QUASI-DYNAMIC ANALYSIS OF THERMAL PERFORMANCE OF PARABOLIC TROUGH COLLECTORS

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Abstract

Thermal performance testing of parabolic trough collectors and collector loops plays an important role in prototype testing, collector certification and solar field commissioning. When testing for thermal performance, power output is calculated from measurements of mass flow, heat capacity and temperature difference between in- and outlet of the collector row. Testing conditions such as ambient temperature, irradiance and wind velocity are recorded. For the application of the commonly used steady-state testing analysis fluctuations especially in inlet temperature, irradiance and mass flow rate must be kept within a very small range. This restricts suitable testing periods when testing needs to be carried out outdoors and at commercial installations.

Accepting wider ranges of data fluctuations the quasi-dynamic testing method is the preferred approach for obtaining a power output characterization. The underlying quasi-dynamic model as well as the data analysis based on deriving model parameters from preprocessed test data by means of multiple linear regression are described and discussed in this paper. Results are presented and compared to those obtained by steady-state analysis. Tests of a process heat collector carried out at DLR in Cologne serve as data base for this investigation.

Keywords: parabolic trough, thermal performance testing, quasi-dynamic conditions, combined uncertainty, qualification

1. Introduction

A quasi-dynamic test procedure for flat plate and vacuum tube collectors was developed and established in EN 12975-2 [1]. In comparison to long existing steady-state testing procedures, its requirements for stability of testing conditions are less stringent (see Table 1) allowing a wider range of variation of irradiance, mass flow and fluid inlet temperature. This not only proves beneficial in terms of reducing collector testing times but is also more suited to typical test conditions of concentrating collectors [2]. Due to their larger module size and aperture area concentrating collectors for process heat or power generation are typically tested outdoors and thus subject to weather conditions. Concessions with respect to the stability of the above test parameters facilitate test control, time requirements and installation cost. However, current procedures are restricted to small units, as they assume negligible fluid residence time.

As the constraints in terms of testing conditions stated in Table 1 were formulated for non- or low concentrating systems, they have to be adapted for concentrating collectors, i.e. by replacing global by beam irradiance.

	Steady-State	Quasi-Dynamic
T_{in}	± 0.1 K	± 1 K
T_a	± 1.5 K	-
irradiance	G>700 W/m², ±50 W/m²	300 W/m² < G <1100 W/m²
mass flow rate	±1%	±1%

Table 1. Allowed variations in testing parameters for steady-state and quasi-dynamic testing, excerpt from [1]

2. Performance Testing

2.1. Test set-up and conditions

The investigated system was a Solitem PTC1800 collector for process steam generation operated with pressurised water.

Fig. 1. Process heat troughs at the DLR test facility

Test Day	Inlet Temperature	Weather Conditions	Steady-State Evaluation at solar noon	Quasi-Dynamic Evaluation
#1	40°C	clear sky, single cloud	√	√
#2	130°C	clear sky, high cirri	√	√
#3	155°C	clear sky, small clouds	√	√
#4	100°C	clear sky, high cirri	√	√
#5	36°C	clear sky, cloud after s n	√	√
#6	120°C	partly overcast after s n	-	√

Table 2. Performance Testing Conditions (s n = solar noon)

Table 2 gives an overview of performance testing conditions. Test data sequences within 15 min around solar noon are evaluated following the steady-state method (for details see Table 3), during these testing times the collector inlet temperature varied within ±0.25 K and the direct normal irradiance within ±50 W/m² except for days #2 and #6. Variations in mass flow rate amounted to 3% of the mean value. For quasi-dynamic analysis the data base was expanded to test data with inlet temperature variations smaller than ±1 K.

2.2. Performance measurements and uncertainty

The useful thermal collector output corresponds to the increase in fluid enthalpy and is calculated from the measured mass flow rate, temperatures at the inlet and outlet and fluid specific heat capacity according to

$$\dot{Q}_{gain} = \dot{m} \cdot \bar{c}_p (T_{out} - T_{in}) . \tag{1}$$

Measurements of testing conditions such as direct normal irradiance and reflector cleanliness serve for rating the performance in terms of efficiency

$$\eta_{th} = \frac{\dot{m} \cdot \bar{c}_p (T_{out} - T_{in})}{A \cdot \chi \cdot G_b} . \tag{2}$$

The uncertainty of the steady-state measurements is evaluated as combined standard uncertainty according to the Guide to the Expression of Uncertainty in Measurement (GUM) [3]. The application to steady-state parabolic trough performance testing is described in [4].

Due to the nature of quasi-dynamic testing there are no repetative measurements for specific operation points but series of measurements under varying conditions. Hence, Type A uncertainty is difficult to determine. For this reason only Type B uncertainties caused by the uncertainty of the measurement equipment itself are evaluated in this case. As similar conditions in terms of mass flow rate, irradiance and temperature difference across the collector prevailed during testing this uncertainty is assumed constant for the independent and dependent variables of the model equations.

2.3. Model equations for steady-state and quasi-dynamic testing

Steady-state collector efficiency is expressed in terms of optical efficiency and thermal losses depending on the reduced temperature difference to the surroundings T_m^*

$$\eta_{th} = \eta_{opt,b} - a_1 \cdot T_m^* - a_2 \cdot G_b (T_m^*)^2 \qquad \text{with} \qquad T_m^* = \frac{T_m - T_a}{G_b} \tag{3}$$

$$\eta_{th} = \eta_{opt,b} - a_1 \cdot \frac{T_m - T_a}{G_b} - a_2 \cdot G_b \left(\frac{T_m - T_a}{G_b} \right)^2 . \tag{4}$$

Multiplying by incident beam radiation yields the specific collector power

$$\frac{\dot{Q}_{gain}}{A} = a_0 \cdot G_b - a_1 \cdot (T_m - T_a) - a_2 \cdot (T_m - T_a)^2 \tag{5}$$

In order to allow for the wider variations in quasi-dynamic testing conditions this model equation is complemented by a term for diffuse irradiance and one for the effective thermal capacity of the system:

$$\frac{\dot{Q}_{gain}}{A} = \eta_{opt,b} \cdot K_{\theta b}(\theta) \cdot G_b + \eta_{opt,d} \cdot G_d - c_1 \cdot (T_m - T_a) - c_2 (T_m - T_a)^2 - c_3 \cdot \frac{dT_m}{dt} . \tag{6}$$

Hence, although their target values differ the general approach is the same for steady-state and quasi-dynamic model equations, the coefficients a_1 and a_2 of equation 5 correspond to c_1 and c_2 in equation 6. Results for optical beam efficiency and heat loss terms should be very similar for both approaches.

3. Parameter Identification and Results

3.1. Parameter Identification

The parameters of the above model equations are identified using Multi-Linear Regression (MLR). For a test data matrix A containing rows of testing points, a set of parameters $\vec{a}$ and a target vector $\vec{b}$ the formulation of the minimisation criterion χ^2 for parameter identification reads:

$$\chi^2 = \left\lfloor \vec{b} - A \cdot \vec{a} \right\rfloor . \tag{7}$$

Weighting of measurements according to their reciprocal combined uncertainty is included in the matrix A, so that points of larger uncertainty have less impact on the characteristics of the fit than those with small uncertainty. Respective parameter uncertainties resulting from data uncertainty and the adequacy of the model to describe the system's behaviour are calculated from the elements on the diagonal of the covariance matrix of A, while its off-diagonal elements describe the correlation of the parameters obtained. [4]

3.2 Steady-State Results

The evaluation of the steady-state tests yields the results listed in Table 3. As illustrated in Figure 2 uncertainties of measurements at high reduced temperature difference are comparatively high. This is caused by fluctuations in measurement conditions.

	T_{in} [°C]	TB_{out} [°C]	$\dot{m}$ [kg/h]	G_b [W/m²]	χ [-]	T^*_m [Km²/W]	$u(T^*_m)$ [Km²/W]	η [-]	$u(\eta)$ [±]
#1	39.92	56.66	1805	557	1	0.024	0.0009	0.682	0.019
#2	129.21	134.91	1794	684	0.994	0.207	0.0162	0.592	0.069
#3	153.68	160.66	1773	792	0.994	0.203	0.0038	0.593	0.025
#4	99.09	107.63	1860	742	0.984	0.117	0.0066	0.647	0.022
#5	35.12	43.79	1868	894	1	0.038	0.0023	0.680	0.022

Table 3. Steady-state test data and evaluated performance with respective uncertainties

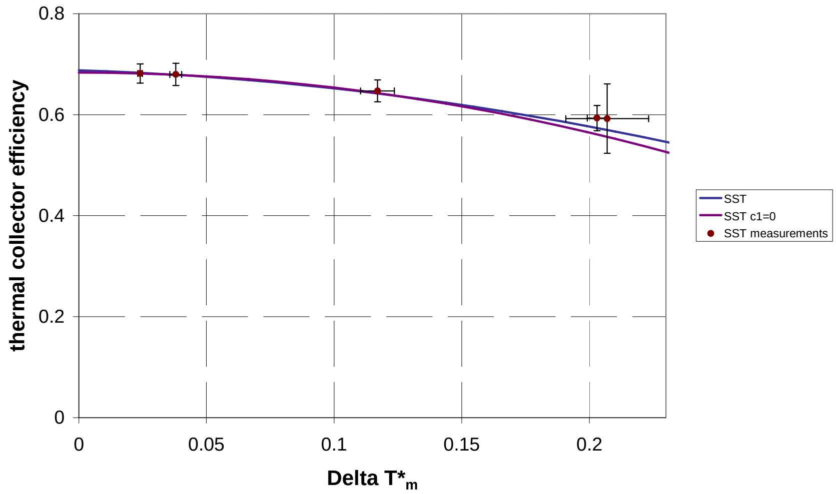

Fig. 2. Thermal collector efficiency as a function of reduced temperature difference to the surroundings obtained from steady state testing

The model parameters identified are listed in Table 4. The number of free parameters is reduced by setting the thermal loss coefficient (see 3.4.2). In combination with the graphs in Figure 2 it can be deduced that both sets of parameters fit the testing results equally well. In term of uncertainty however, the formulation without linear thermal loss term (a_1=0) is preferred.

model parameter		units	full model eq.		model eq. with a_1=0	
			value	uncertainty (k=1)	value	uncertainty (k=1)
$\eta_{opt,b}$	optical efficiency	-	0.6864	0.032	0.6833	0.014
a_1	thermal loss	W/m²K	0.1058	0.087	0	-
a_2	thermal loss	W/m²K²	0.0026	0.006	0.0033	0.001

Table 4. Collector parameters according to steady-state testing

3.3 Incidence Angle Modifier

Collector performance is always referenced to the beam irradiance in the aperture area, thus already including the effect of the angle of incidence as cosine factor. The additional influence of the angle of incidence of the incoming solar irradiance on the collector output is expressed as the incidence angle modifier (IAM), either by means of a complete function or using discrete nodes and interpolating in-between. The latter is particularly advantageous when investigating more complex collector geometries like linear Fresnel systems. A possible function describing the IAM is a polynomial of the absolute value of θ:

$$K_{\theta b}(\theta) = b_0 + b_1 \cdot \theta + b_2 \cdot \theta^2 + b_3 \cdot \theta^3 \tag{8}$$

IAM function parameters				
parameter	b_0	b_1	b_2	b_3
units	-	$(°)^{-1}$	$(°)^{-2}$	$(°)^{-3}$
Value	1	$-5.782\ 10^{-3}$	$1.485\ 10^{-4}$	$-2.955\ 10^{-6}$
uncertainty (k=1)	0.002	$1.02\ 10^{-3}$	$4.36\ 10^{-5}$	$5.22\ 10^{-7}$

IAM nodes					
angle	0°	20°	40°	60°	90°
value	1	0.924	0.830	0.586	0
uncertainty (k=1)	0.034	0.033	0.032	0.031	-

Table 5. IAM function parameters and nodes

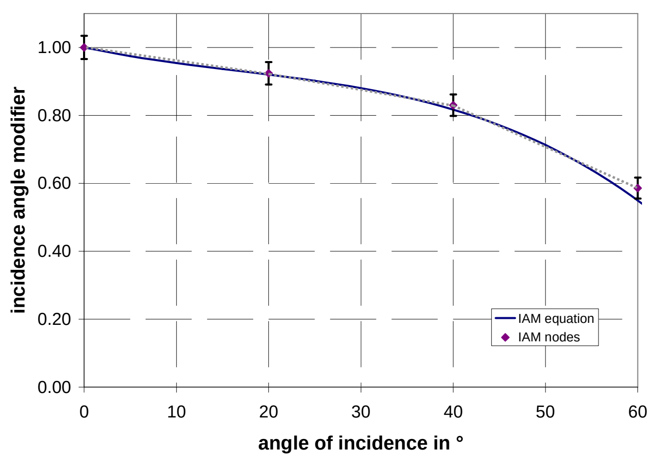

Fig. 3. Collector IAM as a function of angle of incidence comparing the IAM equation and node approach

As illustrated in Figure 3 deviations in resulting IAM values are small compared to data uncertainty. They can be further decreased by adding nodes in the relevant range of angles of incidence, provided there is sufficient test data.

3.4 Quasi-Dynamic Results

The results of the parameter identification of quasi-dynamic collector performance testing are stated in Table 6.

model parameter	units	value	uncertainty (k=1)
$\eta_{opt,b}$	-	0.683	0.006
$\eta_{opt,d}$	-	0.012	0.034
c_1	W/m²K	0	-
c_2	W/m²K²	0.0046	0.0003
c_3	J/m²K	2100	600

Table 6. Collector parameters according to quasi-dynamic testing

3.4.1. Optical efficiencies

In quasi-dynamic analysis optical collector efficiency is distinguished with respect to the nature of the irradiance. While optical efficiency for beam irradiation is clearly an important characteristic of a collector the relevance of diffuse irradiance for concentrating systems can be argued. The possible contribution of the latter is limited to a fraction of the incident diffuse radiation determined by the concentration ratio of the system. Uncertainty in determining diffuse optical efficiency is typically high because of low sensitivity of the specific thermal power and relatively high measurement uncertainty.

3.4.2. Heat loss terms

Multi-Linear Regression is best suited to multivariate model equations of linear independent quantities. In the case of performance equations with several heat loss terms all depending on the temperature difference to the surroundings and powers thereof there is a strong non-independence of quantities to be fitted. This leads to high sensitivity of the parameters to slight deviations in measurement points (uncertainty) and hence increased parameter uncertainty as shown for the steady-state model equation. In order to make the parameter identification more robust it is worthwile considering the elimination of some of the terms provided this does not compromise the overall fit quality. In the present case the linear term may be dropped (see Figure 2 and Table 3).

3.4.3. Effective heat capacity

The identification of the effective heat capacity of an installation from quasi-dynamic test data is challenging for two reasons: Most importantly, due to the restriction in testing conditions changes in mean system temperature are small and can be masked by signal fluctuations. Furthermore, because of the typically small changes in temperature the capacitive term only contributes very little to the target value that is used in the minimisation criteria i.e. the specific collector output. Consequently, the uncertainty of c_3 is typically quite high. Nevertheless, values identified by MLR are physically consistent and of the expected order of magnitude compared to theoretical values.

4. Comparison

Within the specified uncertainty there is good agreement of the identified values of optical beam efficiency for both steady-state and quasi-dynamic analysis methods. The thermal heat loss terms a_2 and c_2 however, differ by about 40%. This discrepancy originates from the difference in expressing collector performance in the two cases: Equation 6 decouples effects of optical and thermal loss mechanisms while the heat loss coefficient a_2 in equation 4 is effectively determined from $(T_m - T_a)/G_b$ data. For constant levels of beam irradiance this yields consistent results. Testing outdoors throughout the year this condition is difficult to fulfill in practice. If levels of beam irradiance vary between testing days/points, however, this strongly affects values of a_2. Particularly hot tests carried out at low levels of irradiance lead to too high values to be fitted and consequently result in a too low heat loss coefficient as in the above case. This effect is less pronounced for the full model equation (a_1 or $c_1 \neq 0$) that is problematic in terms of uncertainty, however.

As expected there is little difference in terms of shape characteristics between the simulated performance of the two model equations on an exemplary day. Under quasi-dynamic operation conditions performance fluctuations are mainly caused by changes in irradiance. A typical characteristic of the specific collector output as shown in Figure 4 exhibits alternating slight over- and underestimations of calculated power compared to measured power. This effect arises from the least-squares method used to identify the empirical parameters of the collector model.

Due to very small changes in mean system temperature the effect of the additional capacitive term in the quasi-dynamic model equation is barely visible.

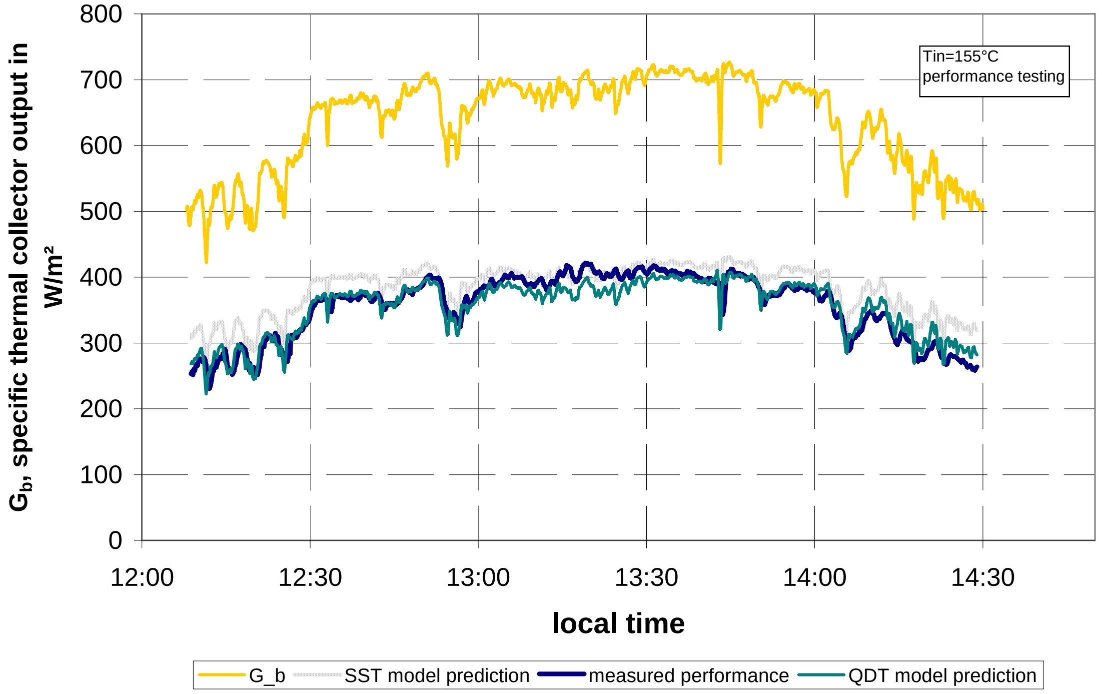

Fig. 4. Comparison of measurement data and results of the quasi-dynamic (QDT) model for an exemplary testing day operating the collector at a mean inlet temperature of 155°C

Furthermore, a significant time shift of 30 to 60 s between the measured and modeled performance is observed, with the measured performance following the modeled. This characterizes the inertia of the system beyond its effective heat capacity and fluid transit time.

5. Conclusion

Steady-state and quasi-dynamic testing and analysis of the thermal performance of a process heat parabolic trough collector was carried out following procedures of EN-12975-2 developed for flat plate collectors. Performance parameters were identified from measured data by means of MLR. There is good agreement of the resulting values for optical beam efficiency for both analysis methods. Discrepancies between identified thermal loss coefficients are attributed to variations in irradiance levels on different testing days affecting the steady-state parameter identification. Values for diffuse optical efficiency and effective heat capacity are physically cosistent and of the right order of magnitude. As they have little effect on the performance of a parabolic trough collector under the present testing conditions their uncertainty is regarded as acceptable.

Quasi-dynamic performance testing has proved beneficial for outdoor testing of concentrating systems and is a first step towards dynamic testing of larger installations. Parameter identification routines are being improved and data quality assessment implemented.

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Symbols

a_1, a_2	K m²/W, (K m²/W)²	thermal loss parameters
A	m²	aperture area
b_0, b_1, b_2, b_3	-,(°)$^{-1}$,(°)$^{-2}$,(°)$^{-3}$	empirical coefficients of IAM function
c_1, c_2, c_3		empirical collector parameters (heat loss, effective heat capacity)
c_p	J/(kg K)	specific heat capacity
G, G_d, G_b	W/m²	global irradiance, direct irradiance, beam irradiance (normal to collector aperture)
k	-	coverage factor
$K_{\theta b}$	-	incidence angle modifier for direct radiation
$\dot{m}$	kg/s	mass flow rate
$\dot{Q}_{gain}$	W	heat gain
T_m^*	K m²/W	reduced temperature difference
t	s	time
T_{in}, T_{out}, T_a, T_m	°C	fluid inlet, outlet, ambient, mean temperature
$u(x_i)$	*	standard uncertainty of x_i
η_{th}	-	thermal collector efficiency
$\eta_{opt,b}$	-	optical beam efficiency
$\eta_{opt,d}$	-	diffuse optical efficiency
θ	°	angle of incidence
χ	-	collector cleanliness factor, minimization criterion

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