

# **Development and Validation of Flat-Plate Collector Testing Procedures**

Report for December, 2006

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<sup>1</sup>. Currently, these tests are only provided in Florida (outdoors) by the Florida Solar Energy Center (FSEC).

Wisconsin's flat plate collector testing program will be done at Madison Area Technical College (MATC). The UW-Solar Energy Laboratory is assisting MATC personnel in establishing a suitable implementation of the ASHRAE test method. The UW 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. What follows is the third report of this activity.

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### 1. Test raw data

This chapter describes which data are recorded during the collector tests. The measurements taken for all three tests described in the last report (collector time constant test, thermal efficiency test, and incident angle modifier test) are basically the same. The following procedure applies to all three kinds of tests.

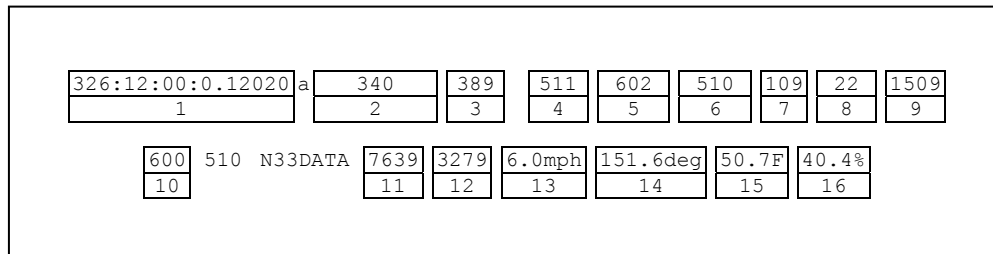
The raw test data are stored by the data logging server in text format. The 19 different values in every data package are separated by spaces. The first line in Figure 1 is an example of a data package stored by the data logging server. The 16 relevant values are numbered in Figure 2 and described in Table 1. Every variable is described in the section that follows Table 1.

All test data are logged in this raw format on the server. One log file exists for every test day, Further processing of the raw data is described in the next section of this report.

```

326:12:00:0.12020 a 340 389 511 602 510 109 22 1509
600 510 N33DATA 7639 3279 6.0mph 151.6deg 50.7F 40.4%
    
```

**Figure 1** Test data sent by data logging server



**Figure 2** Variable names for test data

**Table 1** Test data sent by the data logging server

Number	Name	Description	Example	Measured value in	Factor
1	DATE	Local date and time	305:17:52:27.70966	doy:hh:mm:ss.sssss	-
2	T0MIX_raw	Temperature outlet mixing valves	1454	mV	0.1 °F/mV
3	T1PRE_raw	Temperature inlet heaters	1202	mV	0.1 °F/mV
4	T2IN_raw	Temperature inlet collector	1204	mV	0.1 °F/mV
5	T3OUT_raw	Temperature outlet collector	1169	mV	0.1 °F/mV
6	T4AMB_raw	Ambient temperature	369	mV	0.1 °F/mV
7	PIN_raw	Pressure inlet collector	214	mV	0.02 (PSI)/mV
8	POUT_raw	Pressure outlet collector	63	mV	0.02 (PSI)/mV
9	HEAT_raw	Heater control	2866	mV	10/4096 V/mV
10	SUN_raw	Solar irradiance	-2	mV	$(1/8.64) \cdot 10^3$ (W/m <sup>2</sup> )/mV
11	GALCT1_raw	Gallons fast counter	7853	pulses	1/7463 gal/pulse
12	GALCT2_raw	Gallons slow counter	625	pulses	32768/7463 gal/pulse
13	WSPD	Wind speed	1.7	mph	1
14	WDIR	Wind direction	382.6	deg	1
15	AMBTEMP	Ambient temperature weather station	36.6	°F	1
16	RELHUM	Relative Humidity	38.1	%	1

### 1.1. Day of year and time

Every time data arrives at the data logging server, the data logger adds a time stamp to the data package. The time stamp represents local time (daylight saving time) and uses the following format:

doy:hh:mm:ss.sssss

The first three numbers represent the day of year (001...365), followed by two numbers representing the hour of the day and the next two numbers represent the minutes of the hour. The remaining digits represent the seconds of the minute given as decimal number with two digits for the integer part and 5 digits for the fractional part.

### 1.2. Temperatures

Four temperatures are measured during the test:

**T0MIX\_raw**: Fluid outlet temperature mixing valves. This temperature is used to help control the inlet temperature of the collector. It is not relevant for the test evaluation.

**T1PRE\_raw**: Fluid temperature at the heater inlet. This temperature is used to help control the inlet temperature of the collector. It is not relevant for the test evaluation and therefore measured with a lower accuracy.

**T2IN\_raw**: Fluid inlet temperature collector.

**T3OUT\_raw**: Fluid outlet temperature collector.

**T4AMB\_raw**: Ambient air temperature.

All temperature values must be multiplied by 0.1 to obtain values in °F.

### 1.3. Pressure values

Two pressure values are measured during the test:

**PIN\_raw**: Pressure at collector inlet.

**POUT\_raw**: Pressure at collector outlet.

The pressure data must be multiplied by 0.02 to receive values in PSI.

### 1.4. Heater control

The heaters are controlled by the control voltage given in the next column **HEAT\_raw**. The heater voltage value must be multiplied by 10/4096 to receive values in Volt.

### 1.5. Radiation data

**SUN\_raw**: The solar irradiance is measured by a pyranometer; the measured voltage is recorded in 100mV. The factor  $8.64 \mu\text{V}/(\text{W}/\text{m}^2)$  must be applied to receive values in

watts per square meter, so the recorded values must be multiplied by  $(1/8.64)*10^3$  to receive values in  $W/m^2$ .

### **1.6. Flow rate**

The next two columns contain the flow meter data. The columns represent two integer counters (**GALCT1\_raw**, **GALCT2\_raw**). As soon as the counter in the first column exceeds the value of 32768, it is set to zero and the value in the second column is increased by 1. The flow meter gives one pulse for every revolution and 7463 pulses correspond to 1 gallon. The volume in gallons can be calculated from the recorded values using the following equation:  $V=(GALCT1\_raw +GALCT2\_raw *32768)/7463$ .

The volume of two measurements A and B can be used to calculate the mean flow rate during the time between the measurements:  $(V(B)-V(A))/\Delta time[min]$ .

### **1.7. Wind velocity, wind direction, ambient temperature, relative humidity**

A weather station provides the values of wind velocity (variable **WSPD**, miles per hour), wind direction values (variable **WDIR**, degree), ambient temperature (**AMBTEMP**, degree Fahrenheit) and relative humidity (**RELHUM**, percent). The values are converted to the right units by the weather station, so no further conversion is necessary.

## 2. Raw data processing

The raw data for one day are logged in a single file. This file is then processed using sed and awk scripts. The sed script shown in Figure 3 removes undesirable parts of the raw data, e.g., the units sent by the weather station. The awk script shown in Figure 4 performs the required calculations to generate values of the variables in the desired units.

```
s/
//g
s///g
/^\$/d
/Trying/d
/Connected/d
/Escape/d
s/a//
s:/ / /g
s/N33DATA//
s/ / /g
s/mph//
s/deg//
s/F//
s/\%///
```

**Figure 3** Sed script: sed\_first removes undesirable parts of the raw data, written by Thomas Kaminski, MATC

```
BEGIN { heat = 0 ; time = 0.0 ; gallons = 0 ; pyranometer = 0 ;
printf
("DATE,SECONDS,T0MIX,T1PRE,T2IN,T3OUT,T4AMB,PIN,POUT,HEAT,SUN,SP,GA
LLONS,WSPD,WDIR,TEMP,RH\n");
}
{
time = $2*60*60 + $3*60 + $4 ;
gallons = ( $15 + $16*32768) / 7463.0 ;
pyranometer = $13*10.0/8.64 ;
if(((10*$12/4095)-2) < 2) heat = 0 ; else heat =
100*(10*( $12/4096) -2)/8 ;
printf
("\'%d:%d:%d:%4.1f,%f,%4.1f,%4.1f,%4.1f,%4.1f,%4.1f,%5.3f,%5.3f,%4.
2f,%6.1f,%4.2f,%10.4f,%4.2f,%4.2f,%4.2f,%4.2f\n", \
$1,$2,$3,$4,time,$5/10,$6/10,$7/10,$8/10,$9/10,$10*0.02,$11*0.02,he
at,pyranometer,$14/10,gallons,$17,$18,$19,$20);
}
```

**Figure 4** Awk script awk\_first generates values in the desired units, written by Thomas Kaminski, MATC

Using these scripts a new test data file is generated, here called the production file. The production file contains text data in 17 columns separated by comma, which are listed and described in Table 2. These files will be used for the data analysis.

Number	Name	Description	Units
1	DATE	Local date and time	doy:hh:mm:ss.sssss <sup>1)</sup>
2	SECONDS	Time of day in seconds	sec
3	T0MIX	Temperature outlet mixing valves	°F
4	T1PRE	Temperature inlet heaters	°F
5	T2IN	Temperature inlet collector	°F
6	T3OUT	Temperature outlet collector	°F
7	T4AMB	Ambient temperature	°F
8	PIN	Pressure inlet collector	PSI
9	POUT	Pressure outlet collector	PSI
10	HEAT	Heater control	V
11	SUN	Solar irradiance	W/m <sup>2</sup>
12	SP		
13	WSPD	Wind speed	1
14	WDIR	Wind direction	1
15	GALLONS	Value of gallons counter	gal
16	TEMP	Ambient temperature weather station	°F
17	RH	Relative Humidity	%

**Table 2** Test data production file columns <sup>1)</sup>doy = day of year



### 3. Data analysis collector time constant test

#### 3.1. Data processing

The time constant test has been described in Report 2 (Nov 2006) chapter 1. A program has been written to analyze the test data and calculate the time constant as defined in ASHRAE 93-2003. The program code is presented in Figure 5, a description of the code follows here:

First the test data are loaded into the variable file and the start and stop points of the time constant test are set. The variable start defines the point where the steady state period ahead to the shading of the collector begins; the variable teststart defines the point where the collector is shaded from the sun. These values are set manually.

The following steps are then performed to generate the result (according numeration in the code in Figure 5):

1. The inlet temperature must remain constant within  $\pm 2\%$  or  $1.8^\circ\text{F}$  whichever is greater. The mean value of the inlet temperature during the test and ahead to the test is calculated, the upper and lower limit is determined based on the mean value. The inlet temperature is plotted together with the limits in the first plot of the result sheet and can then be checked by inspection.
2. The temperature difference between ambient and inlet temperature must be within  $\pm 1.8^\circ\text{F}$  ahead to the test and during the test. The temperature difference is calculated and plotted. The requirement can then be checked by inspection. The ambient temperature must vary no more than  $2.7^\circ\text{F}$  to maintain steady state conditions. This requirement is met if the temperature difference requirement is met, so a separate check for ambient temperature is not necessary.
3. The solar irradiance ahead to the test must be at least  $790 \text{ W/m}^2$  and is not allowed to vary more than  $\pm 32 \text{ W/m}^2$ . This requirement is checked by calculation of the mean value for the period ahead to covering the collector and setting the upper limit  $32 \text{ W/m}^2$  above the mean value and the lower limit  $32 \text{ W/m}^2$  below the mean value. In case the value of the lower limit is smaller than the required minimum of  $790 \text{ W/m}^2$ , the lower limit is set to  $790 \text{ W/m}^2$ . If even the upper limit is below the required minimum, both limits are set to  $790 \text{ W/m}^2$ . The solar irradiance and the two limits are then plotted into the second plot on the result sheet and the irradiance can be checked by inspection.
4. The volume flow rate must remain constant within  $\pm 2\%$  or  $0.005 \text{ gpm}$  whichever is greater. The mean value of the volume flow during the test and ahead to the test is calculated, the upper and lower limits are determined based on the mean value. The volume flow rate is plotted together with the limits in the fourth plot of the result sheet and can then be checked by inspection.
5. The last step is the calculation of the time constant. The point where the collector gets shaded is the start point for the calculations. This point has been set before, in the variable teststart. The initial collector outlet and inlet temperatures at the point teststart are read from the test data and the initial temperature difference is calculated. Then the temperature differences of the measurements following

teststart are calculated until the difference is 0.368 times the initial difference. The time constant is the time difference between the initial and the final point. A plot is generated to visualize the calculation.

```

% Parameters
file=B_mean01;
start=25443;
stop=26004;
teststart=25623;

% 1. Inlet temperature check
clear UL;
clear LL;
clear Mean;
Mean(1:(stop-start)+1)=mean(file(start:stop,5));
UL=Mean(1:(stop-start)+1)+max(1.8,0.02*Mean(1,1));
LL=Mean(1:(stop-start)+1)-max(1.8,0.02*Mean(1,1));
subplot(4,1,1);
plot(file(start:stop,1),file(start:stop,5:7),file(start:stop,1),UL,file(start:stop,1),LL);
xlabel('Time of day [sec]');
ylabel('Temperature [F]');
legend('Inlet temp','Outlet temp','Ambient temp','Upper limit temp','Lower limit temp');

% 2. Temperature difference check
tempdiff=file(start:stop,5)-file(start:stop,7);
clear UL;
clear LL;
clear Mean;
Mean(1:(stop-start)+1)=0;
UL=Mean(1:(stop-start)+1)+1.8;
LL=Mean(1:(stop-start)+1)-1.8;
subplot(4,1,2);
plot(file(start:stop,1),tempdiff,file(start:stop,1),UL,file(start:stop,1),LL);
xlabel('Time of day [sec]');
ylabel('Temperature [F]');
legend('Difference inlet ambient','Upper limit','Lower limit');

% 3. Solar irradiance check
clear UL;
clear LL;
clear Mean;
Mean(1:(teststart-start)+1,1)=mean(file(start:teststart,10));
LL_abs(1:(teststart-start)+1,1)=790;
UL=Mean(1:(teststart-start)+1,1)+32;
if UL(1,1)<LL_abs(1,1)
    UL=LL_abs;
end
LL=Mean(1:(teststart-start)+1,1)-32;
if LL(1,1)<LL_abs(1,1)
    LL=LL_abs;
end

```

```

subplot(4,1,3);
plot(file(start:stop,1),file(start:stop,10),file(start:teststart,1),UL,
file(start:teststart,1),LL);
xlabel('Time of day [sec]');
ylabel('Solar irradiance [W/m2]');
legend('Solar irradiance','Upper limit','Lower limit');

% 4. Volume flow rate check
clear UL;
clear LL;
clear Mean;
Mean(1:(stop-start)+1)=mean(file(start:stop,12));
UL=Mean(1:(stop-start)+1)+max(0.005,0.02*Mean(1,1));
LL=Mean(1:(stop-start)+1)-max(0.005,0.02*Mean(1,1));
subplot(4,1,4);
plot(file(start:stop,1),file(start:stop,12),file(start:stop,1),UL,
file(start:stop,1),LL);
xlabel('Time of day [sec]');
ylabel('Volume flow rate [gpm]');
legend('Volume flow rate','Upper limit','Lower limit');
% Save plot
hgsave('TimeConstantSSCCheck')

% 5. Calculation of collector time constant
t_f_e_initial=file(teststart,6);
t_f_i=file(teststart,5);
diff_initial=t_f_e_initial-t_f_i;
i=teststart;
diff(i,1)=diff_initial;
diff_rel(i,1)=diff(i,1)/diff_initial;
while (diff(i,1)>0.368*diff_initial)
    i=i+1;
    diff(i,1)=file(i,6)-file(i,5);
    diff_rel(i,1)=diff(i,1)/diff_initial;
end
clf('reset');5
clear UL;
clear LL;
UL(teststart:i,1)=1;
LL(teststart:i,1)=0.368;
plot(file(teststart:i,1),diff_rel(teststart:i,1),file(teststart:i,1),
UL(teststart:i,1),file(teststart:i,1),LL(teststart:i,1));
xlabel('Time of day [sec]');
ylabel('Temperature difference ratio');
legend('Actual divided by initial temprature difference','Initial
value','1/e value');
'Start time: '
disp(file(teststart,1))
'End time: '
disp(file(i,1))
timeconstant=file(i,1)-file(teststart,1)
% Save plot
hgsave('TimeConstant')

```

Figure 5 Matlab code for the time constant test analysis

### 3.2. Results

Two time constant tests were performed at MATC on 22/11/2006. The test data have been analyzed with the program described above and the results are presented here. The parameters are listed in Table 3. The first number is the row in the test data file and the value in brackets is the related time of day in seconds. Also the results of the steady state checks and the calculations of the time constant are shown in Table 3. As both tests fail in the steady state check, the test results are not conforming to the ASHRAE 93-2003 standard.

<b>Variable</b>	<b>Test 1</b>	<b>Test 2</b>
start	24900 (46312.55944 sec)	25443 (46870.61639 sec)
teststart	25168 (46588.00007 sec)	25623 (47055.63542 sec)
stop	25500 (46929.18969 sec)	26004 (47447.35607 sec)
<b>SSC check<sup>1)</sup></b>	failed	failed
<b>Result</b>	73 sec	78 sec

**Table 3** Parameters for collector time constant calculation <sup>1)</sup> SSC = steady state conditions

In Figure 6 the steady state behavior of Test 1 and in Figure 8 the steady state behavior of Test 2 are presented. Inlet temperature, inlet and ambient temperature difference, and volume flow rate are within the required limits. However, the solar irradiance before the shading exceeds the lower limit in both tests, so steady state conditions are not given. The test result can not meet the ASHRAE 93-2003 requirements. The calculation of the time constant for Test 1 results in a value of 73 seconds, Test 2 results in a value of 78 seconds, as shown in Figure 7 for Test 1 and Figure 9 for Test 2.

The ASHRAE 93-2003 Standard does not precisely define how long steady state conditions must be maintained before the collector is shaded. The intervals used here have been chosen arbitrarily. The Standard should describe in more detail what requirements are expected over which time period during the collector time constant test.

3.2.1. Collector time constant Test 1

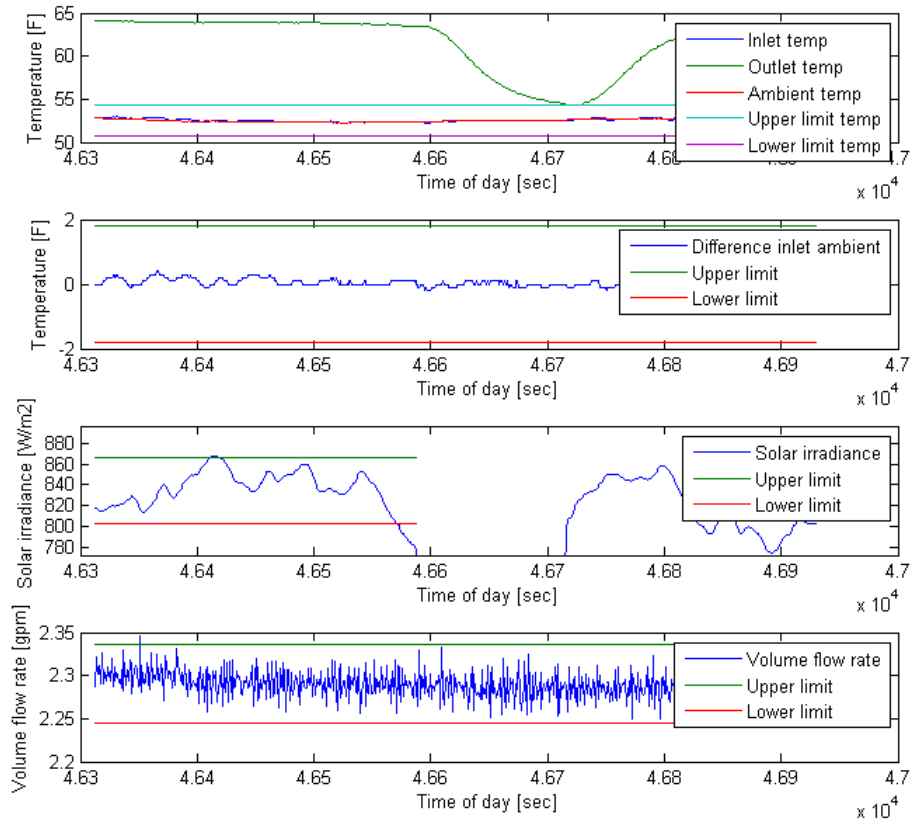


Figure 6 Steady state conditions check for Test 1\

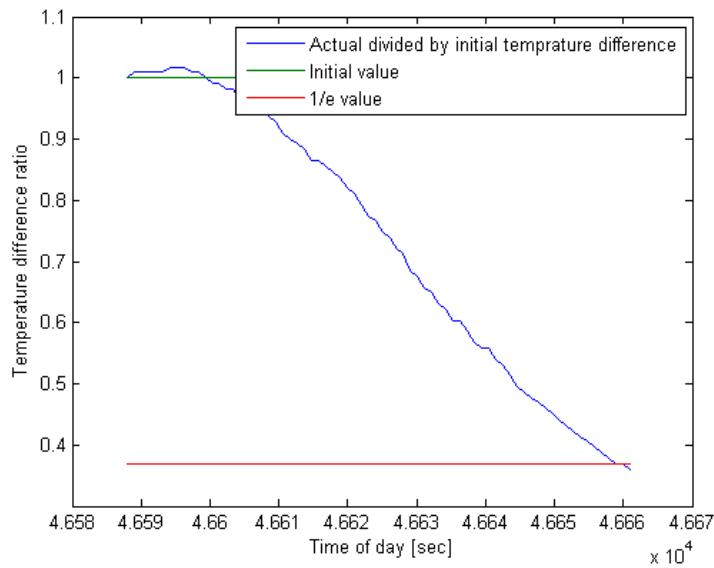
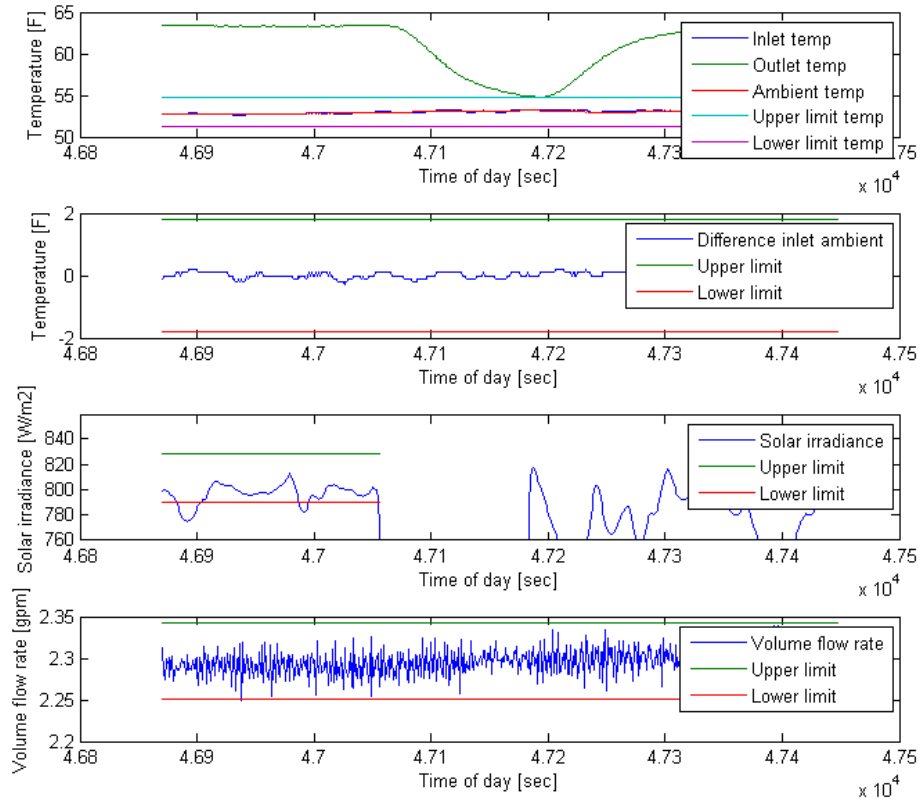
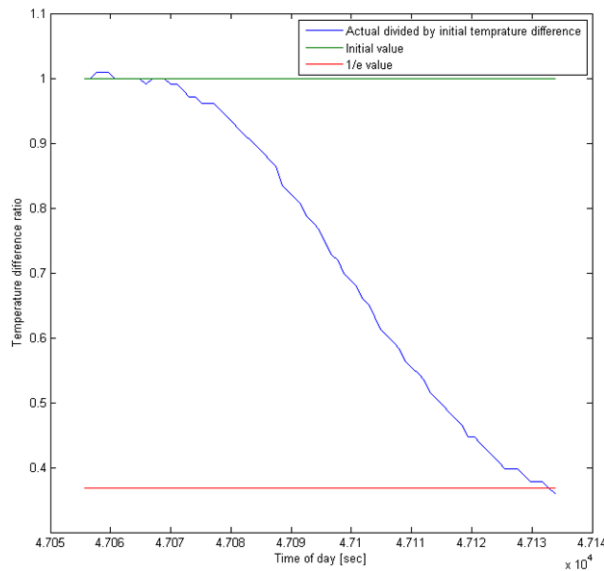


Figure 7 Collector time constant calculation for Test 1

**3.2.2. Collector time constant Test 2**



**Figure 8** Steady state conditions check for Test 2



**Figure 9** Collector time constant calculation for Test 2

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<sup>1</sup> *ANSI/ASHRAE Standard 93-2003, Methods of Testing to Determine the Thermal Performance of Solar collectors*. ISSN 1041-2336, ASHRAE, Inc., 2003, 1791 Tullie Circle, Ne, Atlanta, GA30329