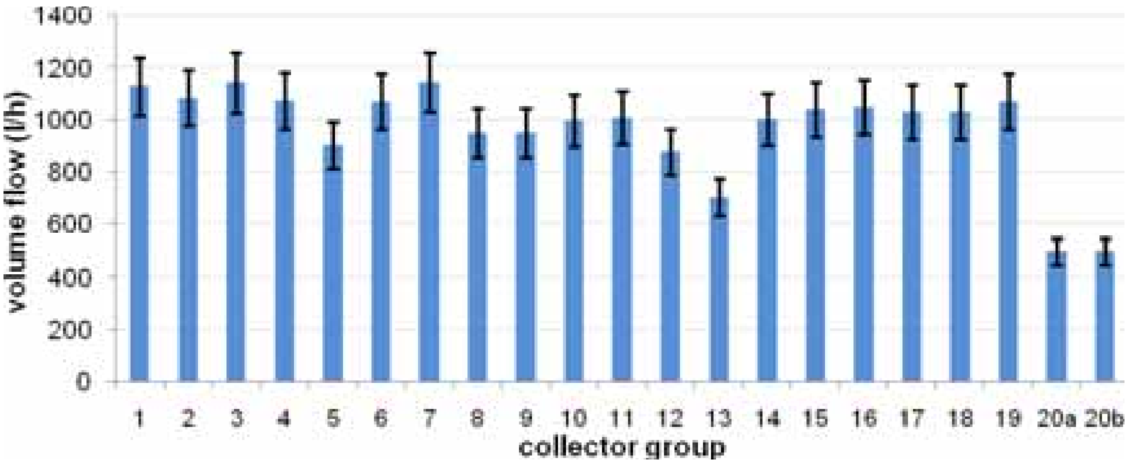

Fig. 3. Volume flow in the collector groups after the installation of the balancing valves.

Bigger variations have to be found inside the collector groups, but direct measurements of the flow rate was not possible here. Instead, the temperature at the outlet of the vacuum tubes was measured with clamp-on sensors. Fig 4 shows these measurements during the day (left) and during the night (right) in collector group 11. One collector group consist of two pairs with a one-sided collector connection. The 60 tubes on the inside pair are named Ri1 to Ri60 and on the outside pair Ro1 to Ro60. Ri1 and Ro1 are situated on the side of collector in- and outlet. During the day, only tubes from the outer collector pair have shown the typical temperature fluctuation of partial stagnation. During the night measurements, the collector circuit was heated with district heat. Here it can be seen that the last tubes in the outer collector pair have a significant lower outlet temperature.

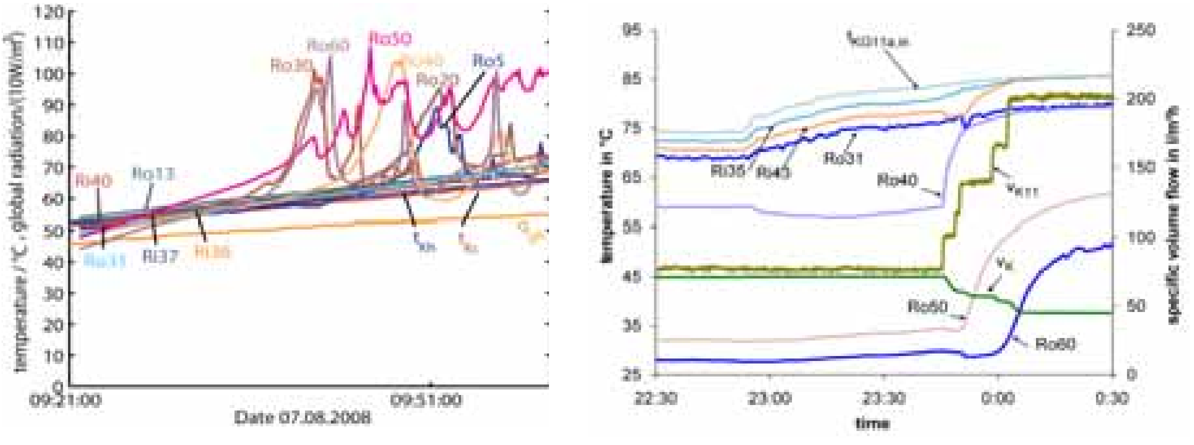

Fig. 4. Temperatures at the outlet of the vacuum tubes in collector group 11 during day (left) and night (right). .

At 23:45, the volume flow rate was increased in the collector group by closing the balancing valves in the other collector groups. The outlet temperature in the last vacuum tubes increased, but even at a specific volume flow rate of 200 l/m²h, the difference to the mean outlet temperature remains high. As the real flow rate in the vacuum tube could not be determined precisely, a significant reduction in the pipe volume flow was assumed. This could be caused by sludge and solid particles which can easily be accumulated in the collector tube due to the low velocity in the laminar flow region. Single tubes have been removed for further inspection. A significant amount of deposits could only be found in collector tube pipes which show no partial stagnation behaviour during the day. The turbulent two phase flow probably contributes to the cleaning of the pipe. The last collector header of the outer collector pair was exchanged and cut open. No clogging in the header pipe was found.

2.5. Detection of additional heat losses in the collector loop with thermal imaging

In order to detect additional heat loss in the collector loop, thermal imaging was used. Since high temperature differences in the environment make it difficult to evaluate the thermal images during the day, the infrared photographs were taken during the night while the collector loop was heated with district heat. Several areas of damage in the pipe insulation were detected. In the curves, the cover of the insulation was not tight so that rain water would have penetrated and wetted the insulation (Fig5, left). The total area of the defected insulation was estimated so that an additional heat loss coefficient similar to equation (1) could be developed.

The thermal images also detected differences in the surface temperature of the collectors (Fig 5, right). In the first place, these temperature differences were caused by a varying quality of the vacuum inside the glass envelope of the collector. In the second place, these temperature differences point out differences in the flow distribution in the collector array. Several tubes with high surface temperatures during the night test were taken out of the array and their thermal behavior was tested in the lab. Heat loss coefficients for every tube were measured. Details of the experiments as well as possible causes for the vacuum deterioration are described in [6].

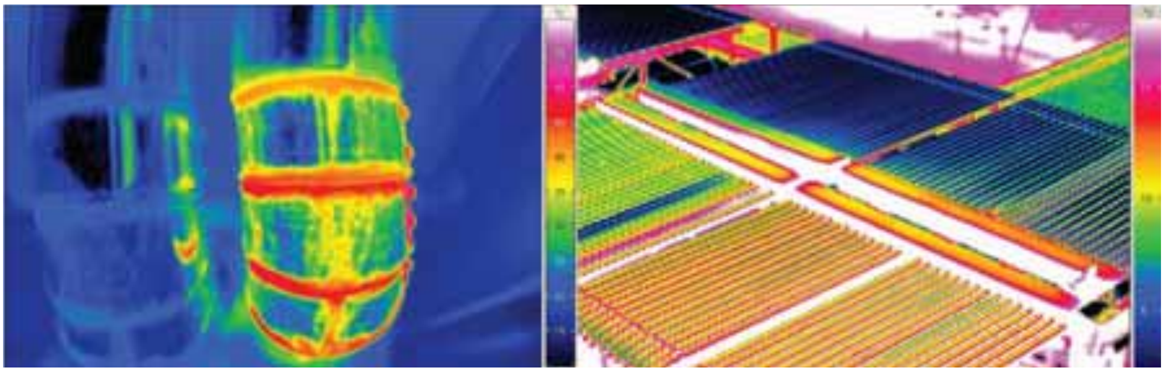

Fig. 5. Infrared photography in thermal reverse mode during night showing damages in the pipe insulation (left) as well as vacuum loss in the collector tubes (right).

3. Conclusion

The performance reduction of a vacuum tube collector array can be determined with a TRNSYS simulation. Experiments on the partial stagnation behavior showed that the collector efficiency is not reduced by this effect. But partial stagnation in the collector array indicates drastically reduced volume flow rates in parts of the collector array. The effects of the vacuum deterioration as well as the uneven flow distribution on the efficiency of the whole collector array were quantified using measurements and calculations. The implementation of all the determined additional performance reductions into the simulation model showed a good agreement with the measured collector loop performance. The biggest contribution (65%) to the performance reductions has been attributed to the reduced vacuum in most of the collector tubes due to a missing getter. A lower collector efficiency due to a reduced volume flow rate accounts for about 22% of the additional loss. The damages in the pipe insulation contribute 9% and tubes with a broken glass 4 % to the additional heat loss.

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