Development and Validation of Quasi-Dynamic Flat-Plate Collector Testing Procedures

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1. Introduction

Focus on energy (FOE) supports solar thermal systems that displace conventional fuels by offering cash-back rebates that provide an incentive for residents to invest in this renewable energy technology. To be eligible for rebates, FOE requires solar collectors to be certified by the Solar Rating and Certification Corporation (SRCC). The certification program involves testing of the solar collectors in accordance with ASHRAE Standard 93-2003. This standard involves steady-state conditions testing in order to obtain the collector thermal performance parameters. Currently, these tests are only provided in Florida (outdoors) by the Florida Solar Energy Center (FSEC).

Wisconsin's flat plat plate collector testing program will be done at Madison Area Technical College (MATC). The UW-Solar Energy Laboratory (UW-SEL) is assisting MATC personnel in establishing a suitable implementation of the ASHRAE test method. The UW-SEL further intends to identify alternative test methods that can be done indoors or under conditions that are more suitable to Wisconsin weather, but still provide the information required by the ASHRAE 93-2003 test.

The requirement for minimum incident solar irradiance (800 [W/m^2]) defined by the ASHRAE standard is very difficult to achieve particularly during Wisconsin winter. Other international steady-state collector standards, such as the European EN 12975-2: 2001 and the ISO 9806-1, have similar requirements regarding incident irradiance. This situation means that the time required to collect a valid data set to meet those standard requirements could be very long during Wisconsin winter.

Quasi-steady collector tests appear more suitable to Wisconsin weather during the year, due to their less restricted requirement of solar irradiance. Those methods allow for variations in solar irradiance during testing, and take account of this situation by using a more detailed collector model. The minimum required solar irradiance is then much less restricted than in steady-state methods. The purpose of this research project is to explore the suitability of quasi-dynamic collector thermal performance methods and compare their results with conventional steady-state methods.

2. Quasi-Dynamic European Test Standard (EN 12975-2: 2001) Review

This test is applicable to glazed and unglazed solar collectors that operate with liquid transfer fluids, and is based in the outdoor steady state conditions test. The idea is to measure the useful energy gain of the collector under different combinations of solar irradiance (minimum global 300 [W/m^2]) and mean plate temperatures over small time intervals (5 to 10 [min]), keeping all the remaining operation parameters within a specified range. The collected measurements are feed into a detailed collector model in order to obtain the collector parameters using a multiple linear regression technique. The specified range for the non-dynamic test conditions is:

- Collector orientation and tilt angle: facing south +-5 [deg] @ 45+-5 [deg]
- Air speed: 1 to 4 [m/s]
- Fluid flowrate: 0.02 [kg/s-m^2] +- 1% (10% between different days)

The recommended test sequence consists of 4-5 days, but the actual duration of the test will of course depend on the weather conditions during testing. Day types (DT) are defined as different combinations of mean plate temperature and weather conditions. At each DT, the inlet temperature shall be fixed to satisfy the mean plate temperature requirements defined in Table 2.1[1].

Table 2.1: Combination of Mean Plate Temperature and Weather Conditions for Test Days

Mean plate temperature	Clear sky	Partly cloudy
Ta ±3K	DT 1[2]	DT 2
(Ta + Thot) / 3	DT 3[3]	DT 3
2 * (Ta + Thot) / 3	DT 3	DT 3
Thot (see Table 2)	DT 4	DT 4

It is specified that the data record shall contain enough variability and dynamic range in all important normal operating conditions, to give decoupled collector parameters. The election of the hottest temperature (T_{hot}) is related to the collector application, and defined by Table 2.2:

Table 2.2: Highest Fluid Temperature as a Function of Collector Type

Collector type	T_{hot}
Domestic hot water preparation	Ambient temperature + 60 C
District heating	Ambient temperature + 70 C
Swimming pools	Ambient temperature + 15 C
Process heating	Ambient temperature + 90 C

2.1 Measurements and Data Collection

The following measurements shall be made during testing:

- Aperture, absorber, and gross collector area
- Fluid capacity
- Global and diffuse solar irradiance at collector aperture
- Incident longwave radiation at collector aperture[4]
- Incidence angle of direct solar radiation
- Azimuth and tilt angle
- Surrounding air speed
- Surrounding air temperature
- Inlet and outlet temperature of heat transfer fluid
- Flowrate of heat transfer fluid

All the measurements above must be collected using a sampling rate of 1 to 6 [s], and should be later averaged considering an interval of 5 to 10 [min].

The data collected should be evaluated before the collector parameters identification, to ensure its suitability and dynamic range. The evaluation procedure consists in providing

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[1] For unglazed collectors only 1 intermediate mean plate temperature is required (T_a + T_{hot}) / 2

[2] Day type 1 and 2 could last less than 1 day, but symmetric pairs are expected

[3] Day type 3 could last more than 1 day, normally 2

[4] This parameter is not measured in the steady-state test

plots that show expected relations and enough variability of the measured variables. Those plots should be included in the final results of the test.

2.2 Collector Parameters Identification

The model is basically the same as the steady-state model, but with added correction terms. In the expression below, the dependence of direct and diffuse radiation, wind speed, sky temperature, incidence angle effects and effective thermal capacitance are covered:

$$\frac{\dot{Q}}{A} = F(\tau\alpha)_{en} K\theta_b(\theta)G_b + F(\tau\alpha)_{en} K\theta_d G_d - c_6 u G^* - c_1(t_m - t_a) - c_2(t_m - t_a)^2 - c_3 u(t_m - t_a) + c_4(E_L - \sigma T_a^4) - c_5 \frac{dt_m}{dt}$$

Where the coefficients are:

- c_1: heat loss coefficient at $(T_m - T_a) = 0$ $(F_R U_L)$
- c_2: temperature dependence of the heat loss coefficient
- c_3: wind speed dependence of the heat loss coefficient
- c_4: sky temperature dependence of the heat loss coefficient
- c_5: effective thermal capacity
- c_6: wind dependence in the zero loss coefficient

A multiple linear regression should be made using the collector data that suits the test specifications, in order to simultaneously identify the collector parameters:

- $F_R(\tau\alpha)$
- $F_R U_L$
- Incident angle modifier (b_0)
- Thermal capacitance (c_5)

After all the parameters are identified, it should be determined if the coefficients c_3, c_4 and c_6 should be included in the test results. In order to be included in the test results, the T-ratio (parameter value / standard deviation) of each coefficient should be greater than 2. If this is not the case, the regression should be repeated setting the parameter to 0. By including the data that satisfies the steady state requirements, this collector model will allow for steady-state parameter identification as well.

3. Literature Review

Kratzenberg et al., Analysis of the collector test procedures for steady-state and quasi-dynamic test conditions in view of the collector coefficients uncertainties and model stability, 2005

This paper compares the collector parameters and their associated uncertainties obtained by testing the same collector under steady-state (SS) and quasi-dynamic (QD) conditions, according to the EN 12975 standard. A large data set from 3 months of operation is applied, and then separated in various single data sets fulfilling either the conditions of a complete steady-state or a complete quasi-dynamic test. The facility was located in Florianopolis, Brazil.

The data set provides 4 independent data sets for the quasi-dynamic test and one for the steady-state test. The collector parameters obtained by both methods are compared and check to see if they are “identical”. “Identical” is defined as within a 95% confidence interval taking into account the uncertainties of the parameter identification procedures.

In addition, the same procedure is applied to verify the quasi-dynamic model stability, by comparing the collector parameters obtained from 4 different datasets. The collector model used does not consider the effects of wind speed and long wave irradiance.

The results from this study are as follows[5]:

- In 3 of the 4 QD data sets, the parameter $F_R(\tau\alpha)$is statistically equal between the SS and the QD tests.
- In 2 of the 4 QD data sets, the parameter F_RU_L is statistically equal between the SS and the QD tests.
- In 1 of the 4 QD data sets, the coefficient c_2 is statistically equal between the SS and the QD tests.
- Comparing the QD data sets results, the coefficients $F_R(\tau\alpha)$, b_o (incidence angle modifier), $K_{\theta d}$ and the thermal capacitance (c_5) are stable in all 6 comparisons. Instability is detected on the quadratic heat loss coefficient (c_2), which fails 1 time and the linear heat loss coefficient, which fails twice.
- Using the obtained QD collector parameters to model the useful energy gain during data testing delivers errors below 1.6% for all 4 sets of parameters.
- In contrast, the useful energy gain predicted by the SS parameters overestimate the actual value by 6.2%.

The conclusions in the paper are the following:

- The QD collector test is more cost effective as it can be accomplished in less time.
- Due to the increased completeness of its underlying model, the QD collector coefficients can estimate the energy production of the collector with lower uncertainties than the SS estimate based on a limited model.
- Even though they cannot find full model stability of the parameters within the QD test, energy estimation using different test data sets and combining these data sets with different QD coefficients sets have high model stability. In addition, instability of the collector coefficients does not affect the stability for energy estimations.
- Diffuse fractions between 0 and 1 (instead of between 0 and 0.5) can be used in the QD test to get reliable energy estimations.

4. Proposed Activities

4.1 Dynamic Test Using Data from MATC

Measurements have been collected at MATC considering the steady-state test requirements. The plan is to use those measurements in the dynamic test data, given that the data already collected fulfill the requirements of all the sunny day weather conditions showed in Table 2.1.

The dynamic test requires the measurement of long wave irradiance, which was not measured at MATC during the steady-state test data collection. This fact means that the data from MATC does not meet all the requirements defined in the dynamic test. However the collector model for the dynamic test can still be used by setting the coefficient c_4 (related to the long wave irradiance in the collector model) to 0, and then performing the parameter identification procedure as the standard requires. The standard

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[5] Nomenclature is the same as used in section 2.2

allow to set c_4 as 0 only if its T-ratio is lower than 2, so this would be the implicit assumption of using MATC data for the sunny weather conditions.

The data required for the dynamic standard would not be complete even using all the data already collected at MATC. Measurements in partly cloudy conditions are required to complete all the DT conditions in Table 2.1. In the meantime, however, the multiple linear regression method allows obtaining the collector parameters from a selection of the entire measurements. Then, it is possible to run the method using the dynamic collector model and compare the results against the steady-state test.