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

Report 2: April, 2007
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1. Introduction

Quasi-steady collector tests, such as the European EN 12975-2: 2001, appear to be more suitable to Wisconsin weather, due to their less restrictive requirement on solar irradiance. The quasi-steady methods allow for variations in solar irradiance during testing and take account of these variations 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.

In order to implement the European EN 12975-2: 2001 test using the data collected at MATC, it was necessary to revise the manner in which experimental data are processes. This report shows the steps necessary for processing MATC collector test data to make it suitable for the application of the quasi-steady test. In addition, preliminary results are shown and the next steps of this research project are discussed.

2. Nomenclature

$(\tau\alpha)_{en}$	Transmittance-absorptance product for beam radiation at normal incidence	[-]
AI	Average interval	[s]
C	Heat capacity	[kJ/kg-K]
c_1	Heat loss coefficient at $(T_m-T_a)=0$	[W/m^2-K]
c_2	Temperature dependence of heat loss coefficient	[W/m^2-K^2]
c_3	Wind speed dependence of heat loss coefficient	[J/m^3-K]
c_4	Sky temperature dependence of the heat loss coefficient	[W/m^2-K]
c_5	Effective thermal capacity	[J/m^2-K]
c_6	Wind speed dependence in the zero loss coefficient	[s/m]
date	Date	[ymmdd]
DF	Diffuse fraction	[%]
dT_m/dt	Mean plate temperature derivative	[C/s]
E_L	Longwave irradiance	[W/m^2]
F'	Collector efficiency factor	[-]
G	Hemispherical solar irradiance	[W/m^2]
G_b	Direct solar irradiance (beam)	[W/m^2]
G_d	Diffuse solar irradiance	[W/m^2]
$K\theta_b$	Incidence angle modifier for direct radiation	[-]
$K\theta_d$	Incidence angle modifier for diffuse radiation	[-]
m_{flow}	Mass flowrate	[kg/s]
$m_{flow\ dev}$	Mass flowrate deviation	[%]
P_{in}	Inlet pressure	[kPa]
P_{out}	Outlet pressure	[kPa]
Q	Useful energy gain	[kJ]
RH	Relative humidity	[%]
ST	Solar time	[s]

T_a	Ambient temperature	[C]
T_{in}	Inlet temperature	[C]
T_m	Mean plate temperature	[C]
T_{out}	Outlet temperature	[C]
u	Wind speed	[m/s]
η	Collector efficiency	[%]
θ	Incident angle	[deg]
σ	Stefan-Boltzmann constant	[W/m^2-K^4]

3. Experimental Data Processing

The EN 12975-2: 2001 standard requires data points based on 5 to 10 minutes averages for the measured variables[1] and also sets maximum variation ranges for some parameters. The objective of the experimental data processing is to filter the data in order to provide a set of data points that meet the standard requirements. The main standard requirements are:

- Minimum solar irradiance: 300 [W/m^2]
- Collector orientation and tilt angle: facing south +-5 [deg] @ 45+-5 [deg]
- Average air speed: 1 to 4 [m/s]
- Mass flowrate: 0.02 [kg/s-m^2] +- 1% (10% between different days)

To maximize the amount of data points selected, an integration time of 5 minutes was selected. The main issues faced in data processing were:

- To select time sequences with steady state (or close to steady) inlet temperatures
- To select data points that meet the maximum deviation to the reference mass flowrate

3.1 Input Files

The input files for MATC tests were provided by the MATLAB application written by Jan Beermann (University of Wisconsin Solar Energy Laboratory), which delivers 10 second averages of the experimentally measured variables. Some of the information in the input files was not required for the quasi-dynamic test, and thus was not considered. Table 3.1 indicates the experimental data used for data processing.

3.2 File Generation for Multiple Linear Regression

The objective of the file generation step is to provide a file that contains 5 minute averages of the measured parameters during periods in which all other standard requirements are met. This file will be used to perform a multiple linear regression (MLR) step in order to obtain the final collector parameters. MATLAB was used to generate the output file for this process. The code developed allows one to provide multiple input files (from different days data) to generate a single output file.

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[1] See 2.1 in Report 1

Table 3.1: Experimental Data Considered for Quasi-Dynamic Test

Variable	Name	Units	Column in Input File
Average interval	AI	[s]	2
Inlet temperature	T_{in}	[F]	5
Outlet temperature	T_{out}	[F]	6
Ambient temperature	T_a	[F]	7
Inlet pressure	P_{in}	[psi]	8
Outlet pressure	P_{out}	[psi]	9
Solar irradiance	G	[W/m^2]	10
Wind speed	u	[mph]	11
Mass flowrate	m_{flow}	[kg/s]	13
Heat capacity	C	[kJ/kg-K]	14
Useful energy gain	Q_u	[kJ]	15
Collector efficiency	η	[%]	17
Incidence angle	θ	[deg]	18
Diffuse fraction	DF	[%]	25
Solar time	ST	[s]	19

Several filters were performed to each input file. Table 3.2 shows the operations done at each filter stage.

Table 3.2: Filter Stages Applied to Input Files

Filter Stage	Operation
1	• Selects rows with G > 300 [W/m^2] • Selects rows with m_{flow} > 0 [kg/s] • Selects rows with Q_u > 0 [kJ]
2	• Cuts transitions in T_{in} • Selects time sequences with more than 5 minutes
3	• Calculates Tm and dT_m/dt • Converts all units to SI • Removes first row at beginning of time sequences

After the 3 filter stages detailed above, the file 'data_f3' was created. This file basically corresponds to the input file in SI units without transitions in the inlet temperature, and also without time sequences lasting less than 5 minutes. In addition, 'data_f3' contains 2 new columns, the mean plate temperature T_m and its derivative dT_m/dt.

Using the file 'data_f3' the rows for calculating 5 minutes averages (30 rows) were selected, considering a reference value of approximately 0.02 [kg/s-m^2] for the mass flowrate[2]. The 2 following conditions should be met to select a set of 30 consecutive rows for averaging in each time sequence:
- The maximum allowed inlet temperature difference should be less than 1 [K]
- The average mass flowrate should be the closest to the reference value

The general approach was to select the maximum possible amount of data points in each time sequence. First, the program selects for averaging the 30 consecutive rows that have the average mass flowrate closest to the reference value. Then, it checks to ensure that there are

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[2] The standard says *'the fluid flowrate shall be set at approximately 0.02 [kg/m^2-s]'*. The reference value taken during MATC testing was 2.3 [gal/min], which corresponds to 0.0186 [kg/s-m^2] for the tested collector.

enough rows remaining to create a new data point. If yes, it selects the 30 consecutive rows with the second closest average mass flowrate to the reference value. This process is repeated until there are no 30 consecutive rows left in the time sequence.

After all the average locations in 'data_f3' are selected, the averages are calculated and stored in the output file. The output file also contains a new column with the deviation of the average mass flowrate respect to the reference value. The output file contains 5 minutes averages of the experimental data displayed in Table 3.3.

Table 3.3: Output File Content

Column	Variable	Name	Units
1	Date	date	[ymmdd]
2	Average interval	AI	[s]
3	Solar time	ST	[s]
4	Inlet temperature	T_{in}	[C]
5	Outlet temperature	T_{out}	[C]
6	Ambient temperature	T_a	[C]
7	Mean plate temperature	T_m	[C]
8	Mean plate temperature derivative	dT_m/dt	[C/s]
9	Solar irradiance	G	[W/m^2]
10	Diffuse fraction	DF	[%]
11	Useful energy gain	Q	[kJ]
12	Collector efficiency	η	[%]
13	Heat capacity	C	[kJ/kg-K]
14	Incident angle	θ	[deg]
15	Wind speed	u	[m/s]
16	Mass flowrate	m_{flow}	[kg/s]
17	Mass flowrate deviation	$m_{flow\ dev}$	[%]
18	Inlet pressure	P_{in}	[kPa]
19	Outlet pressure	P_{out}	[kPa]

Column 15 and 17 of the output file contain the average values for the wind speed and the mass flowrate deviation for each data point. This information permits a straightforward filtering process for both variables, in order to meet the standard requirements.

3.3 Long Wave Irradiance Estimation

The quasi-dynamic collector model requires as one of its inputs the long wave irradiance, a quantity that has not been measured at MATC during testing. In order to consider this parameter in the model, it has been estimated based on collected information about the relative humidity and the ambient temperature.

The heat flux on the collector provided by the sky thermal irradiance will be:

$$Q = c_4 \left(\sigma T_{sky}^4 - \sigma T_a^4 \right)$$

The sky temperature can be estimated considering the time of the day, and the ambient and dew point temperatures[3]:

$$T_{sky} = T_a \left(0.711 + 0.0056 T_{dp} + 0.000073 T_{dp}^2 + 0.013 \cos(15t) \right)^{\frac{1}{4}}$$

where T_{sky} and T_a are in degrees Kelvin and T_{dp} (dew point temperature) is in degrees Celsius. The parameter t represents the hour from midnight. The dew point temperature is estimated as a function of the ambient temperature and the relative humidity.

$$T_{dp} = T_a - \frac{100 - RH}{5}$$

3.4 Multiple Linear Regression (MLR)

The collector model proposed by the standard covers the dependence of direct and diffuse radiation, wind speed, sky temperature, incidence angle effects and effective thermal capacitance.

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

In the next expression b_0 is the incidence angle modifier:

$$K\theta_b(\theta) = 1 - b_0 \left(\frac{1}{\cos(\theta)} - 1 \right)$$

Expanding the first term in the collector model we get:

$$F'(\tau\alpha)_{en} K\theta_b(\theta) G_b = F'(\tau\alpha)_{en} G_b - b_0 F'(\tau\alpha)_{en} G_b \left(\frac{1}{\cos(\theta)} - 1 \right)$$

The MLR method requires as inputs the beam and diffuse radiation; these values can be obtained knowing the total radiation and the diffuse fraction. The method estimates the coefficients for the linear collector model, as detailed in Table 3.4.

The average power for each data point was calculated as:

$$\dot{Q} = m_{flow} C (T_{out} - T_{in})$$

The multiple linear regression was programmed using MATLAB. This allows the user of the code to perform all steps of the parameter identification process using the same routine, from raw experimental data filtering to the final results.

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[3] Solar Engineering of Thermal Processes, Duffie & Beckman, Third Edition, 2006, Page 149.

Table 3.4: Provided Values and Predicted Coefficients by Linear Collector Model

Term	Provided Value	Predicted Coefficient
1	G_b	$F'(\tau\alpha)_{en}$
2	$-G_b\left(\dfrac{1}{\cos(\theta)}-1\right)$	$b_0 F'(\tau\alpha)_{en}$
3	G_d	$F'(\tau\alpha)_{en} K\theta_d$
4	$-uG$	c_6
5	$-(T_m - T_a)$	c_1
6	$-(T_m - T_a)^2$	c_2
7	$-u(T_m - T_a)$	c_3
8	$(E_L - \sigma T_a^4)$	c_4
9	$-\dfrac{dT_m}{dt}$	c_5

4. Preliminary Results

This results are based in data collected at MATC the following dates:
- 12-09-2006 (input file 'meanmatrix_10_16')
- 12-19-2006 (input file 'meanmatrix_10_17')
- 08-02-2007 (input file 'meanmatrix_10_19')

The 3 dates above correspond to sunny days. During each day, a range of different collector inlet temperatures T_{in} were set, in accordance to standards requirements. In the data set above, the range of (T_m-T_a) goes approximately from 0 to 50 [C]. The input files do not provide the relative humidity value during testing, although this variable has been measured. For this reason, the term related to the long wave irradiance has not been considered in the parameter identification process. For further steps of this project, the MATLAB code that generates the input files will be modified to include relative humidity data.

It is important to note that the results obtained during these tests do not meet the standard requirements. The main reason is that there is no experimental data collected in cloudy days, which is required by the standard in addition to experimental data taken during sunny days[4]. Cloudy days experimental data will be further collected at MATC in May, using the same temperature range than in sunny days.

The three input files have been filtered following the steps described in section 3.2. In addition, only data points with less than 1% mass flowrate deviation were considered. The

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[4] See Table 2.1 in Report 1

output file contained a total of 94 data points. Then, it was processed using the MLR routine in MATLAB. The results are shown in Table 4.2.

Table 4.2: Predicted Coefficients by MLR

| Term	Predicted Coefficient	Value	Standard Error
1	$F'(\tau\alpha)_{en}$	0.6144	0.01967
2	$b_0 F'(\tau\alpha)_{en}$	0.06768	0.02722
3	$F'(\tau\alpha)_{en} K\theta_d$	0.9543	0.04799
5	c_1	2.330	0.5282
6	c_2	0.02592	0.004972
7	c_3	0.3397	0.2088
8	c_5	4991	437.2
9	c_6	0.004676	0.009880

The regression has a R^2 coefficient of 95.47%. At the end, the predicted collector parameters are:

- $F'(\tau\alpha)_{en}$: 0.6144

- b_0 : 0.110

- $K\theta_d$: 1.553

- c_1 : 2.330 [W/m^2-K] (heat loss coeffcient)

Note that the value obtained for $K\theta_d$ is higher than 1, which is uncommon and likely incorrect. The reason for this result lies in the collected experimental data for the incidence angle modifier prediction. As displayed in Figure 4.1, the collected data the range for the incidence angle is between 0 and 45 [deg]. At this range, the incidence angle modifier varies very little from 1 (see Figure 4.2), its value at normal incidence. For this reason, the incidence angle range in the collected data is not well suited to provide an accurate estimation of the incident angle modifier.
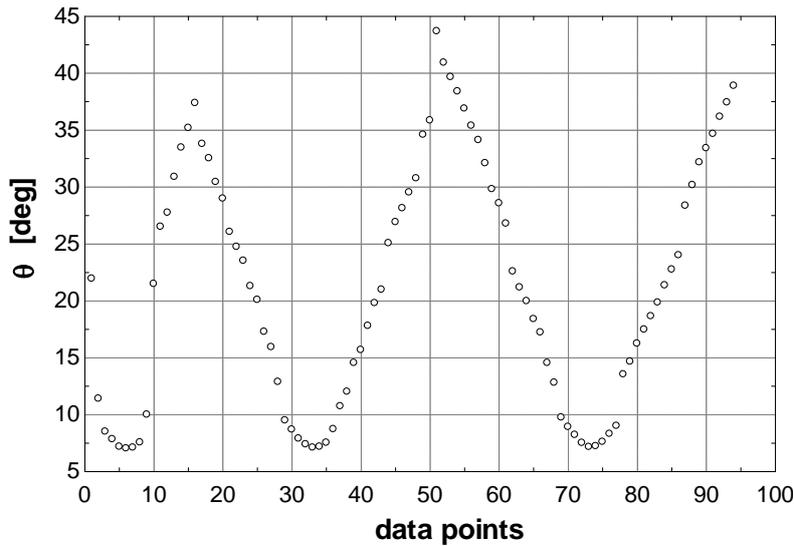
Figure 4.1: Incidence Angle Range in Filtered Data Points
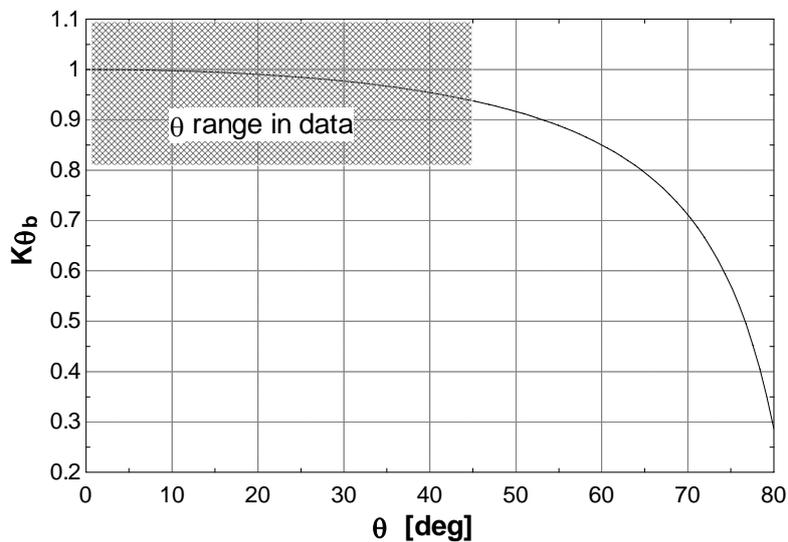
Figure 4.2: Typical Curve for Incidence Angle Modifier (Beam Radiation)

5. Next Steps

5.1 Data Collection

- Cloudy day data will be collected at MATC facility in May for at least 2 days. The setup will be the same that had been used to collect the sunny day data, as well as the range of (T_m-T_a).

- In addition, more experimental data for sunny days will be considered. These data together with cloudy day data to be collected, will complete the experimental data set required by the standard for the parameter identification process[5].

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[5] See Table 2.1 in Report 1

5.2 Code Development

- The code that provides the collected data input files will be modified to include relative humidity data, which is required for the long wave irradiance estimation. The multiple linear regression code will be modified as well, to consider long wave irradiance in the estimated correlation.

- To ensure the suitability and range of the data to be correlated, graphical tools that allow the user to plot the most relevant measured parameters will be added to the code. In addition, the code will automatically detect the temperature range considered during measuring, and then it will classify the data points accordingly.

5.3 Post-Processing of Obtained Collector Parameters

- The obtained collector parameters will be compared to those from the steady state method defined in the ASHRAE 93-2003 standard. The steady-state standard identifies less collector parameters than the quasi-dynamic European standard, so a methodology to compare both results will be developed.

- The long term thermal performance of solar water heating systems will be simulated using TRNSYS using the model used by the quasi-dynamic standard and thesteady-state standard model. A comparison will be conducted regarding the long term performance estimation capability of the models as a function of operating conditions and location.