LONG TERM PERFORMANCE PREDICTION FOR DHW SOLAR SYSTEMS BASED ON INPUT-OUTPUT TEST METHOD

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ABSTRACT

A Long Term Performance Prediction (LTPP) method based on the results obtained with the Input-Output test method for DHW Solar Systems, developed by the Collector and System Testing Group (CSTG,1987), is described. An analyses of the influence of measurement errors in the LTPP is presented.

KEYWORDS

Long Term Performance Prediction (LTPP); Input-Output (I-O) Test Method; Domestic Hot Water (DHW) Solar System

INTRODUCTION

The basic decision criteria for the purchase of a solar water heater are the cost of the system and the value of the energy delivered by the system over its lifetime. To determine the latter, a standard test procedure is necessary. This procedure should: i) allow prediction of long term average performance for any set of reasonable operating conditions; ii) have sufficient accuracy to permit a meaningful ranking of candidate systems; and iii) not impose a significant cost burden.

In Europe the Solar Collector and System Testing Group (CSTG, 1987) developed a test procedure for which the system is considered to be a black box with certain input-output parameters. This method is very flexible for extrapolation to different utilization conditions. In this work a LTPP method, based on this test method is presented. A systematic analysis of measurement errors and their consequences for the uncertainty of the LTPP can be found in (B.Bourges et al.,1989) and will be summarized here.

TEST PROCEDURE

The CSTG test procedure is based on the linear Input-Output model for the daily performance of solar water heaters. According to this model the heat Q [in MJ] added to the tank during the day is a simple linear function

$$Q = \alpha_0 + \alpha_H H + \alpha_T T \quad \text{with} \quad T = (T_a - T_s) \quad (1)$$

of three variables,

H = daily total solar irradiation on collector aperture [MJ/m^2],
 T_a = daytime average ambient temperature [$^{\circ}\text{C}$], and
 T_s = temperature of storage tank at start of day [$^{\circ}\text{C}$],

with three coefficients, α_0 , α_H and α_T . Storage is assumed well mixed at the start of the day. The relation is valid only for positive Q . A sample plot of test data is presented in Fig.1. It refers to one of three systems tested in different European Laboratories during a Round Robin test programme (1986-1987), following the CSTG procedure.

Fig.1 Input-Output Diagram for a DHW solar system (BP-Calpak).

The essential steps of the CSTG test procedure are the following:

- 1) **Preconditioning:** before the start of the all-day test, water at constant temperature T_c is circulated through the system (with collector shielded from sun) until the entire system is at uniform temperature $T_s = T_c$.
- 2) **Exposure:** from 6:00 to 18:00 (solar time) the system is allowed to function normally, and the solar radiation H during this period is recorded. The wind speed should not exceed the range of 3-8 m/s, and use of fans is recommended to maintain 3-5 m/s. No water is withdrawn during this time.
- 3) **Draw-off:** At 18:00 three tank volumes are withdrawn at constant flow rate of $0.600 \text{ m}^3/\text{h}$, while replenishing the tank with cold water at constant temperature T_c (same as at start of day). The temperature T_{out} during this withdrawal is monitored, as function $T_{\text{out}}(V)$ of the withdrawn volume V . This temperature profile is called "draw-off temperature profile".
- 4) **Loss coefficient of storage:** The heat loss coefficient of the tank, U_s , is determined in a separate test by measuring the temperature decrease during the night after the tank has been filled with hot water.

PRECEDITION OF LONG TERM PERFORMANCE

Day-by-Day Simulation

The CSTG test procedure determines the parameters α_0 , α_H and α_T as well as U_s and the draw-off profile γ ,

$$\gamma = 1 - \int_0^V \frac{dQ}{Q_0} \quad (2)$$

which is the energy remaining in the tank after extraction of a volume V of water, with $Q_0 = C[T_{\text{out}}(V=0) - T_c]$ where $C = V_s \rho c_p$ (V_s -storage tank volume; ρ -water density; c_p -water specific heat). Assuming that the system does not change and that the operating conditions (load, insolation

and ambient temperature) are known, one can predict the long term average performance of the system. We choose to state it in terms of Q , the long term average daily useful energy supplied by the system.

To calculate Q we begin with the input-output relation for an arbitrary day i :

$$Q_i = [\alpha_o + \alpha_H H_i + \alpha_T (T_{a,i} - T_{s,i})]_+ \quad (3)$$

where the subscript i indicates that all quantities correspond to day i . Only positive values are counted, as indicated by the $+$ subscript of the bracket; during days with negative values the system is not turned on and Q_i vanishes.

The energy in storage is measured relative to the cold water temperature $T_{c,i}$; thus the storage starts the day with an energy content of $C(T_{s,i} - T_{c,i})$. Adding Q_i to the energy at the start of the day, one finds that the total energy in storage at the end of the day is

$$Q_{e,i} = C (T_{s,i} - T_{c,i}) + [\alpha_o + \alpha_H H_i + \alpha_T (T_{a,i} - T_{s,i})]_+ \quad (4)$$

A fraction $(1-\gamma_i)$ of $Q_{e,i}$ is withdrawn as useful energy, $Q_{use,i} = (1-\gamma_i)Q_{e,i}$. On days when the storage temperature stays entirely below T_{load} , γ_i is equal to

$$\gamma_{min} = 1 - \frac{V_1}{Q_0} \quad (5)$$

where V_1 is the volume extracted for the load. But when the temperature is higher, we assume the user to temper the overheated water with cold water to obtain the temperature T_{load} and we have

$$a) \gamma_i = \text{MAX}[\gamma_{min}, (1-Q_{load,i}/Q_{e,i})] \quad \text{and} \quad b) Q_{use,i} = \text{MIN}[(1-\gamma_{min})Q_{e,i}, Q_{load,i}] \quad (6)$$

$Q_{load,i}$ is given by $V_1 \rho c_p (T_{load} - T_{c,i})$; load volume and temperature could also vary from day to day but here we have taken them as constant, for simplicity.

The heat loss from storage during the day is implicitly included in (3). To calculate the heat loss from storage during the night, we define $T_{e,i}$ as the average temperature of storage at the end of the day after the draw-off; it is given by

$$T_{e,i} = T_{c,i} + Q_{e,i} \gamma_i / C \quad (7)$$

Since the heat loss is relatively small, one can approximate the time dependence of the storage temperature during the night by a straight line that decreases from $T_{e,i}$ to $T_{s,i+1}$. From the nocturnal energy balance equation, established with this assumption, we obtain

$$T_{s,i+1} = r T_{e,i} + (1-r) T'_{a,i} \quad \text{with} \quad r = \frac{C - U_s t_{night}/2}{C + U_s t_{night}/2} \quad (8)$$

and t_{night} = duration of night [in s]; and

$T'_{a,i}$ = average temperature of the tank environment during the night following the i 'th day.

The recursion relation between $Q_{e,i}$ and $Q_{e,i+1}$ will be obtained taking (4) for day $i+1$ and substituting in it $T_{s,i+1}$, given by (8), and $T_{e,i}$, given by (7)

$$Q_{e,i+1} = C [r (T_{c,i} + Q_{e,i} \gamma_i / C) + (1-r) T'_{a,i} - T_{c,i}] + [\alpha_0 + \alpha_H H_{i+1} + \alpha_T [T_{a,i+1} - r (T_{c,i} + Q_{e,i} \gamma_i / C) - (1-r) T'_{a,i}]]_+ \quad (9)$$

This is the basic equation for the calculation of long term system performance, to be used together with

(6a) for γ_i and (6b) for $Q_{\text{use},i}$. The long term system performance Q can be calculated numerically by evaluating these equations for a sequence of meteorological data, and averaging over the year.

Simple Correlation

The calculation would be simplified greatly if one had a correlation that would yield Q directly in terms of average meteorological quantities. As a step in that direction we note that there are two thresholds in this problem. The turn-on threshold H_- corresponds to the insolation at which the $\llbracket \rrbracket_+$ in (3) vanishes. The second threshold H_+ is the value at which the insolation becomes greater than necessary to satisfy the load. A solar water heater is most cost-effective if the climate is sunny and the collector area is not oversized. For that important case H_i will rarely if ever fall outside the interval H_- to H_+ . Then threshold effects are negligible, (9) is free of nonlinearities, and averaging it over a number N of days permits to replace H_i and H_{i+1} by the average $\bar{H}$, with analogous replacements for the other variables. The result is

$$\bar{Q}_0 = \frac{1-\gamma_{\min}}{1-\gamma_{\min} r(1-\alpha_T/C)} [\alpha_0 + \alpha_H \bar{H} + \alpha_T \bar{T}_a + (1-r)(C - \alpha_T) \bar{T}_a - [(1-r)C + r\alpha_T] T_c] \quad (10)$$

This solution could be corrected for thresholds if one develops correlations between the solar fraction f (=ratio of Q and annual average load Q_{load}) = $Q/\bar{Q}_{\text{load}}$ and the variable $\bar{Q}_0/\bar{Q}_{\text{load}}$. The first approximation

$$f \doteq 1 - \exp\left(-\frac{\bar{Q}_0}{\bar{Q}_{\text{load}}}\right) \quad (11)$$

is already quite close to the exact result (maximum error about ten percent), and further corrections could be incorporated.

INFLUENCE OF MEASUREMENT ERRORS OF I-O METHOD ON LTPP.

Before discussing the predictive process of the method described above, a few comments must be made on the measurement errors associated with the I-O method itself. During 1986-87 three different solar systems were tested in different European Laboratories in a Round Robin test programme, following the CSTG test procedure. Five quantities were measured during the test:

- H = daily irradiation on collector aperture (approx. $\pm 3\%$);
- T_a = ambient temperature (± 0.5 K);
- T_{in} = temperature at inlet of storage (± 0.1 K);
- T_{out} = temperature at outlet of storage (± 0.1 K); and
- $\dot{V}$ = flow rate during draw-off ($\pm 1\%$).

The numbers in parentheses are the tolerances for the measurements as specified by CSTG (CSTG,1987), with which the tolerances reported by the individual laboratories are essentially in agreement. Based on an examination of the tolerances specified for the measurements, we have derived a priori estimates of the errors to be expected for the parameters of the linear I-O model. For a possible explanation of laboratory-to-laboratory differences of the results, we have distinguished random and systematic errors. While we find that the tolerances are, for most part, well chosen, two important sources of uncertainty remain: the determination of the effective ambient temperature T_a , and the difference $(T_s - T_{e3V})$ between the storage temperature T_s at the start of the test and the temperature T_{e3V} of storage after withdrawing 3 tank volumes.

Assuming reasonably tight control of the uncertainties due to T_a and T_c , The analysis of measurement errors indicates that the standard error σ of the regression should be around 0.5 MJ for the systems

tested under the round robin program. But in reality the standard errors of the actual test results are about twice as large, as we found by carrying out a systematic regression analysis of the Round Robin test results. The explanation for the large errors appears to reside mostly in the uncertainties of T_a and T_c , and to some extent in various and sundry little deviations from the CSTG procedure that usually pass unreported. Another part of the discrepancies may reside in shortcomings of the input-output model itself. Repeating the analysis with simulated test sequences (Ernst et al., 1987) permits to conclude that a significant part of the scatter of the data arises from I-O model itself.

We are now in a position to conclude about the LTPP method and its application. In fact we have used the method of LTPP, which we state in terms of Q , as ultimate accuracy criterion for the testing method. Considering the day-by-day simulation we developed a procedure for translating the standard error σ of the regression into the standard error σ_Q of Q . The latter depends on the utilization scenario, in particular on the climate. In absolute terms σ_Q for a given test sequence and load scenario is roughly the same for a cloudy climate ($U_{ccl}, \bar{K}_T = .36$) and for a sunny climate (Carpentras, $\bar{K}_T = .55$); the relative error for the cloudy climate is about twice that for the sunny climate.

Most Round Robin sequences, if taken alone, appear to yield acceptable precision for the LTPP, with a standard error σ_Q below 0.3 MJ. But differences between different sequences, especially from different laboratories, are much larger, with σ_Q on the order of 1MJ (relative error around 5% in sunny, 10% in cloudy climates) or even more in some cases. Thus the precision of a single sequence cannot be trusted as long as one does not exercise tighter control over systematic errors. These could be reduced to perhaps half by tightening certain aspects of the test procedure, i.e., the constancy of the cold water supply and the ventilation of the collector.

The accuracy of the results depends not only on the accuracy of the measurements, but also on the meteorological conditions and the duration of the test. The precise relationship between σ_Q and the test conditions is not very transparent, involving as it does a day-by-day simulation. As an alternative we have derived an approximate formula that shows the relationship in simple closed form. The number of test days, required to obtain a specified accuracy, depends very much on the range of insolation and temperature values during the test. Typically a range of ten to fifty days will suffice. Since the actual test conditions cannot be foreseen, it is not advisable to impose a fixed upper limit for the test duration. Instead, to minimize the duration, we urge that the error σ_Q be evaluated automatically at the end of each test day. This could be done for several typical operating conditions. The necessary calculations take less than a minute on a personal computer, and can easily be incorporated in the software of the data acquisition system.

As for the simple correlation for $\bar{Q}$ it was found that it yielded good results as long as H_1 stayed within the thresholds, H_- and H_+ , i.e. in most well designed systems in actual DHW situations.

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