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376 - Overview of Monitoring and Failure Detection Approaches for Solar Thermal Systems

A.C. de Keizer[*], K. Vajen and U. Jordan

Kassel University, Institute of Thermal Engineering, 34125 Kassel, Germany, www.solar.uni-kassel.de

[*] Corresponding Author, solar@uni-kassel.de

Abstract

Continuous monitoring and failure detection during the life time of a solar thermal system is important to detect occurring failures as quick as possible. Therefore, several methods have been developed during the last decades. However, so far application is mainly limited to research and demonstration projects. In this paper several failure detection methods are described and compared with a partial multi-criteria analysis.

Up to now monitoring approaches have primarily been applied with data analysis by an expert, but without an automatic analysis of the data through the method. There are some methods that include automatic failure detection; which is based on a static function control or on a simulation based comparison. Up to now none of the systems include the auxiliary heating.

Keywords: monitoring, failure detection, solar thermal systems

1. Introduction

The solar thermal energy market is growing. Solar thermal systems are designed to function for at least 25 years, but failures and malfunctions of parts of the system are likely to occur at a certain time. This can cause energy and economic losses. These can be minimized or largely avoided with the right monitoring approaches. System failures are not easily noticed without performance checks, since the auxiliary heating system always backups the hot water supply. Furthermore, changing weather circumstances and hot water demand make a prediction of the energy yield difficult. During the last decades several methods for monitoring have been developed [2-14], however, so far they have mainly been applied in research and demonstration projects.

Several terms will be distinguished here. Monitoring is defined as data logging of a variable amount of measurement data, however this data is not automatically analysed, so it does not automatically lead to a failure declaration. In a failure detection method, measurement data is automatically analysed and in case of a malfunction a failure indication follows. Failure identification or localisation goes further in that it requires the identification of the type of failure. This will make reparation much easier.

In this paper a partial Multi-Criteria Analysis (MCA) will be used to describe the performance of several monitoring methods for solar thermal systems. The MCA procedure will be described in chapter 2, consecutively the monitoring methods will be described in section 3. The results of the MCA will be given in section 4, conclusion and discussion are described in section 5.

2. Method

2.1. Multi-Criteria Analysis

In this paper a partial multi-criteria analysis (MCA) is used to evaluate and compare methods that can be used for detection and identification of failures or malfunctions during the operation of solar thermal systems. A multi-criteria analysis is often applied to support policy decisions and evaluate different alternatives [1]. One of the advantages of MCA is that the criteria, on basis of which the comparison is made, are explicit. There are several MCA methods; a relatively simple one without weighting the different scores and combining these to a result score will be used here. Since the weights would depend on the application of the method, this will not be carried out here.

The MCA conducted in this paper consists of four steps.

1. Identification of aims and decision makers
2. Identification of failure detection methods that can be used for achieving the objectives
3. Identification of the criteria that are used to compare different options/failure detection methods
4. Generation of a performance matrix in which the expected performance of each method against the criteria is described

The objective of the multi-criteria analysis is to evaluate several failure detection methods with regards to the effectiveness of failure detection. Key players are users of monitoring and failure detection methods and developers. They have similar aims and therefore, this will not be considered here.

2.3. Monitoring and failure detection methods for solar thermal systems (Step 2)

The monitoring methods have been identified in an extensive literature study. One criterion for inclusion was the ability to operate for the whole lifetime of the system. The following methods will be discussed in this paper:

- Manual monitoring with the example of the Optisol Project (MM)
- Function control for small solar thermal systems without heat measurements (FUKS)
- Input-Output Controller (IOC)
- Guaranteed Solar Results (GSR)
- Method developed at Kassel University (KU)
- Spectral method (SP)
- Failure detection with Artificial Neural Networks (ANN)

A further description of the methods can be found in section 3.

2.4. Criteria to Analyse Performance (Step 3)

The criteria are used to measure the performance of the different failure detection approaches. The selection is very important, since the result will be different, if not all relevant criteria are included.

As most of the methods are still in development, a qualitative evaluation is applied. The criteria are as follows:

- Automatic Failure detection included?
- Accuracy/effectiveness of failure detection
- Automatic Failure identification included?
- Accuracy/effectiveness of failure identification
- Costs (operational and hardware)

3. Overview of Failure Detection Methods

The methods for failure detection will be described in the next sections. Table 3.1 lists some characteristics of the different methods, like what time scale and for what type of systems they are applied to.

Table 3.1 Overview of several Characteristics of Methods

Characteristics	**MM**	**OPT**	**FUKS**	**SPM**	**IOC**	**ANN**	**GRS**	**KU**
Time scale of data logging[1]	Var	15 min	<1 min	1 sec	min	Hour?	var	1 min
Time scale of analysis	Var		?	sec	day	hour	Mon or yr	10 min and day
Simulation?	No	No	No	No	Yes	Yes	Yes	Yes
Scale of the system (tested) (collector area in m^2)	Var	30-250	5	7-16	2-455	40[2]	Very large	88-400
Type of system	Var		DHW	Combi	DHW	DHW (simpl)	DHW	DHW
Stage of development[3]	++	++	++	-	++	-	++	+-
Level of automation[4]	--	--	++	++	++	++	+-	++

[1] Time scale: var = variable, sec = second, min = minute, hour, day = day, mon = month, yr = year

[2] TRNSYS simulation

[3] ++ well developed / can be applied directly, +- further research and development, - early R&D

[4] – not automated, +- partly automated, ++ fully automated

3.1. Manual monitoring with analysis by an expert (MM, e.g. Optisol)

In most cases in which solar thermal systems were monitored, the failure detection consisted of analysis of measurement data by an expert. An expert with enough experience can recognize if a system is performing as expected based on analysis of data. A state-of-the art example is provided in the Austrian demonstration project Optisol (OPT), in which 10 large solar thermal systems were built and monitored for ca. 1 year [2].

In the Optisol project an integrated approach was used for designing, building and monitoring the systems. The monitoring part consisted of a so called optimization phase of two months and a consecutive routine supervision of one year. During the optimization phase many weaknesses of the solar supported heating system were recognized by analysing the temperature profiles of the systems. 35 faults in installation, design or operation were detected in 9 systems, several of these faults were related to the auxiliary heating system. In the routine supervision monthly energy balances and yearly key figures were studied. These are compared to the values determined in the planning phase, which are based on the irradiation and temperature profile of a typical reference year [2].

The optimisation phase was very effective regarding failure detection, however, it is time-consuming and therefore costly. The routine supervision phase is not that time-consuming, but does not deliver a quick feedback if the system is working properly and it does not locate failures.

3.2. Function Control without Heat Measurements (FUKS)

In the second half of the 90's the FUKS-approach (function control without heat measurements) was developed in Germany as a cheap function control (<100€) [3]. This approach applies algorithms to measurement data and notices whether components function correctly. An overview of the developed algorithms is provided in table 3.2. The values in the algorithms could be adapted for other systems.

Several other algorithms were developed which can only be applied with additional sensors, e.g. resistance sensors for defect or inaccurate temperature sensors for the collector output or in the storage tank.

Table 3.2 Failure algorithms developed in the FUKS-approach [4]

Failure description	*Result of failure*	*Algorithm*
1. Collector circuit points interchanged 2. Collector T-sensor falsely positioned	Pump clocks	Pump running time < 10 s.
3. Leakage of heat exchanger 4. Power outage	System pressure too high	(T_{kol} = 20 °C) AND ($p_{system} = p_{system\ soll} + 2$ bar)
5. Incorrect controller software 6. False volume flow setting 7. Air in hydraulic circuit 8. dT setting is inappropriate 9. Defect input or output to the controller	dT too high	Pump on AND $dT = dT_{soll} + 15$ K
10. Gravity brake is open 11. Fouling of gravity brake 12. Time switch is programmed wrongly	Pump on at night	Pump on AND time between 22:00 and 6:00

The method was for test purposes partially implemented in controllers of Esaa and Wagner. Several failures were recognized, but there were also false positives, detection of a failure while the system was functioning correctly. The approach stays cheap by using mainly sensors that are used for the control, however, with analysis and pressure measurements, the price may be slightly higher than mentioned. Although the method succeeds at detecting several failures in the lab, location of failures is limited, as can be seen in Table 3.2. Furthermore, there is no yield measurement, which could mean that large energy losses are not detected.

3.3. Spectral method (SPM)

The spectral method is based on analyzing the transient temperature changes in the collector circuit after the pump is started [5; 6]. Temperature signals on a secondly basis are transformed with a Fourier transformation in the spectral range. A failure free training phase results in a characteristic vector and an uncertainty boundary. A measured vector out of this range indicates a failure. Only one extra temperature sensor about a meter after the collector exit in the collector pipe is necessary. 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 even impossible.

3.4. Fault Detection with Artificial Neural Networks (ANN)

The development of a neural network-based fault diagnostic system for the solar circuit 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 are calculated, which characterize e.g. the actual temperature increase in the collector compared to the predicted one. In the last step a diagnosis module is run. The failure detection was only successfully tested for introduced failures in TRNSYS [7; 8]. 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.

3.5. Input-Output Controller (IOC)

The Input-Output Controller is a simulation based failure detection method available on the market since 2007. The first variant of the method monitors only the energy yields in the solar circuit. Furthermore, two temperature values in the storage are used as input for the simulation. A second approach also includes the buffer storage discharging. 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 % (σ). 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. There is a failure tree to establish if the fault occurred inside or outside the solar loop, and if it is for example the control or the solar station which causes the problems. The IOC is sold for 1190 € 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 [9; 10].

3.6. Kassel University method (KU)

At Kassel University a failure detection method was developed, that combines a static algorithm based function control with dynamic simulation based failure detection [11]. The method consists of three steps. In the first step it is checked if too much data is missing due to data gaps and sensor defects. A minimum of 95 % of data points should be available to continue with the failure detection. In a second step a plausibility check is carried out, in which the correct operating of individual components is checked, similar to the approach used in [3]. The third step is a simulation based step in which the system is modelled with TRNSYS. Measured and simulated energy gains are compared at the heat exchanger for charging and or discharging the storage unit. If the difference is larger than the uncertainty margins on both sides an error is reported [12; 11].

Several failures were detected and partially identified. These were for example air in the collector field and a calcified heat exchanger. This approach is being further developed.

3.7. Guaranteed Solar Results (GRS)

In Guaranteed Result of Solar Thermal Systems the energy yield is guaranteed by the seller/builder of the system. Sophisticated measurement equipment is installed and monitors the system, costs for the 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, although also other simulation programs could be used. A comparison on a shorter basis is not possible, due to limitation of the simulation program. Large failures on a yearly basis can be detected; however failure analysis is not possible [13; 14].

4. Results – Performance Matrix

The result of the comparison of the failure detection methods against the criteria described in §2.4 is presented in table 4.1. The performance matrix shows the performance of the failure detection method based on the different criteria. A few things need to be clarified before interpreting the table. First of all, it is assumed that without automatic failure detection there is a possibility for checking data with a manual analysis. This can be effective but is costly (dependent on the level of the analysis). This could be (and is partially) applied for all methods. Therefore, the criterion is limited to automatic failure detection. Because a lot of information is qualitative, it is hard to determine how much a method will cost in future application when it is still in the R&D phase. Also the effectiveness of a method may increase based on practical experience. Furthermore, the (literature) publications in general do not provide a very accurate description of effectiveness and accuracy of the method.

Table 4.1 Performance matrix

Criteria	*MM*	*FUKS*	*SP*	*IOC*	*ANN*	*GRS*	*KU*
Automatic failure detection included?	--	++	++	++	++	--	++
Automatic failure identification included?	--	+	--	+-	--	--	+
Accuracy of failure detection	++	+-	?	+	?	+-	+
Accuracy of failure identification	++	+-	n.a.	+-	n.a.	n.a.	+-
Costs (operational/hardware)	-- var	++ 100 €	+?	+ 1190 €[1]	+?	-- 10 k€[2]	+- 20-80€[3]
Monitored part of solar heating system (so far)[4]	var	sl	sl	sl, bs	sl	-aux	-aux

Qualitative scale: ++ yes/very good/cheap via +- = reasonable to -- no/very bad/expensive
? = unclear

[1] IOC: only hardware

[2] costs for measurement equipment, including one year monitoring

[3] Costs per month for 20 year monitoring and at least 30 monitoring systems sold. The main costs are expected for maintenance and improvement of software (between € 15 and 50 per month) [11].

[4] var = variable, sl = solar loop, -aux = whole system besides auxiliary heating system, bs = buffer discharging loop (optional for IOC)

The IOC is the first method which could result into the implementation of a monitoring and failure detection method into general use of larger solar thermal systems. It has been tested and is commercially available against a reasonable price, but it does not apply to the whole solar system. Manual monitoring, though more costly, is much easier adapted to extensive variation in hydraulics and systems. The method developed at Kassel University is still in development, but could also provide an automatic monitoring solution for large systems. It includes more sensors and a larger part of the system than the IOC approach, and can therefore also analyse individual components. For very small systems the approach followed in FUKS detects several failures at reasonable additional costs.

However, so far none of the above described approaches takes the auxiliary heating system into account, which is also an important source of errors.

5. Conclusion, discussion and outlook

An overview of methods for monitoring and failure detection has been presented in this paper. Several differences are highlighted by means of a partial multi-criteria analysis. The results are presented in a performance matrix, in which the methods are qualitatively evaluated with certain criteria. Quite a few methods are in an (advanced) stage of research and development, this complicates the analysis of the functioning of the different approaches. The Input/Output Controller, Guaranteed Solar Results and Manual monitoring can already be applied in commercially built solar thermal systems. Of those, the Input/Output Controller is the only one that analyses the measurement data automatically and provides an automatic failure indication.

However, none of the approaches include the auxiliary heating system. Several approaches, e.g. the method from Kassel University, are being developed further to increase the ability of detection and identification of failures. Furthermore practical experience has to be gained for a better evaluation of the performance of several approaches.

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