Quality assurance of solar thermal systems with the ISFH-Input/Output-Procedure

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Abstract

Input/Output-Controllers for in situ and automatic function control of solar thermal systems that were developed within the research project have been installed in 12 systems. After five years seven solar thermal systems benefited from the installation of I/O-Controllers by detecting failures several times. In three systems the I/O-Controllers were even helping to optimize the system performance. The accuracy of the simulation model has been validated against data from measurement. The average deviation is less than 10 %, which is acceptable because the uncertainty of the procedure is about 7 %. The uncertainty was determined in a sensitivity analysis concerning the uncertainties of parameters and measurement. The simulation model is solvable analytically and enables low costs for I/O-Controllers, because it can be integrated into standard control units. Thereby the I/O-Procedure is even attractive for medium solar systems beginning with a collector area of 20 m². I/O-Controllers from RESOL will be available in 2006.

Keywords: Input/Output-Procedure, quality assurance, uncertainty, modelling

1. Introduction

The demand for solar thermal collectors is increasing because of the actual trend of the fuel prices. In order to assure the operator that the solar system is still working properly after a couple of years a procedure for function control is necessary, because failures can't be recognised easily.

In our research project we were developing Input/Output-Controllers that are assuring the quality of solar thermal systems by an in situ and automatic comparison of measured and expected collector yields on a daily basis. They help to remove the reluctance of investors by increasing the confidence in solar thermal energy.

We developed a mathematical simulation model that can be integrated into standard control units. Prototypes of I/O-Controllers with an implemented algorithm were installed in 12 different solar systems. The simulation model was validated with measured data. The deviation between measured and expected outputs is less than 10 %.

In a sensitivity analysis that takes the uncertainties of parameters and measurement into account we determined the uncertainty of the procedure. The uncertainty results to about 7 %.

2. The ISFH-Input/Output-Procedure

2.1 General specifications

For the daily comparison of measured and expected collector yields, the I/O-Controller has to measure the heat output as well as the input quantities of the simulation model for the calculation of the expected output.

The following schematic (**Fig. 1**) shows the required sensors for the Input/Output-Procedure. Optional sensors may be installed for more information or in order to facilitate trouble-shooting in case of a failure. Supplementary sensors may be necessary for some special solar systems (e. g. solar systems with several storages). This is not discussed here.

For the measurement of the yield of the collector loop $Q_{meas,CL}$ the volume flow rate V_{CL} and the temperature difference between inlet and outlet of the heat exchanger ($\vartheta_{HX,in}$-$\vartheta_{HX,out}$) are required.

The expected yield $Q_{exp,CL}$ is simulated with measured data of irradiance G_g, ambient air temperature ϑ_a, typical solar load temperature ϑ_{TSL} and the temperature at the relevant position for the high limit cut-out ϑ_{Tmax}. Furthermore the I/O-Controller has to know about 40 parameters of the solar system (e. g. collector efficiency coefficients like zero loss coefficient and heat loss coefficients, tilt, collector area).

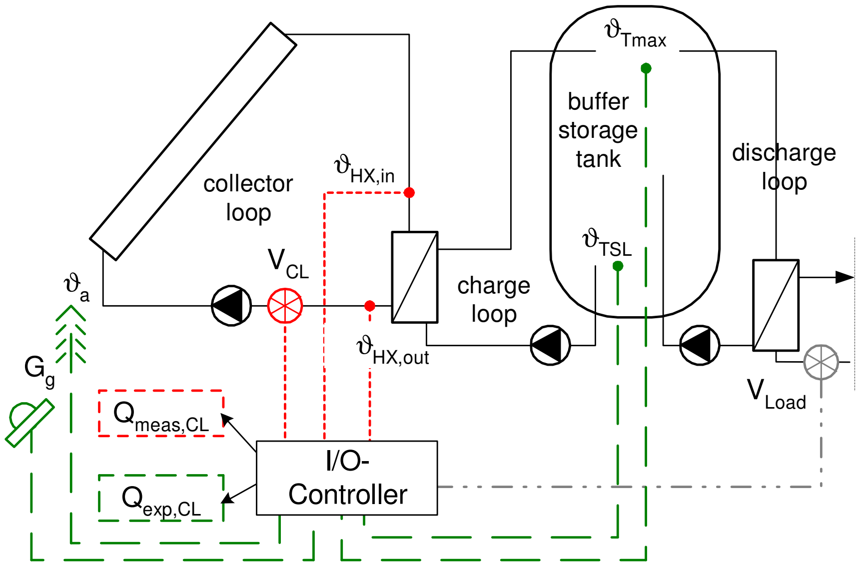

Fig. 1. Schematic diagram of metrological integration of an Input/ Output-Controller into a solar system with buffer storage tank and direct discharging

The ϑ_{TSL} describes the temperature of the heat sink of the collector loop. In different solar systems evaluated in the project the heat sink has been a (buffer) storage tank, a swimming pool or a return pipe of a district heating system. An advantage of using the ϑ_{TSL} is that the same mathematical model can be taken for the collector loop of all kinds of systems (q. v. **chapter 2.2**).

The measured and expected daily <u>outputs</u> of the collector loop can be plotted in an Input/Output-Diagram (q. v. **Fig. 2**) over the daily irradiation (<u>input</u>). Solar domestic hot water systems show a well-known linear relationship, as published in the IEA SHC Tasks VI (1980) and XIV (1996). But also solar systems for space heating that do not show such a linear population can be controlled with an Input/Output-Controller, because of the dynamic simulation of an expected output.

Failures in the collector loop can be seen easily in an Input/Output-Diagram, because the measured values strongly deviate from the expected values.

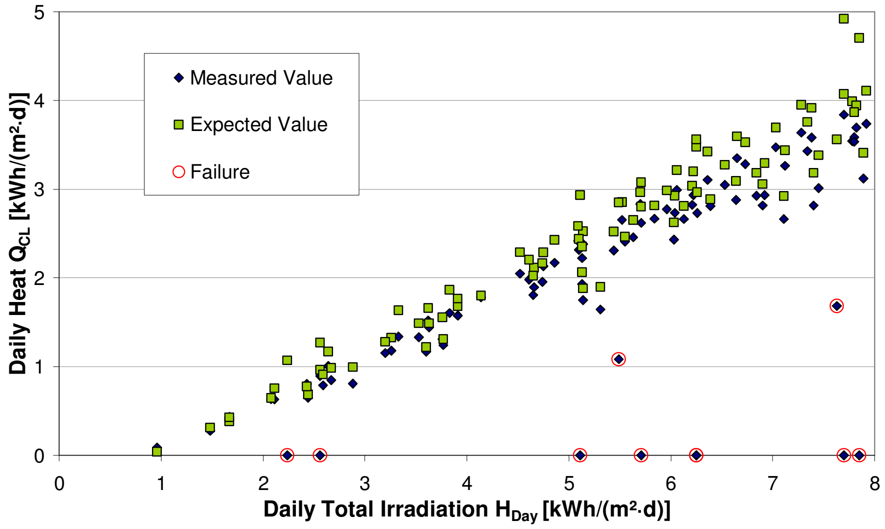

Fig. 2. Input/ Output-Diagram of an attended solar system of a hospital in Solingen (192 m²) from 2003. The failure occurred in the collector loop. The measured yields of the collector loop strongly deviate from the expected yields (encircled in red).

The volume flow rate of the load V_{Load} (warm water consumption) and the storage temperature at the relevant position for the high limit cut-out ϑ_{Tmax} are important information for the algorithm to distinguish a failure in the discharge loop from the effects of lacking heat demand, so that discharging failures can be detected. A detected blockage of a discharge heat exchanger by build up of scale was already published in [3].

In case of low heat demand, e. g. in holidays or in summer periods for solar combi-systems, no significant difference between measured and expected values results. This is important to avoid false signals that confuse the operator, because this is a normal state of solar systems.

2.2 Mathematical model

The developed mathematical model for simulating the yield of the collector loop needs to be able to be integrated into standard control units. For that reason the heat demand V_{Load} is not a necessary input for the model different from common simulation programs. Instead the input quantity for the model is the typical solar load temperature ϑ_{TSL} describing the temperature of the heat sink of the collector loop. By using the ϑ_{TSL} we achieved the following advantages:

- Applicability for various solar system-types without adaptation of the algorithm
- Differential equation is solvable analytically, accurate enough and can be integrated into standard control units

→ Possibility for implementation into small inexpensive I/O-Controllers!

The disadvantage of using the ϑ_{TSL} is that a failure in the discharging loop also decreases the expected yields a little bit. In order to get a sufficient difference of measured and expected output (>20 %) for an alarm signal, a high limit cut-out has to occur on a sunny day. This means that the detection of this kind of failure is less quick.

The simple mathematical model for simulating the working collector loop results from the heat balance of the whole collector loop. **Figure 3** gives a schematical drawing for a collector loop with an external heat exchanger. Treatment of pipe heat losses inside and outside of the building occurs within the algorithm but is neglected here. The pump energy that leads to an increase in temperature of the fluid can be neglected for big solar systems. It is not discussed further.

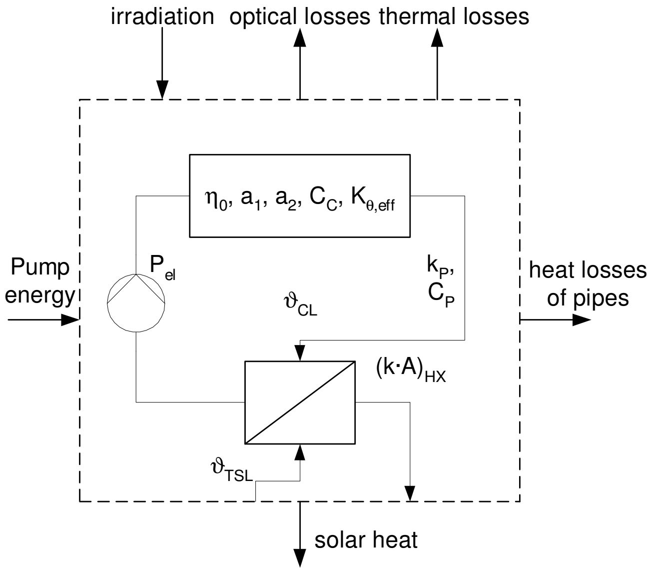

Fig. 3. Schematic diagram of the heat balance of a collector loop in operation

An ordinary quadratic differential equation describes the mean temperature of the collector loop:

$$C_{CL}\cdot\frac{d\vartheta_{CL}}{dt}=\eta_0\cdot K_{\theta,eff}\cdot G_g-\left(a_1+a_2\cdot(\vartheta_{CL}-\vartheta_a)+k_P\right)\cdot(\vartheta_{CL}-\vartheta_a)-k'_{HX}\cdot(\vartheta_{CL}-\vartheta_{TSL})$$

Eq. 1

ϑ_{CL} is the mean temperature of the collector loop. G_g is the total irradiance on the tilted surface. Parameters are the collector properties η_0, $K_{\theta,eff}$, C_C, a_1, a_2, the properties of the pipes k_P and C_P and the heat transfer coefficient of the heat exchanger $(k \cdot A)_{HX}$. C_{CL} is the total heat capacity of the collector loop ($=C_C+C_P$). ϑ_a is the ambient air temperature and ϑ_{TSL} is the typical solar load temperature.

k'_{HX} is derived from the heat transfer property of the heat exchanger $(k \cdot A)_{WT}$. It describes the heat transfer rate relative to the temperature difference (ϑ_{CL}-ϑ_{TSL}). This conversion is done in the algorithm with equation 2 (without derivation). The primary and secondary heat capacity flow rates $\dot{m} \cdot c_f$ (Indices: CL = collector loop, BL = Buffer charge loop) are to be entered as parameters. The heat exchanger effectiveness ε is also calculated in the algorithm.

$$k'_{HX} = \begin{cases} \dfrac{2 \cdot \varepsilon \cdot \left(\dot{m} \cdot c_f\right)_{BL} \cdot \left(\dot{m} \cdot c_f\right)_{CL}}{2 \cdot \left(\dot{m} \cdot c_f\right)_{CL} - \varepsilon \cdot \left(\dot{m} \cdot c_f\right)_{BL}} & \forall \left(\dot{m} \cdot c_f\right)_{CL} > \left(\dot{m} \cdot c_f\right)_{BL} \\ \dfrac{2 \cdot \varepsilon \cdot \left(\dot{m} \cdot c_f\right)_{CL}}{2 - \varepsilon} & \forall \left(\dot{m} \cdot c_f\right)_{CL} \le \left(\dot{m} \cdot c_f\right)_{BL} \end{cases} \qquad \textbf{Eq. 2}$$

The Input/Output-formula [2] for calculating the daily expected yield Q_{CL} follows after integrating equation 1 (without derivation).

$$Q_{CL} = -\eta_0 \cdot \overline{K_{\theta,eff}} \cdot H_{insuf} + \eta_0 \cdot \overline{K_{\theta,eff}} \cdot H_{Day} - Q_{th} - Q_{Cap} \qquad \textbf{Eq. 3}$$

Eq. 3 describes the typical population in an Input/Output-Diagram. It implicitly depends on the typical solar load temperature.

- The insufficient irradiation H_{insuf} increases with ϑ_{TSL}. This irradiation part is not utilisable because the temperature level of the collector is not yet high enough to load the storage tank.
- Thermal losses during operation increase with the mean temperature level of the collector loop which is depending on ϑ_{TSL}.

The different heat loss mechanisms of a thermal solar system are shown in an Input/Output-Diagram in **Fig. 4** with measured data. Herein the capacity effects are not plotted.

I Optical losses

II Thermal losses while temperature level not high enough

III Thermal losses during operation of collector loop

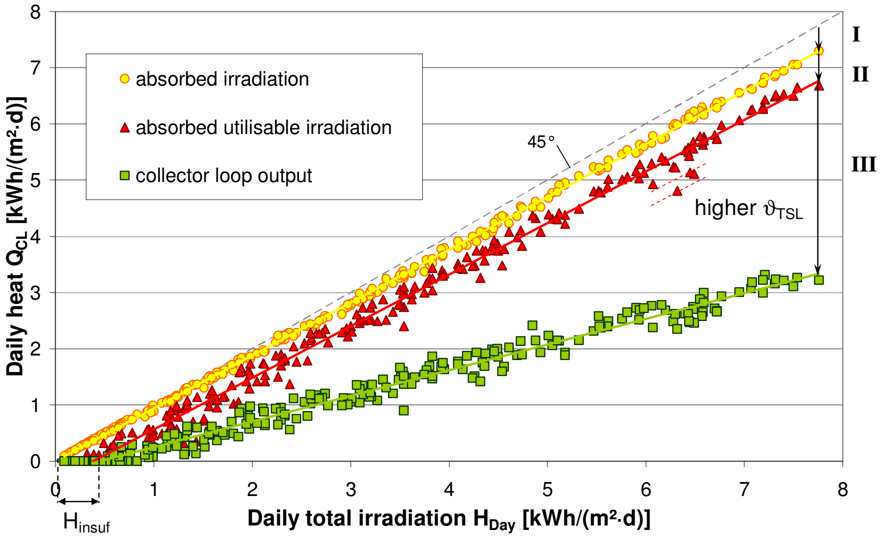

Fig. 4. Different heat loss mechanisms shown in an Input/Output-Diagram for a solar system in Munich (110 m²), having a low solar fraction and accordingly a small insufficient irradiation

The mathematical model proved its accuracy and applicability in all 12 different solar systems. The mean deviation between measured and expected output is less than 10 %.

2.3 Sensitivity analysis

The uncertainty of the Input/Output-Procedure u(ΔQ) depends on the uncertainties of parameters, measured values and simplifications of the simulation. Comparisons with TRNSYS results showed that the simplifications can be neglected, while the solar system is running properly. The uncertainties of the collector properties come from different testing conditions. Their uncertainty values can be taken from [1]. The uncertainties of the other relevant parameters were assumed conservatively.

Tolerances of the sensors and systematic errors in measurement cause the uncertainties of the measured values. Only for ϑ_{TSL} that is measured under the insulation of the storage instead of inside the storage tank a systematic error was considered.

The joint influence of the uncertainties of parameters and measurement on the uncertainty of the I/O-Procedure was analysed in a sensitivity analysis. Therefore the original values μ of the parameters and the measured data were modified with their standard uncertainty s. The effect was calculated with data of one year of a typical solar system. The following diagram shows the mean influences on the uncertainty of the expected (simulated) value $u(Q_{exp})$.

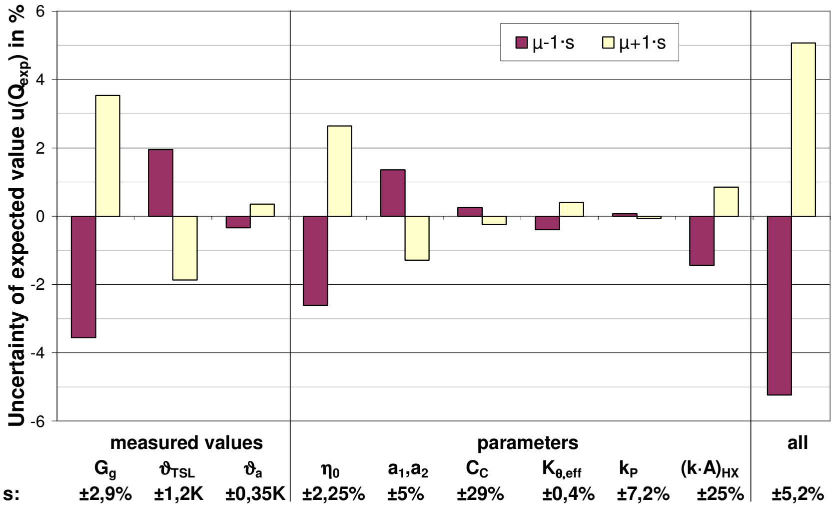

Fig. 5. Mean uncertainty of the expected daily collector output $u(Q_{exp})$ based on the uncertainties of measured values and important parameters.

All the individual uncertainties have to be added as root sum of squares because they do not occur in the same direction. The mean uncertainty of the expected yield of the collector loop results to 5,2 %. It is strongly influenced by the measurement of the irradiance with the photovoltaic sensor. By additional individual calibration on a solar tracker and consideration of the incidence angle this influence was reduced by a factor of 3. Among the parameters the uncertainty of the zero loss coefficient η_0 has the biggest influence. Its uncertainty as well as the uncertainties of the other collector properties a_1, a_2, C_C and $K_{\theta,eff}$ are mainly determined by varying test conditions (e. g. diffuse radiation) according to EN 12975-2. These uncertainties can not be corrected unless the test conditions are given in the test report or the properties have to be related to a fixed basis.

The uncertainty of the measured yield of the collector loop $u(Q_{meas})$ was also determined with the uncertainties of parameters (density and heat capacity of the fluid) and measurement (volume flow rate and temperature difference). It is approx. 4 %.

Taking both effects into account, the standard uncertainty of the Input/Output-Procedure u(ΔQ) follows to about 7 %. If the limit of tolerance between measured and simulated yield of e. g. 20 % is exceeded, which is the triple standard uncertainty of the procedure, a fault is existent with a probability of 99 %.

Conclusion

- Quality assurance of solar thermal systems is necessary because failures cannot easily be recognised by an operator.
- The ISFH-Input/Output-Procedure is automatically and in situ controlling the measured yield of the collector loop by comparing it with a simulated value.
- The dynamic simulation algorithm to calculate the expected yield can be integrated into standard control units because the mathematical model is simple and analytically solvable. This enables low-cost Input/Output-Controllers.
- The mathematical model has been validated against measured data of 12 different solar systems. The average deviation is under 10 % which exceeded our expectations.
- The model is applicable for various solar systems without adaptation of the algorithm.
- The uncertainty of the I/O-Procedure concerning the uncertainties of parameters and measured data is about 7 %. If the limit of tolerance between measured and simulated yield of e. g. 20 % is exceeded a fault is existent with a probability of 99 %.
- RESOL will offer inexpensive I/O-Controllers in 2006 for about 1000 € incl. sensors.

Acknowledgements

The authors wish to thank the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) for funding the research project (contract no. 032 9718A).

As well, we are thankful for the confidence and the engagement of the hardware-partners RESOL and INGA, the software-company DR. VALENTIN ENERGIESOFTWARE and the collector manufacturers SOLVIS, VIESSMANN, WAGNER and BUDERUS.

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