Fault detection for solar thermal systems: Evaluation and improvement of existing algorithms

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Abstract

This paper evaluates fault detection algorithms for solar thermal systems, with regard to the most important faults in solar thermal systems. The relevant algorithms from literature are described and sorted according to their respective detection approach. The algorithms are then evaluated with measurement data from 10 solar thermal systems of different sizes (collector area between 3 m² and 2500 m²). The performance evaluation of the algorithms shows that most false alarm messages are generated due to transient system behaviour, which was not taken into account in the development or description of said algorithms. Main problems are caused by short operating phases, switching of the solar pump(s) in rapid succession, start phases of the solar thermal system, and delayed reactions of temperatures or sensors.

Keywords: Fault detection, solar heating, monitoring, function control, FDD

1. Introduction

Algorithm based fault detection and diagnosis (FDD) for solar thermal systems (STS) has been subject of research since the 1990s. Important foundations were laid by (Altgeld and Mahler, 1999), where they defined FDD algorithms for small solar thermal systems without heat meters (FUKS project). The algorithm-based approach was improved, refined, and adapted for different sized systems (Gerardts et al., 2011; Ohnewein et al., 2016) and led to the German VDI 2169 “Functional checking and yield rating of solar thermal systems” (VDI 2169, 2012). Even more algorithms or adaptations of already existing ones have been published in various papers and reports on research projects (Bartenstein, 2015; Brandstetter, 2007; Duff and Millard, 1980; Fink et al., 2010; Stryi-Hipp et al., 2007; Sun et al., 1999; Thür et al., 2011; Wiese, 2006). Despite the fact that these algorithms are publicly available and that the majority of solar controllers advertise an automatic function control, no system or approach is currently widely used.

2. Important faults in STS and existing algorithms

To show the reliability of solar thermal systems and to determine the most common faults or defects, several studies and projects have been conducted in the past. Often, the planning, installation, and operation of several STS was monitored to identify common mistakes and potential for optimisation for the whole life cycle.

In the projects “Solarthermie2000(+)” (Croy et al., 2011), OPTISOL (Fink et al., 2006), and COMBISOL (Thür et al., 2011) a large number of solar thermal systems were monitored. The studies focussed on assessing the performance of solar thermal systems, and to identify common faults and dysfunctions throughout planning, installation, and operation. For additional studies with the same or similar objectives, see (Breidler and Thür, 2010), (Fink et al., 2010), (Schenk et al., 2010). While the observations vary slightly between different publications, there is a common baseline regarding the reliability of STS. In every study a significant proportion of the investigated STS required repairs or at least optimisation. Since most of these dysfunctions were found by manually analysing system data and on-site evaluation of the systems, this process was very time consuming, requires expert knowledge, and therefore expensive. The following algorithm development aims at an automatic detection of the most important faults based on measurement data. With this, faults and system failure could be detected early and at low additional costs.

Based on the literature review and in discussion with several manufacturers of solar-assisted heating systems, the following list of important faults in STS was defined.

- Defective pumps (no volume flow)

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- Pumps too small (low volume flow)
- Undissolved air in solar circuit (unstable volume flow, uneven flow distribution)
- Soiling in heat exchangers and pipes, clogged filters (low volume flow)
- Collector temperature sensor at wrong position or does not measure fluid temperature
- Heat exchanger (HX) too small (or soiled) - UA value

Regarding these faults, several existing algorithms can be found. For better clarity and easier implementation, the algorithms can be sorted by fault groups (faults with similar or the same symptoms), see table 1.

Table 1: Fault groups and existing algorithms, sources: "FUKS" (Altgeld and Mahler, 1999), "VDI" (VDI 2169, 2012), "UNIKS" (Wiese, 2006), "PARA" (Bartenstein, 2015), "QSOL" (Brandstetter, 2007)

Group nr.	Faults	Algorithms
1	Defective pump(s) Blockage Undissolved air	[FUKS_FLOW] [FUKS_NOHEAT] [VDI_PUMP] [UNIKS_FLOWSENS] [PARA_PUMP] [QSOL_FAILURE_a/b]
2	Pumps too small [or wrong pump stage]	[FUKS_FLOW] [UNIKS_FLOWSENS]
3	(Undissolved) Air [unstable volume flow]	[VDI_UNEVEN_FLOWDIST] [UNIKS_UNSTABLE_FLOW] [QSOL_AIR] [FUKS_FLOW] [UNIKS_FLOWSENS]
4	T_{coll} wrong position or bad thermal contact	[UNIKS_TCOL_a/b]
5	HX too small (UA)	[VDI_HX] [UNIKS_HX]

Table 2 shortly presents the existing literature algorithms (concerning the prioritised faults). The respective main approaches are described and information on thresholds – if present in the literature source – are provided.

Table 2: Investigated algorithms and respective detection approaches

Algorithm	Source	Approach, Notes
FUKS_FLOW	(Altgeld and Mahler, 1999)	Check for high temperature differences between collector and storage; Threshold specified: $\Delta T_{nominal} + 15\ K$
VDI_PUMP	(VDI 2169, 2012)	Check volume flow rate during pump operation
VDI_UNEVEN_FLOW	(VDI 2169, 2012)	Compare outlet temperatures of parallel collector modules or fields; Deviations of less than 10 % are acceptable; fields must be of the same size
VDI_HX	(VDI 2169, 2012)	Check if secondary flow temperature is lower than primary return temp (in operation)
UNIKS_FLOWSENS	(Wiese, 2006)	Check flow sensor reading if temperature difference at HX indicates system operation
UNIKS_UNSTABLE_FLOW	(Wiese, 2006)	Check for decreased and/or unstable volume flow rate (and increased stagnation)
UNIKS_TCOL_a	(Wiese, 2006)	Check for increased switching operations of the pump

UNIKS_TCOL_b	(Wiese, 2006)	Check if flow temperature exceeds collector temperature after the pump starts
UNIKS_HX	(Wiese, 2006)	Calculate UA value; Proposes method to compare measured UA values to nominal data sheet values.
PARA_PUMP	(Bartenstein, 2015)	Check if collector or flow temperature stay constant after the pump was turned on
QSOL_FAIL_a	(Brandstetter, 2007)	Check if collector temperature is significantly higher than storage temperature while storage is not fully charged.
QSOL_FAIL_b	(Brandstetter, 2007)	Check for operation by temperature difference between collector and flow temperature, system should be in operation, if collector exceeds storage temperature by 10 K
QSOL_AIR	(Brandstetter, 2007)	Check for temperature spikes in the solar thermal system; Already checked with QSOL_FAIL_a

3. Evaluation of fault detection algorithms and common problems

To evaluate the existing algorithms, they are implemented in python and tested on measurement data of 10 STS with collector areas reaching from 3 m² to 2500 m² (data of 3 additional STS can only be used for very few algorithms due to the respective system design or sensor equipment). At least one year of measurement data is available for each system. For most of the systems, there is no additional information if there were faults, stagnation or stand still periods or repair works. On this basis, “false negative” alarms cannot be checked, but “false positive” alarm reports can be identified manually.

The overall main problem of almost all described literature algorithms lies in operating states of the STS that were not expected or disregarded in the development phase. Since most algorithms were not at all or scarcely tested on measurement data, many false symptoms are generated.

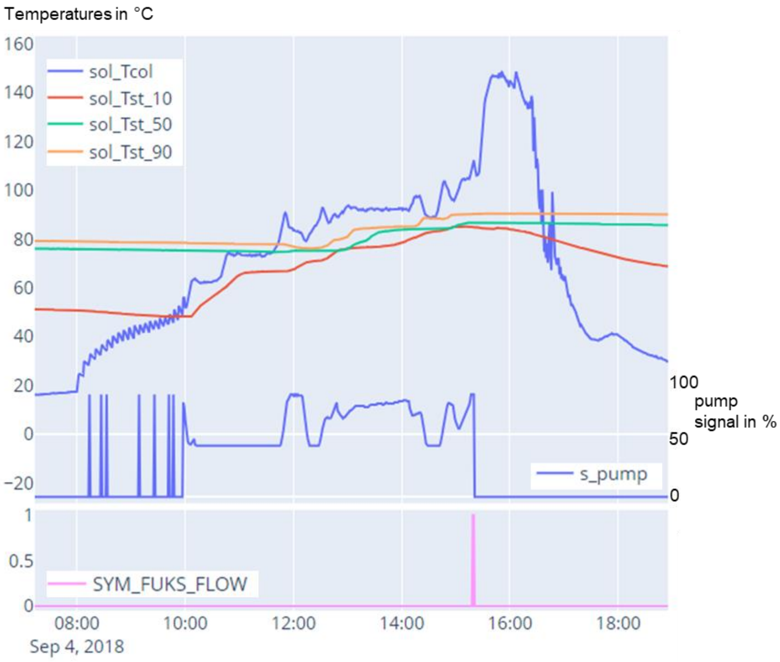

Figure 1: FUKS_FLOW algorithm applied to a small STS.

Figure 1 shows the application of the algorithm FUKS_FLOW for a small STS. The upper graph illustrates system temperatures (left y-axis) and the pump signal (right y-axis). Below this, the algorithm’s output is shown (0 – nothing detected; 1 – alarm message / symptom). It can be seen that the STS can increase the lower storage temperature “sol_Tst_10” from approx. 50 °C to 80 °C. Then probably a maximum temperature is reached, and a stagnation phase begins. In the transition between operation and stagnation, a few time steps of already very high temperatures can be observed while the pump is still running. This triggers the algorithm, without a real dysfunction being present.

Stagnation phases can generally be a problem for simple FDD algorithms since high collector temperatures usually signify a sufficient irradiation. If the storage temperatures are not checked for a maximum threshold, false alarm messages can be created easily. Of course, this problem is obvious for experts or operators and would be dismissed immediately in manual analysis, but for automated FDD algorithms every operating state or boundary condition must be considered explicitly.

Other problems arise if the pump is switched on and off in rapid succession. At the beginning of a day with sufficient irradiation to charge the storage, the collector field heats up gradually until the collector temperature exceeds the storage lower temperature by a defined threshold. Then, the pump is switched on and cold fluid from the pipes and/or storage is transported to the collector, usually causing a steep temperature decrease at the sensor. Depending on the collector area, irradiation intensity, and cold storage temperature, this can lead to several successive switching operations of the pump. Another scenario with rapid switching operations usually occurs at the end of operation phases on days with high irradiations. If the storage is charged to its maximum temperature, the pump is switched off. The storage temperature then decreases due to heat losses or energy demand, so that the STS is switched on again. Again, depending on the boundary conditions, this can lead to rapid successive switching operations. To a certain extent, both described scenarios are considered as normal system operation and do not justify alarm messages.

Figure 2 (left and right) shows the algorithms FUKS_NOHEAT and PARA_PUMP applied to small STS. Again, the upper graphs illustrate system temperatures (left y-axis) and volume flows or pump signals (right y-axis), the lower graphs depict the outputs of the respective algorithms. FUKS_NOHEAT (left) checks if the flow temperature is higher than the lower storage temperature at least once per operation phase. Since the operation phases are short in the beginning and even the lower storage temperature is > 40..50 °C, the flow temperature stays below the storage temperature for a few short operation periods, thus causing (unwanted) alarm messages. After this, the STS passes over to normal operation. The algorithm PARA_PUMP works differently: Here, the collector temperature is analysed after the pump starts – if it stays constant (in the limits of defined thresholds) a dysfunction is assumed. Figure 2 (right) shows the algorithm’s performance. As the storage temperature draws near to its allowed maximum, the pump is switched on and off in rapid succession, while the collector and flow temperatures do not change much. Thus, a false alarm message is generated.

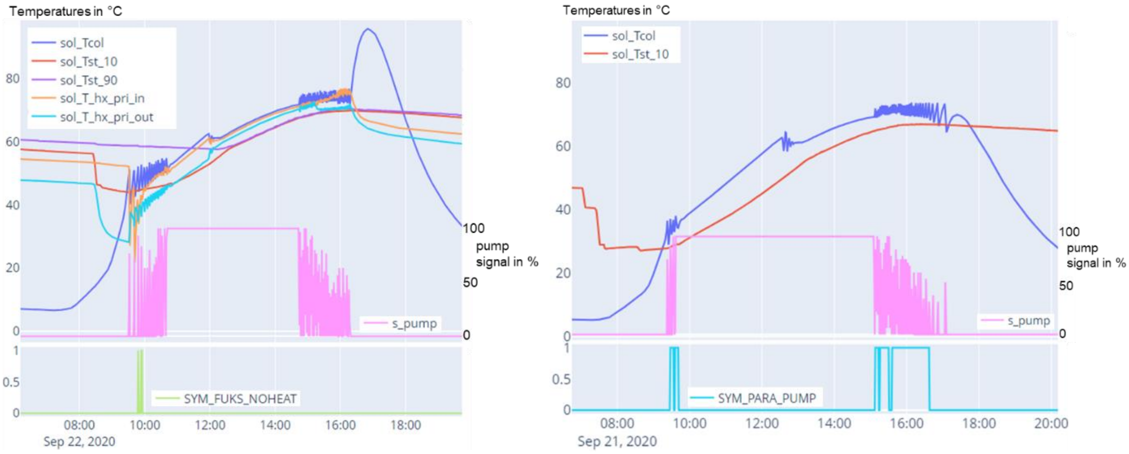

Figure *2*: FUKS_NOHEAT (left) and PARA_PUMP (right) algorithms applied to small STS.

Figure 3 and figure 4 illustrate another main problem arising from unexpected operating states, or system behaviour during the algorithm development. Here, the delayed reaction of temperatures and temperature sensors are decisive. Figure 3 shows the application of the algorithms VDI_PUMP, VDI_HX, and UNIKS_TCOL_b. VDI_PUMP (left) checks the volume flow if the pump is turned on. It can be seen that the flow sensor occasionally reacts slightly delayed. This causes an alarm message because for one or a few time steps no volume flow is detected despite a present pump signal. VDI_HX (right) checks if the flow temperature on secondary side is higher than the return temperature on the primary side of an external heat exchanger. For short operation periods, the temperature sensors at the heat exchanger may not measure the actual temperatures, because the heat supplied by the collector did not “arrive” at the HX. In these cases, alarm messages are created based on the fluid temperature in the pipes, which is not the original intention and only by chance indicates a real dysfunction.

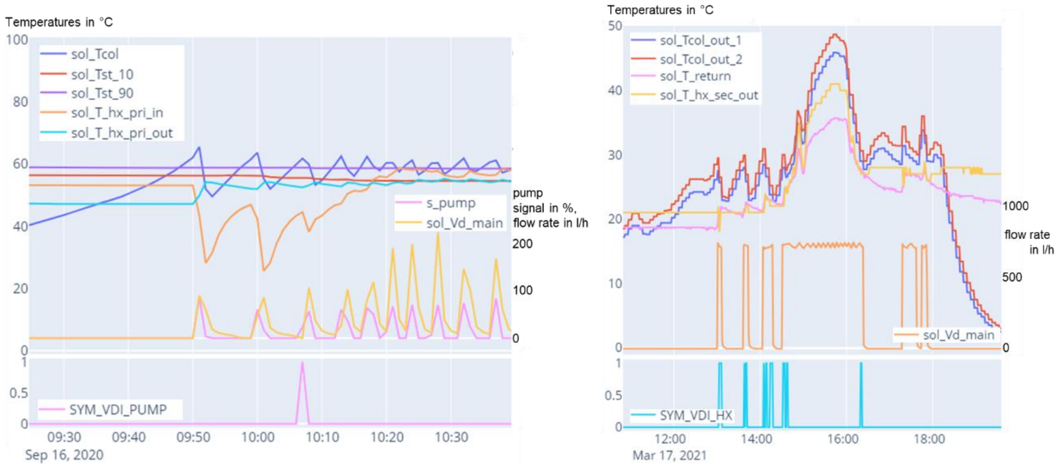

Figure 3: VDI_PUMP (left) and VDI_HX (right) algorithms applied to STS.

The performance of the algorithm UNIKS_TCOL_b is illustrated in figure 4. The algorithm compares temperatures as well, checking if the flow temperature is higher than the collector temperature after the pump starts. Here, a combination of circumstances causes false alarm messages: On the one hand, the system temperatures are rather high, starting with > 40 °C in the whole storage. This leads to high return temperatures in the primary and secondary solar circuit throughout the whole day. Moreover, the irradiation does not suffice for very high collector temperatures, only surpassing the storage temperature (plus hysteresis) slightly. Consequently, the pump is switched on/off often with only a few longer operation periods for the day. This causes several cases, where the current flow temperature is (slightly) higher than the current collector temperature.

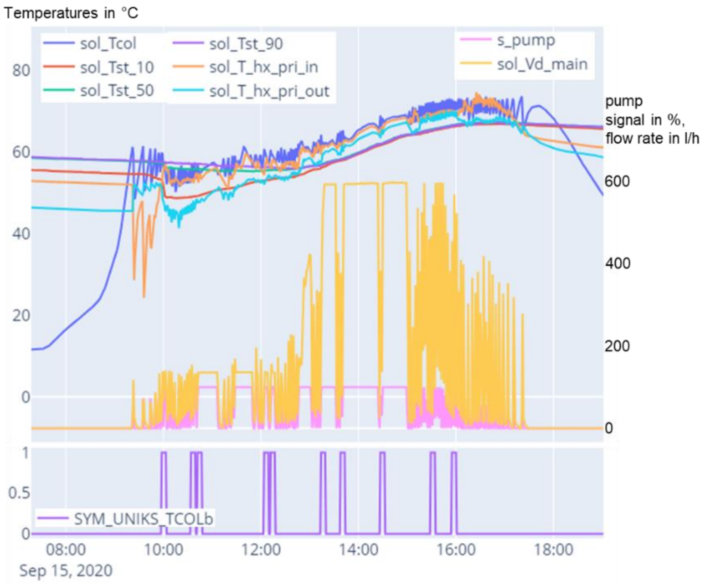

Figure 4: UNIKS_TCOL_b algorithm applied to a small STS.

Moreover, almost all existing algorithms share one central problem: the approaches for detecting faulty system behaviour are missing flexibility regarding the available sensor data. Even for the evaluation on real measurement data at hand, several algorithms had to be adjusted to work with a more flexible data base. STS are planned and built individually, especially including the measurement equipment. Except the collector and storage temperature sensor, almost no common sensor equipment can be assumed. And even this minimal equipment can cause ambiguity if two collector sensors are installed, e.g. for parallel fields. To compensate this individuality, algorithms must be developed, coded, and tested accordingly.

On the other hand, selected algorithms work well without the need for extensive adjustments:

UNIKS_FLOWSENS reliably detects if the flow sensor reading does not indicate an apparent system operation. In our available measurement data, no or few false alarms could be seen. However, for several plants the algorithm detects that the flow temperature does not decrease or reach the ambient temperature after an operation cycle. This could be an indicator for convection current.

UNIKS_TCOL_a checks the cumulated switching operations of the solar pump against a defined threshold. Since this approach does not rely on non-transient system states or explicitly involves temperatures or other measurements, it is quite robust. The informative value of the algorithm only depends on choosing the right threshold for each plant.

QSOL_FAIL_b like FUKS_FLOW checks the operational temperature difference between collector and storage. The plant's operation is assumed if the difference between collector and flow temperature undercuts a threshold. This approach (for detecting operation) is beneficial because transient start phases or very short operation phases are note used for the analysis. Thus, less false alarm messages are generated.

UNIKS_HX algorithm basically calculates the UA value of a heat exchanger. As described in (Wiese, 2006), system operation has to be stationary for an analysis of the UA value. Additionally, the UA value depends on the boundary conditions, e.g. flows and temperatures on primary and secondary side. Thus, the calculated UA value cannot usually be compared to the datasheet value (if available), but a reference value must be calculated according to the actual conditions. This drastically complicates the application of the algorithm. Moreover, not only the temperatures (flow and return) but also the flow rates must be measured on primary and secondary side for the algorithm to be applicable.

4. General recommendations and improvements for FDD algorithms

As shown, most literature algorithms tend to generate false alarm messages for non-stationary or transient operating states. These occur at the beginning (and end) of longer operating states, and especially if the pump is switched on/off in rapid succession. This can either be caused by hardly sufficient collector temperatures (or irradiation) or because of maximum temperature limits or hysteresis settings. False alarms because of delayed sensor readings or delayed temperature increases are covered by this as well. The easiest way to address this is to cut off start phases and only use operating phases with a minimum duration for the system analysis.

Figure 5 (right) shows the exemplary improvement of the algorithm PARA_PUMP. Here, the algorithm has been adjusted to only analyse the temperature at the start of operation phases that exceed a minimum duration of 10 minutes. Thus, short phases are filtered out. The improvement becomes clear in comparison to the original performance, see figure 5 (left). All false alarm messages from the afternoon are now prevented. For the beginning of the long operation period still an alarm message is generated. Here, the temperature change at the start of the phase simply does not exceed the expected 5 K.

Another general remark has to be made regarding the flexibility of FDD algorithms. The algorithms described above are inflexible regarding different sensor configurations. Thus, if a flow or temperature sensor is not available, the respective algorithm cannot be applied. To address this problem, "parallel" detection paths can be designed. For instance, the (theoretical) operation of the STS can be detected using the pump signals, a flow meter or temperature differences between flow and return or between collector and flow temperatures.

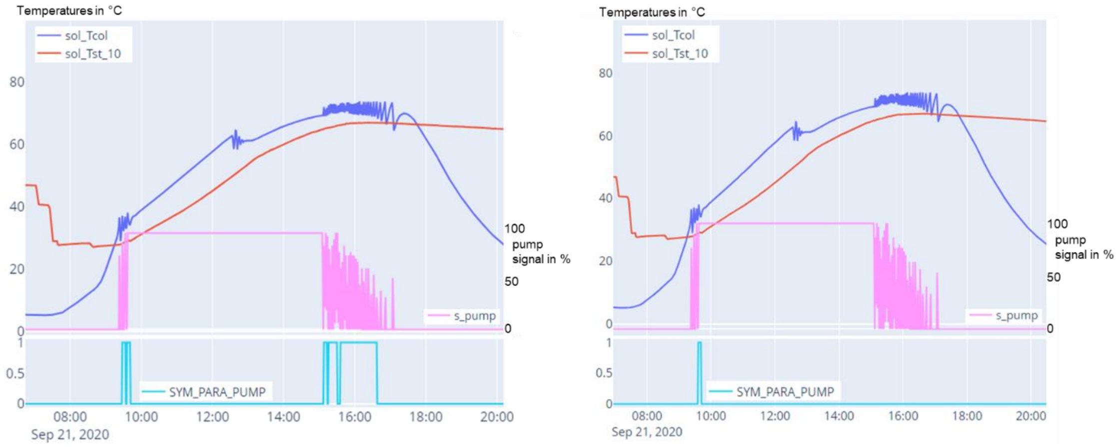

Figure 5: Performance of original (left) and improved algorithm (right) PARA_PUMP: the adjusted algorithm only analyses phases longer than specific duration (here 10 minutes)

5. Conclusion and outlook

As discussed in the performance evaluation, many of the algorithms show problems with transient system behaviour, which causes false alarm messages. Mostly, these problems occur because the respective system states were not considered in the development or description of the literature algorithms, and because the algorithms were not tested on real measurement data. Main problems are due to short operating phases, switching of the solar pump(s) in rapid succession, start phases of the solar thermal system, and delayed reactions of temperatures or sensors.

In the future work, flexible and robust FDD algorithms will be developed and tested on the available measurement data. The algorithms will build on the lessons learned from the described literature algorithms and will focus especially on the applicability for different sensor configurations. Moreover, the measurement data will be used to extract default values for thresholds to reduce false positive alarm messages.

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