MONITORING AND FAILURE DETECTION FOR LARGE SCALE SOLAR THERMAL SYSTEMS: A SIMULATION BASED APPROACH

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1 Kurzfassung / Abstract

1.1 Abstract - English

Long-term monitoring and failure detection of solar thermal systems is important to assure that a system is functioning well and to realize the expected solar gain. A large share of possible failures will not be found easily without using a long-term monitoring method.
Several approaches for long term monitoring, failure detection and failure identification have been developed during the last decade(s). Seven methods are shortly described in this paper. These include monitoring with manual analysis of the data by an expert. This can be very effective, but is very time intensive and therefore costly. An automated method can make data analysis faster and cheaper, but an accurate detection and identification of failures can be difficult.
At Kassel University a monitoring method for large solar thermal systems was developed, in which a function control step and a simulation based step are integrated. The method is able to detect several failures and to identify some of them. However, further development of the method is planned for implementation and testing of more types of solar heating systems and to increase the effectiveness. The dynamic simulations, failure detection and failure identification will be thoroughly validated against measured data.

1.2 Kurzfassung - Deutsch

Eine Langzeitüberwachung bei solarthermischen Anlagen ist unerlässlich um eine einwandfreie Funktion und so das Erreichen des zu erwartenden Solarertrags sicherzustellen. Anders kann ein großer Teil der möglichen Fehler kaum erkannt werden.
In den letzten Jahrzehnten wurden eine Reihe von Methoden für die Langzeitüberwachung, Fehlerdetektion und Fehleridentifikation entwickelt. Sieben dieser Methoden werden in diesem Beitrag kurz beschrieben, darunter die manuelle Auswertung der Daten durch einen Experten. Diese Methode kann sehr effektiv sein, ist aber zeitintensiv und daher teuer. Eine Automatisierung der Datenauswertung kann schneller und günstiger sein, allerdings ist hier die korrekte Fehlerdetektion und -identifikation schwierig.
An der Universität Kassel wurde eine Überwachungsmethode für große thermische Solaranlagen entwickelt, die zusätzlich zu einer statischen Funktionskontrolle eine Kontrolle anhand dynamischer Systemsimulationen vorsieht. Mit dieser Methode können viele Fehler detektiert und zum Teil auch identifiziert werden. In einem nächsten Schritt sollen weitere Anlagenschemata integriert sowie die Effektivität der Fehlderdetektion und die Möglichkeiten der Fehleridentifikation verbessert werden. Die Ergebnisse der dynamischen Systemsimulationen sowie die Fehlerdetektions und -identifikationsalgorithmen sollen mit Messdaten validiert werden.

2 Introduction

Long-term monitoring and failure detection for solar thermal systems is getting more and more important, since reliable systems are essential for a rapidly growing market. Failures and malfunctions are likely to occur during the 25 year operating time of a solar heating system, resulting in energy and economic losses. Solar thermal systems are complex and therefore malfunctions or a non optimal performance of the system are not easily noticed. Due to the auxiliary heating, warm water will be available regardless if the solar thermal system is functioning or not. Furthermore several parameters, like hot water demand and weather conditions, may be different than anticipated. Therefore projected yearly energy yields can differ a lot from measured ones. Monitoring and failure detection approaches can increase the reliability of a system and reduce down times and energy losses.

Since the 1990's several monitoring and failure detection methods for solar heating systems have been developed. An overview and short analysis of methods for long term monitoring of solar thermal systems is presented in Section 3. In Section 4 a method for monitoring and failure detection developed at Kassel University will be presented and discussed. Plans for future work are presented.

3 Overview of Methods

Several approaches for monitoring, failure detection and failure identification have been developed during the last decade(s). In Table 1 several methods for long term monitoring are listed. There are large differences between the methods in e.g. costs, what type and size of system they are developed for, accuracy and effectiveness. Several methods are still in the development stage and experience has to be gathered if they are applicable to other system hydraulics and how good the detection efficiency really is.

Table 1 – Overview of monitoring methods

Method	*Abbr.*	*Description*	*References*
Manual Monitoring (Optisol used as state of the art)	MM	Automatic monitoring but with manual analysis of measurements	(Fink *et al.*,2006)
FUKS, FAUSOL	FC	Cheap function control	(Altgeld and Mahler,1999)
Spectral Method	SP	Based on temperature gradients	(Grossenbacher,2003; Synetrum AG,1998)
Artificial Neural Networks	ANN	Based on simulation with artificial neural networks	(Kalogirou *et al.*,2008)
Input-Output Controller	IOC	Simulation based, only solar circuit (so far)	(Pärisch and Vanoli, 2007a ; Pärisch and Vanoli, 2007b)
Guaranteed Solar Results	GRS	Simulation based	(Luboschik *et al.,*1997; Peuser *et al.*,2002)
Kassel University	KU	Function control and simulation	(Wiese *et al.,*2007; Wiese,2006)

Monitoring with automatic data logging, but with data analysis by an expert can be very effective in finding malfunctions or failures, but is often time-intensive and therefore costly. This method has been extensively used in demonstration and research projects. A good example is the Optisol project, in which 8 demonstration solar thermal systems with a collector area between 30 and 250 m^2 were monitored for a year. In the first two months a so called optimization phase was carried out. Many failures and weak spots were found in installation, design or operation. These were, for example, air inside a parallel collector circuit, failures concerning integration and operation of conventional heating and an unnecessary large heated volume in the storage unit, part of the malfunctions were connected to the auxiliary heating. In the routine supervision the fundamental system functions were monitored and monthly energy balances were prepared for a year. Key values were calculated and compared to those in the planning phase. The optimisation phase is very effective, but costly since all analysis is done by an expert. The routine supervision gives an indication of the performance, but it is too inaccurate to point out minor failures.

The function control without heat measurements (FUKS) developed by Altgeld *et al.*, was developed for small systems (~5 m^2 collector area) and for integration in a controller. Because there are no heat and pressure measurements integrated in the method, the costs are expected to be low (~100 Euro). 4 algorithms were developed for the detection of 15 different malfunctions. With extra measurements (e.g. pressure), 3 more algorithms could be used. As an example, one algorithm checks if the temperature difference between collector and storage is too high. In the test phase several failures could be detected, however in the initial integration in two controllers the method resulted in several failure indications where there was none.

The spectral method (SP) is based on analyzing the transient temperature changes in the collector circuit after the pump is starting. Temperature signals on a secondly basis are transformed with a Fourier transformation in the spectral range. In a failure free training phase specific vectors for specific situations are deducted. Only one extra temperature sensor is necessary about a meter after the collector exit in the collector pipe. Several larger failures could be recognized, especially in high flow systems. These are e.g. a 40 % reduction of collector performance, a 20 % change in pump power and air in the heat exchanger. However, a failure free training phase of at least half a year is necessary and that may be difficult or impossible.

The development of a neural network-based fault diagnostic system for the solar circuit (ANN) is still in a research phase. The method consists of three steps. In the prediction module, artificial neural networks are trained with fault-free system operating data obtained from a TRNSYS model. The model is trained so that 4 temperature values (collector in and output and storage in and output) can be predicted for different environmental conditions. The input consists of weather data (global and beam radiation, ambient temperature, incidence angle, wind speed, relative humidity, flow availability and inlet temperature), together with one of the other measured temperature values. In the second step residual values, which characterize e.g. the actual temperature increase against the predicted temperature increase in the collector are calculated. In the last step a diagnosis module is run. The failure detection was only successfully tested against introduced failures in TRNSYS. Since the network was trained with TRNSYS, and there are no measurement uncertainties it has to be seen how it compares to real system behaviour.

The Input-Output Controller (IOC) is a simulation based failure detection method available on the market since 2007. It monitors the energy yields in the solar circuit, although the warm water consumption and two temperature values in the storage are also used as input for the simulation. A second approach in which also the buffer storage discharging is included is being developed. The IOC compares the daily measured and expected energy yields in the solar loop. The standard uncertainty (σ) of the IOC-procedure, including measurements and yield calculation, is about 7 %. If the difference between measured and simulated yield is larger than 20 % (3 σ) a fault is detected, this leads to a 99 % reliability for a correct fault prediction. Below a yield of 1.5 kWh/m^{2}d the uncertainty margins are higher. The IOC is sold for 1190 Euro inclusive temperature and irradiance sensors, but without volume flow measurements. To be able to check the performance from home an extra data logger is necessary.

In Guaranteed Result of Solar Thermal Systems (GRS) the energy yield is guaranteed by the seller/builder of the system. Sophisticated measurement equipment is installed and monitors the system, costs for measurement equipment and one year of operation are in the range of 10 k€. Daily averaged and monthly measured values are sent. Measured yearly energy yields are compared to simulations with f-chart, a simple simulation program. A comparison on a shorter basis is not possible, since the simulation program is too simple. Large failures on a yearly basis can be detected; however failure analysis is not possible.

Several monitoring methods were described. Monitoring with manual analysis can be very effective, but also expensive due to the time spent by experts. Therefore it may be interesting for solar thermal demonstration plants, but not for a large share of the market. Automatic failure detection would be more suitable for the market. Experience with the spectral method and the failure detection based on artificial neural networks is limited so far. The GRS method does not seem to deliver very detailed results and it is quite expensive. The IOC-method is so far the only method that is easily available on the market and applicable. It detects failures, but does not identify them and the main approach studies only the solar circuit.

4 Failure detection method developed at Kassel University

4.1 Method description

The approach developed at Kassel University, was developed for monitoring large solar thermal systems (> 100 m^2) (Wiese, 2006). The goal was to develop a method that functions during the whole operating time of the system, detects failures and if possible identifies these. With detection the method gives a statement on if there is a failure or not, identification refers to recognizing and locating the failure type, which could facilitate reparations. The developed method consists of three steps: an initial data filtering step, a plausibility check or function control and a simulation based yield comparison step.

In the first step, measured data are checked for missing values and sensor breakdowns. If 95 % of the data is available, the process will continue with the second step. The second step consists of a stationary function control, which is comparable to the FUKS method developed by Altgeld et al. Data on a minutely time-scale is used for this analysis. The function control was designed to detect about 20 failures. These include malfunctions of the controller, wrong size of volume flow due to e.g. wrong pump step, embedded air or fouling of hydraulic circuits and malfunctions of the heat exchanger.

Since a reduction of energy yield cannot always be determined with these two first steps, the third step consists of an approach in which results of dynamic system simulations are compared to yield calculations based on measurements. The measured energy gain is calculated at the heat exchangers for charging and discharging the buffer storage with: $\dot{Q} = \rho \cdot c_p \cdot \dot{V} \cdot \Delta T$. Maximum and minimum heat fluxes are calculated by including uncertainties of measured temperatures and volume flow rates in the above equation. The solar heating systems are simulated in TRNSYS, a powerful simulation environment. The simulated energy yield is considered as the design yield of a well functioning solar thermal system. Uncertainties play a role, e.g. caused by uncertainties in measurement data that are used as input (irradiance, ambient temperature, water demand profile), parameters that are used in the model and intrinsic simplification rules. A confidentiality range is defined for the simulations. If the confidentiality ranges of the measured and simulated energy yields overlap, there is no error notification, otherwise there is. For this procedure, data with a lower time resolution, e.g. 30 minutes, can be used.

4.2 Results

The plausibility check or function control was applied to measurement data of three solar thermal systems. In Table 2 the results of the developed plausibility check are presented, which were gathered by an analysis for three large solar domestic hot water systems. It gives a qualitative answer to which failures were recognized by the method and which ones were identified. A plus-minus sign means that in some cases failures can be recognized. The detection of several malfunctions depends on the specific system properties and the failure, e.g. how incorrect is the sensor position, how large is the fouling of the heat exchanger and how large are the uncertainties. In Wiese (2006 and 2007), detection of the fouling of a heat exchanger is illustrated. However, this functions only if the temperature differences between the forward flow in the primary loop and the forward flow in the secondary loop are large enough, e.g. if the heat exchanger is very large detection of problems are not possible.

The comparison of simulations and measurements in the simulation based monitoring procedure, was run on a daily basis for three different large solar domestic hot water systems. It was successful in detecting several failures like air in the solar circuit. Up to now failures cannot be identified by this method.

Table 2 – Results of developed Plausibility Check (Derived from (Wiese, 2006))

		Detection	Identifi-cation
	Verification of functioning of controller		
R1	Breakdown of controller	yes	no
R2	Breakdown of sensor	±	yes/±
R3	Inaccurate sensors	no	no
R4	False control criteria	±/yes	no
R5	Inappropriate control scheme	±	no
R6	Position collector T sensor	±/yes	yes
R7	Inappropriate T/ΔT settings	±	no
R8	Incorrect sensor position	±	no
R9	Breakdown of gravity brake	yes	yes
	Verification of volume flow		
V1	volume flow too small		
V1.1	too small pump, wrong pump step	yes	planned
V1.2	air in hydraulic circuit	yes	no
V1.3	fouling of hydraulic circuit	yes	no
V1.4	primary pressure in hydraulic circuit too low	yes	no
V2	volume flow too high	yes	no
	Verification of heat exchanger performance		
W1	Dimensioned too small	no	planned
W2	Fouling	±	planned
W3	Hydraulics wrongly connected	±	planned
	Verification of collector performance	no	(simulate)
	Verification of storage losses	no	(simulate)

4.3 Summarizing remarks and outlook

The method described in the previous sections, is able to detect several failures and provides an interesting approach for large-scale systems. However there is room for improvement and a more accurate analysis for the results of the method on a long-term basis.

Several steps are suggested, amongst which are an extension of the simulation-based step to include more system types including a validation of the TRNSYS models and their uncertainties. Also an identification of failures in the simulation-based step of the method is foreseen. Furthermore Kassel University is part of the recently started project IP-Solar, together with Solid, TU Graz, Cerebra and Schneid, to develop a well-functioning monitoring and failure detection method for large systems.

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