Development and Validation of Flat-Plate Collector Testing Procedures

Report for November, 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[1]. 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 second report of this activity.

Table of contents

1. Collector time constant test

The *collector time constant* is a measure of the thermal response time of the collector. Knowledge of the response time is important for setting an appropriate time period for the thermal efficiency test described below as well as for simulations of collector energy gain under real conditions. It is also useful for determining an appropriate period to average and report experimental data collected during the test.

In order to quantify a collector's time constant, a collector time constant test is performed as-defined in the ASHRAE 93-2003 test standard. The collector time constant test is performed in two steps as follows. First, the collector is exposed to the sun and the collector inlet temperature is adjusted to the ambient temperature. As soon as steady state conditions have been achieved, the solar irradiance is abruptly reduced to zero. Removing the solar irradiance can be done by moving the collector to face north or by shading the collector with an opaque shield. With removal of the irradiance, the collector inlet and outlet temperatures are continuously observed until the difference between the outlet and inlet temperature decreases to 30% of its initial value. Based on this test, the collector time constant is the time, τ, needed for the temperature difference between the collector outlet and inlet to decrease to a fraction of 1/e ≈ 0.368 of its initial value. The following equation defines the calculation of the time constant.

$$\frac{t_{f,e,\tau} - t_{f,i}}{t_{f,e,initial} - t_{f,i}} = 0.368 \qquad (1)$$

It is important to note that the collector time constant test requires appropriate controls to maintain the collector inlet temperature ($t_{f,i}$)constant at the ambient temperature throughout the test.

According to section 8.3.2 of ASHRAE 92-2003, the collector inlet temperature must be adjusted to within ±1°C (±1.8°F) of the ambient temperature and controlled to within ±0.05°C (±0.09°F) of the set value. The collector fluid flow rate must be maintained as described in Chapter 3.4 of this report. The incident solar flux must be greater than 790 W/m^2 (250 Btu/h-ft^2). What exactly is meant by maintaining steady state conditions is discussed in Section 3 of this report.

2. Thermal efficiency test

The *thermal efficiency test* was described in the Chapter "Introduction to inlet temperature distributions" in the last report. While the measurements required for the test and the analysis of the test data are relatively simple, the test standard requirements concerning steady-state conditions are demanding.

A complete thermal efficiency tests requires 16 measurements (called data points) as described in the last report. The efficiency for one data point is calculated from measurements taken over a defined time period, here called the *data period*. Steady-state conditions must be maintained during the data period . Only the data from measurements taken during this data period are used to calculate the efficiency for each data point. However, steady-state conditions must also be maintained during a defined time interval prior called the *pre-data period*. In section 3.1 of the Standard, the *test period* is defined as the time over which steady state conditions are maintained for a single measured efficiency point. This means that the test period as defined in the Standard consists of the pre-data period and the data period defined in this report. The situation is visualized in Figure 1.

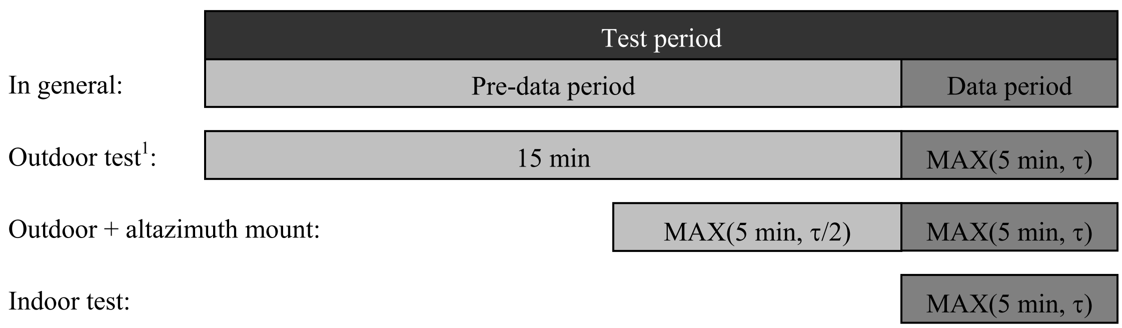

Figure 1 Test and predata periods for the efficiency tests (τ = collector time constant[1] fixed test mount)

The lengths of the *pre-data period* are defined in section 8.3.3.3 of the Standard. The lengths of the pre-data periods depend on the kind of test apparatus used. For the outdoor tests with a fixed test mount, the pre-data period is 15 min; for outdoor tests with an altazimuth (adjustable azimuth) mount (which allows to track the sun) pre-data period is reduced to 5 minutes or half of the collector time constant, whichever is larger; and for the indoor test with a solar irradiance simulator, no pre-data period is required. The length of the *data period* is, independent of the test apparatus and is the greater of a 5 minute interval or the collector time constant.

Pre-data periods have a large effect on the time required for a collector test. In fact, the pre-data period is responsible for the main part of time consumed for a single outdoor fixed-mount test. Assuming a collector time constant of less than 5 minutes (typical for flat plate collectors), the data period during which the efficiency measurements are recorded would be 5 minutes long while the pre-data period is 15 minutes. So 75% of the minimum time required for the test is used for the pre-data period and any measurements taken during this period do not directly contribute to the archived test results. It is not clear if the long pre-data period results in an increase in test quality..

At this point, three different time periods relevant for the efficiency tests are defined. During these periods, steady-state conditions must be maintained. The following section will deal with these steady-state conditions.

3. Steady state conditions

The ASHRAE 93-2003 Standard describes test methods for *steady-state* or *quasi-steady-state* thermal performance, time response and angular response tests. The purpose of performing the tests under steady-state conditions is to avoid transient influences during the test that could inflate the "measured" performance of a collector. The Standard rigorously defines the conditions for steady-state conditions, as listed in Table 1.

Table 1 Steady state conditions of the ASHRAE 93-2003 standard for outdoor tests

Variable	Maximum variation		Lower limit	Upper limit	Reference
	In between data periods	Within data period			
Total irradiance normal to sun	-	±32 W/m^2 (±10 Btu/ft2 · h)	790 W/m^2	-	8.3.1.1.1 8.3.1.1.2
Fraction of diffuse radiation	-	-	-	20%	8.3.1.1.3
Incident angle modifier[2)]	-	±2%			8.3.3
Ambient temperature	range < 30°C (54°F)	±1..5°C ±2.7°F	-	-	8.3.1.1.4 8.3.3.3
Wind	-	-	2.2 m/s	4.5 m/s	
Flow rate	same flow rate for all data points (0.02 kg/s-m^2)	±0.005 gpm[1)]	-	-	8.3.1.1.6 8.3.3.3
Inlet temperature	-	±Max of (1.0°C/1.8°F, 2%)	-	-	8.3.3.3
Incident angle[3)]	-	±2.5°			8.3.3
Symmetry to solar noon[4)]	-	-	-	-	8.3.3.2

1) At a given flow rate of 2.3 gpm this would mean a maximum variation of 0.00217 % (!).
2) Only for thermal efficiency tests
3) Only for incident angle modifier test
4) Only for fixed-mount test apparatus: for every inlet temperature two measurements shall be taken before and two after solar noon, additionally those measurements must form symmetric pairs with respect to solar noon.

Clearly, several of the variables have extremely tight tolerances on variability. These tolerances make the tests both difficult and time-consuming. At this point, we are optimistic that alternative test methodologies which relax the current tolerances are possible while still preserving the integrity of the collector efficiency derived from the data. If alternative methods can be identified and validated, the cost of collector testing along with the time required may be significantly reduced.

3.1 Solar irradiance

3.1.1 Minimum value

Section 8.3.1.1.1 of ASHRAE 93 requires that the average global solar irradiance on a surface normal to direct beam radiation not less than 790 W/m^2 (250 Btu/ft2-h).

The standard does not specify whether the average of the data period or the complete test period (pre-data and data period) shall be used.

Additionally, if a fixed test mount is used, the incident angle of direct beam radiation is not necessary normal to the collector plane. The pyranometer measures the total irradiance upon the collector plane but not necessarily normal to direct beam radiation. If the Standard requirement described above were realized exactly, a second sun tracking pyranometer would be required to measure the total normal direct beam radiation or a calculation method for the total normal direct beam radiation should be provided by the Standard. The requirement to measure efficiency at near-normal incidence conditions as defined in section 8.3.3 of the Standard requires that the collector orientation be adjusted such that the incident angle *modifier* is within a range of ±2% of the normal value. This can, depending on the collector angular response, allow incident angles up to 40°, as shown in Chapter 3.1.4 of this report.

3.1.2 Maximum variation

The maximum allowed variation in solar irradiance upon the collector plane is ±32 W/m^2 (±10 Btu/ft^2 h). For some reason at this point new time intervals are defined in the Standard. The maximum variation shall not occur "for durations of 10 minutes or two time constants, whichever is greater, both prior to and during the period when data are taken." (ASHRAE 93-2003, 8.3.1.1.2). Figure 2 tries to relate the new time intervals for steady-state solar irradiance to the previously defined requirements.

Does the new required time interval increase the time needed for a single test? For outdoor tests with a fixed test mount, more time is required only if the collector time constant is greater than 7.5 min. As most flat plate collectors have smaller time constants the required time is not increased. However, for the outdoor test with an altazimuth mount the pre-data period would at least double in length, in the worst case ($\tau > 10$ min) the length would be four times the length defined above for the pre-data period.

It is not clear how the irradiance variation related to a time interval with a length of MAX(10 min,2τ) should be applied to a data period (= "period when data are taken") with length MAX(5 min, τ). The Standard needs to be clarified in this area.

3.1.3 Fraction of diffuse radiation

The Standard requires that the diffuse irradiance on the aperture plane be a maximum of 20% of the total irradiance on the collector aperture plane. The diffuse fraction can be calculated by the following equation (ASHRAE 93-2003, eq. 8.19).

$$G_d = G_t - G_{DN}\cos(\theta) \tag{2}$$

G_t is the total irradiance, measured by the pyranometer in the collector plane, and G_{DN} is the direct beam radiation, measured by the sun-tracking pyrheliometer.

The diffuse fraction shall have a value of less than 20% throughout the test. Table 9.1 in ASHRAE 93-2003 requires reporting the diffuse fraction only at the beginning and the end of the data period.

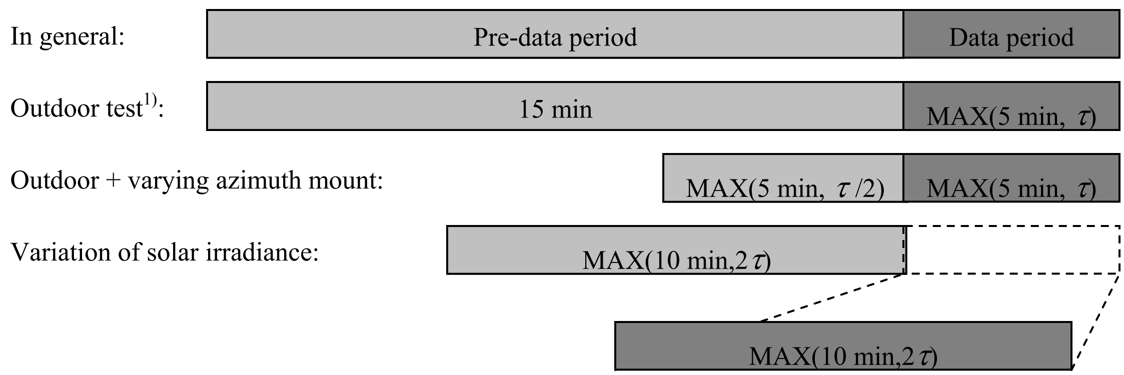

Figure 2 Variation of solar irradiance, 1)fixed test mount

3.1.4 Incidence angle

The incidence angle, θ, is the angle between the incident direct beam radiation and the normal to the collector plane. ASHRAE 93-2003 defines the following incidence angle modifier-related requirements:

8.3.3: ***Experimental Determination of Collector Thermal Efficiency:*** *For tests conducted to determine the thermal efficiency at near-normal incident conditions, the angle of incidence shall be in the range in which the incident angle modifier varies no more than ±2% from the normal incidence value. For tests conducted to determine the incident angle modifier, the orientation of the collector shall be such that the collector is maintained within ±2.5 degrees of the angle of incidence for which the test is conducted, throughout the test period.*

The definition related to the incidence angle modifier tests refers to a certain range of incident angles (±2.5°). This means that for example the incident angle modifier test for an incident angle of 60° can be performed with actual incidence angles between 58° and 62°. Furthermore this means that the collector orientation must be adjusted, with respect to the solar direct beam irradiance, to meet these requirements. The incidence angle modifier test is discussed in more detail in the next section of this report. This incidence angle requirement is not a problem for the actual test setup at MATC.

The second definition in the cited paragraph of the test standard is related to the thermal efficiency tests. The most important question is if the defined range of allowed incidence angle modifier values requires that the collector track the sun during the efficiency tests. If so, manual adjustments in collector orientation throughout the tests would be required. The following analyses show that solar tracking is not required.

For the following considerations, a precise definition of the possible test mounts is required. The different kinds of test mounts are not defined in section 3.1 of the ASHRAE 93-2003 Standard. However an implicit definition can be found in the following citation from the Standard.

8.3.3.2: Number of Data Points. … For the case with a fixed-mount test apparatus, two of the four data points shall be taken during the time period preceding solar noon and the other two shall be taken in the period following solar noon, the specified periods being chosen so that the data points represent times symmetrical to solar noon. This *requirement is made so that any transient effects that may be present will not bias the test results when they are used for design purposes. The requirement for obtaining data points equally divided between morning and afternoon is not mandatory when tested with an altazimuth mount.*

An altazimuth mount can be used to move an instrument along two perpendicular axes of motion (vertical movement = altitude or tilt, horizontal = azimuth). So the altazimuth mount can track the sun throughout the day and maintain an incident angle close to normal (0°). This means the altazimuth mount can perform thermal efficiency tests during the whole day and comply with the incidence angle requirement.

The "fixed mount test apparatus" as mentioned in the cited paragraph must be fixed in at least one of the possible dimensions (tilt, azimuth). The test mount at MATC can be manually adjusted in azimuth. So it is desirable to perform the test with the test mount fixed facing south as this reduces the effort.

What does the requirement of maintaining the angle of incidence in a range where the incident angle modifier varies no more than ±2% mean for a fixed test mount? To answer this question, the incident angle modifier curve for a single glass cover collector given in the Standard (ASHRAE 92-2003, Figure 9) is evaluated. Normal incidence is defined as an angle of incidence, θ, of zero. The normal incidence value of the incident angle modifier (8.3.3, ASHRAE 93-2003) is the value of the incident angle modifier at an incidence angle of zero. At this angle, the value of the incident angle modifier is always unity by definition. According to section 8.3.3 (ASHRAE 93-2003), the thermal efficiency test is to be conducted at near-normal incident conditions. The latter are defined as all angles of incidence for which the value of the incident angle modifier varies no more than ±2% from its normal incidence value. As the normal incidence value is unity and the incident angle modifier is between zero and unity per definition, the range of incident angles is determined by the value of 1 – 2% * 1 = 0.98 for the incidence angle modifier. For a single glass cover collector given in the Standard, a range of incidence angle modifiers between 1 and 0.98 yields a corresponding range of allowed incidence angles from 0° to 41° as shown in the modified figure below.

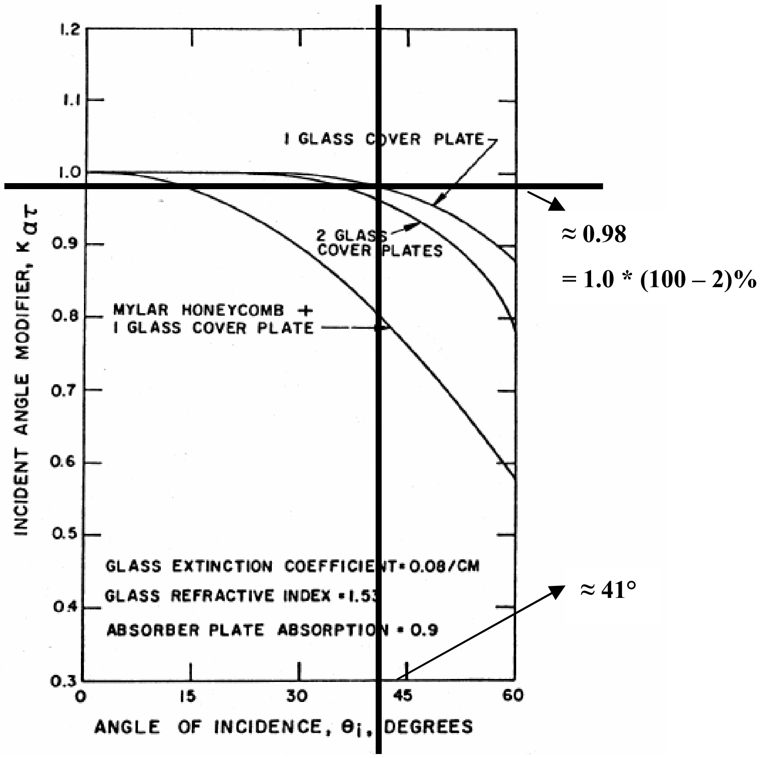

Figure 3 Range of incidence angles for near-normal condition, based on ASHRAE 93-2003 Figure 9

Using a fixed mount apparatus (fixed azimuth angle and slope of the collector) the calculated range of allowed incident angles determines a time window in which the tests can be conducted during the day. However, the range of allowed incidence angles is sufficiently wide such that the possibilities for thermal efficiency tests at MATC are not affected.

3.2 Ambient temperature

3.2.1 Thermal efficiency test

The range of ambient temperatures of all data periods shall be less than 30°C (54°F) (ASHRAE 93-2003: 8.3.1.1.4). This requirement relates different data points of one complete test with each other. Within one test period, the test standard requires to "maintain" the ambient temperature within a variation of ±1.5°C (2.7°F) during the pre-data period. Although not mentioned explicitly in the standard, the same requirement should be applied for the data period.

3.3 Wind speed

The Standard requires the wind speed lie between 2.2 and 4.5 m/s (5 and 10 mph) (ASHRAE 93-2003 5.3.1.1.5). This requirement applies to the test period and a MAX(10 min,2 τ) interval prior to the test period. The Standard further stipulates that some collectors with glass glazing may require a longer interval of up to 20 minutes or four time constants.

If taken literally, this requirement would mean that ahead of every test period (which is defined by the Standard as the time over which quasi-steady-state conditions are maintained, ASHRAE 93-2003, 3.1) an additional time period with the described wind conditions would be required. The situation is shown in the figure below.

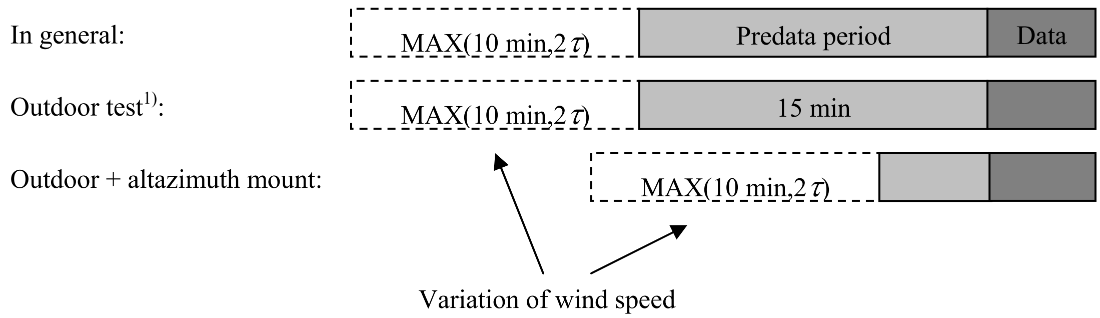

Figure 4 Variation of wind speed, alternative 1 [1)]fixed test mount

This interpretation would further increase the required pre-data time period. It is more likely that there is an inconsistent use of the expression "test period" in the Standard. If the requirements for the wind speed are applied in the same way as those for the solar irradiance as described in chapter 3.1.2 of this report, the requirements for the wind speed must be met prior to the data period instead of the whole test period. This alternative interpretation is shown in Figure 5.

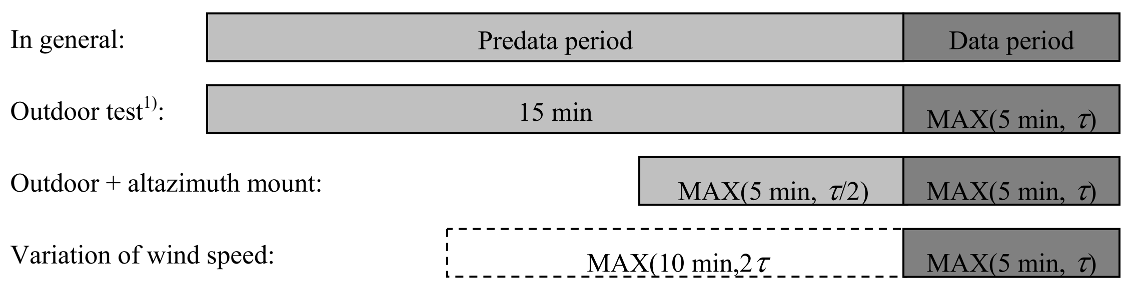

Figure 5 Variation of wind speed, alternative 2 [1)]fixed test mount

Now, the time interval with constant wind speed is directly prior to the data period. This interpretation should be used at MATC.

3.4 Flow rate

The heat transfer fluid flow rate remains fixed for all data points. The recommended mass flow rate per aperture area for a liquid fluid is 0.02 kg/s-m^2 (14.7 lb$_m$/hr-ft^2). An exception is made for collectors which are designed for special flow rates. These collectors should operate with their design flow rates (ASHRAE 92-2003, 8.3.1.1.6). The flow rate shall be maintained constant at the recommended flow rate within ±0.005 gpm (0.000315 liter/sec). (ASHRAE 93-2003, 8.3.3.3).

For the collector actually tested at MATC, the recommended flow rate is 3.2 gpm. A difference of 0.005 gpm requires maintaining the operating flow rate to within 0.0022% of its nominal value! This requirement is very restrictive when compared to the inlet temperature which is allowed to vary within ±1.8°F or ±2%, whichever is larger. It seems that the Standard should prescribe the flow rate accuracy as a percentage of the nominal flow rate, rather than an absolute value.

3.5 Inlet temperature

The Standard requires that the inlet temperature be maintained constant (within ±1°C [±1.8°F], ASHRAE 93-2003, 8.3.2 and 8.3.3.3) during the pre-data and data periods. However, in section 7.1.7, the standard requires the inlet temperature to be controlled within ±0.05°C (±0.09°F) during the complete test period. Why is a device required in the test setup which can control the inlet temperature within ±0.09°F, if the allowed inlet temperature variation for steady state conditions is ±Max of (1.8°F, 2%), which is in the lowest case 20 times greater than the control unit could provide? Again, there seems to be inconsistencies in the variation in controlled and uncontrolled variable related to collector testing. The variables that have extremely narrow tolerances significantly complicate the data collection process for measuring collector performance.

3.6 Conclusion

The steady state conditions defined in the Standard are very challenging and perhaps more restrictive than originally intended. A result of these requirements could be that tests in Wisconsin can be performed in only very few days of the year. This issue will be evaluated in more detail by the SEL.

4. Incident angle modifier test

The thermal efficiency tests are performed at near normal incident angles of the solar beam radiation upon the collector plane. However, the thermal efficiency of a collector depends on the angle of incidence of the solar radiation. The incident angle modifier $K_{\tau\alpha}$ is used to describe this dependence, which can be important for simulating the collector behavior under some conditions.

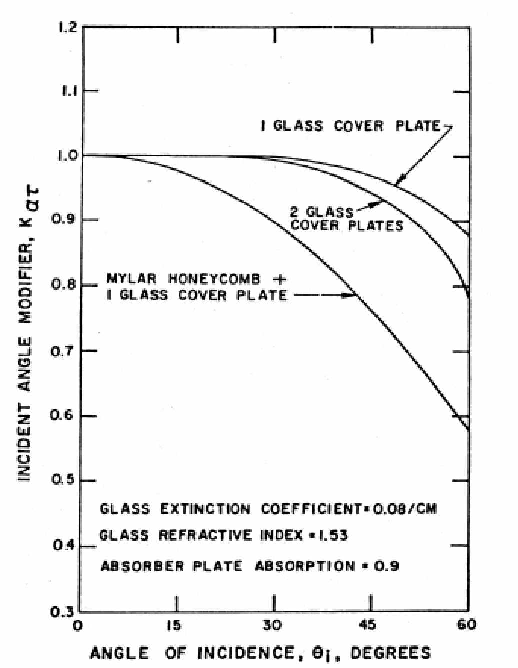

Figure 6 Incidence angle modifier (ASHRAE standard 93-2003, Figure 9)

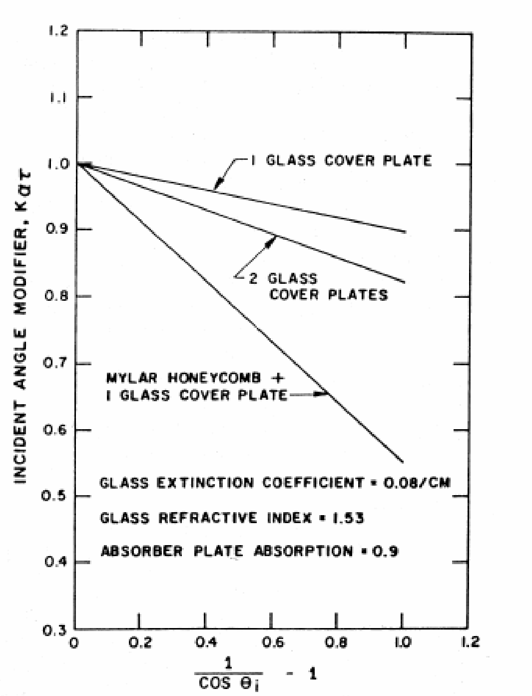

Figure 7 Incidence angle modifier (ASHRAE standard 93-2003, Figure 10)

The results of the thermal efficiency tests look qualitatively like shown in Figure 8. The efficiency has been measured at four different inlet temperatures but at about the same incident angle (close to normal incidence) for all data points (compare to Figure 6 in report 1).

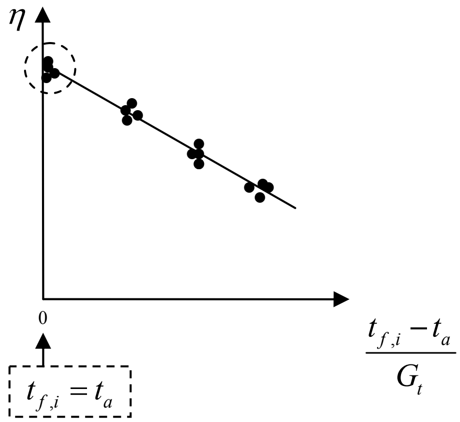

Figure 8 Results of the thermal efficiency test (all at normal incident angle)

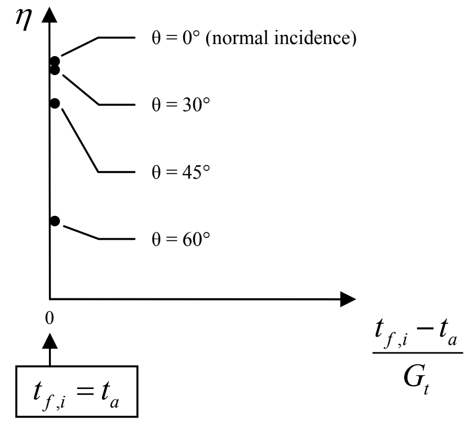

Figure 9 Thermal efficiencies at different incident angles

The purpose of the incidence angle modifier test is to determine the efficiency of the collector at a fixed inlet temperature and different incident angles. The Standard prescribes the collector inlet temperature be maintained at ambient temperature. For the example shown in Figure 8 this would mean, that the efficiency tests have to be repeated for that point of the x-axis where the collector inlet temperature $t_{f,i}$ equals the ambient temperature t_a (highlighted with a dashed line circle and box in Figure 8). Performing tests at these conditions and varying the incidence angles lead to results as shown in Figure 9. For a typical flat plate collector, the thermal efficiency decreases as the incidence angle increases.

Figure 10 shows a plot of efficiency versus incidence angle. The incidence angle modifier is the ratio of the efficiency to the efficiency at the same operating conditions but with normal incidence radiation:

$$K_{\tau\alpha}(\theta) = \frac{\eta(\theta)}{\eta_{normal}} \tag{3}$$

The incidence angle modifier is a function of angle, but in the following sections, the (θ) behind the symbol $K_{\tau\alpha}$ is not shown for brevity. The plot of the incident angle modifier defined by equation (3) is shown in Figure 11. It has the same shape as the efficiency curve in Figure 10. Obviously the incidence angle modifier is not a linear function of the incident angle.

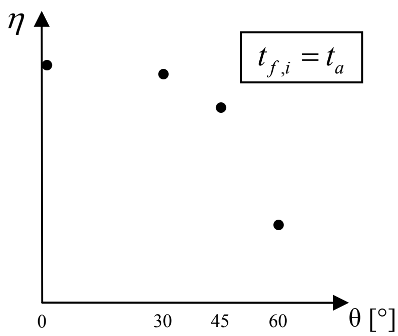

Figure 10 Thermal efficiency as function of incidence angle

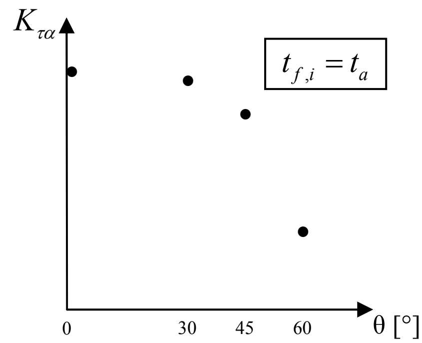

Figure 11 Incidence angle modifier as function of incidence

The Standard assumes, that for non-concentrating collectors, the following equation (4) can be used to describe the behavior of the incident angle modifier depending on the incident angle θ (ASHRAE standard 93-2003, eq. (8.18)).

$$K_{\tau\alpha} = 1 - b_o \left(\frac{1}{\cos(\theta)} - 1 \right) \tag{4}$$

To reach a linear relation, the term in parentheses is named to

$$x = \frac{1}{\cos(\theta)} - 1 \tag{5}$$

and the equation for the incidence angle modifier then simplifies to

$$K_{\tau\alpha} = 1 - b_o x\,. \tag{6}$$

The data points shown in Figure 11 are now plotted in Figure 12 using equation (6). The values of x are shown in Table 2. With the method of the least-squares fit, a straight line is determined as shown in Figure 13. The slope of this line is the coefficient, b_0, from equations (4) and (6). The coefficient, b_0, is called the *incidence angle modifier coefficient* and generally a positive number. As soon as b_0 is determined, the incident angle modifier for all angles can be calculated by equation (4).

Table 2 x-axis values for certain incident angles

θ [°]	x [-]
0	0.0
30	0.2
45	0.4
60	1.0

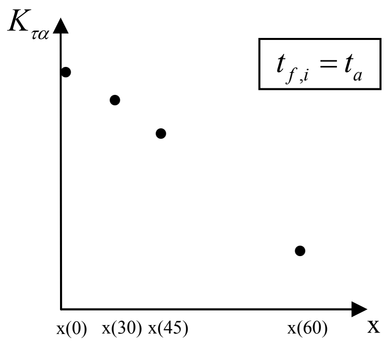

Figure 12 Incidence angle modifier as function of x =

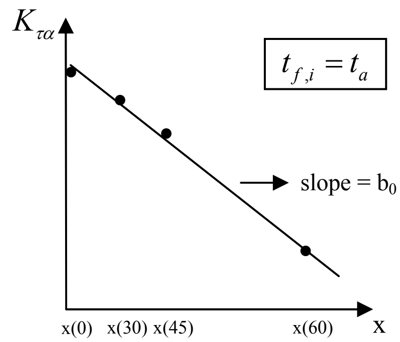

Figure 13 Determining the incidence angle modifier coefficient

Results of such tests are shown in Figure 6 and Figure 7 for different kinds of collectors. For some reason the Standard uses $K_{\alpha\tau}$ (with interchanged indices) as the symbol for the incident angle modifier. As the subscript is based on the transmittance-absorptance product τα, the symbol $K_{\tau\alpha}$ will be used in this report.

4.1 Testing methods

The ASHRAE 93-2003 Standard describes two methods for measuring the collector incident angle modifier (ASHRAE 93-2003: 8.3.4.1). As described above, the incident angle modifier is not measured directly but is derived from a series of thermal efficiency measurements. The procedure for measuring the thermal efficiency is described in section 8.2.1 of the Standard. Both methods for measuring the collector incident angle modifier require maintaining the inlet temperature at ambient temperature. The measurements for the different angles are recommended to be taken on the same day.

Method 1 can be used for indoor or outdoor testing with a movable test rack (collector azimuth angle can be adjusted). In sum, four thermal efficiency measurements are required, at incident angles of 0, 30, 45, and 60 degrees.

Method 2 can be used for outdoor tests with a test rack which can be adjusted in tilt but not in azimuth angle. The incident angle is adjusted to 0, 30, 45, and 60 degrees by varying the tilt angle of the collector. For every incident angle two measurements symmetric to solar noon are necessary. The average efficiency values of the symmetric measurements shall be used for the angle modifier calculations.

The orientation of test rack used at MATC can be adjusted with respect to the north-south line (azimuth angle), but not in tilt. As a result, only method 1 can be used for the incident angle modifier test. The procedure is described in the following section.

4.2 Testing procedure

The movable rack allows incident angle modifier tests to be conducted whenever the conditions for thermal efficiency tests are met. A thermal efficiency test as described in section 8.2.1 of the Standard must be performed at incidence angles of 0, 30, 45, and 60 degree and with a collector inlet temperature equal to ambient temperature. The required azimuth angle must be calculated before the tests are initiated. The proper azimuth angle for a specified incidence angle depends on the day of year, time of day, location of the test facility, the collector tilt angle and the desired incidence angle. The situation is shown in Figure 14.

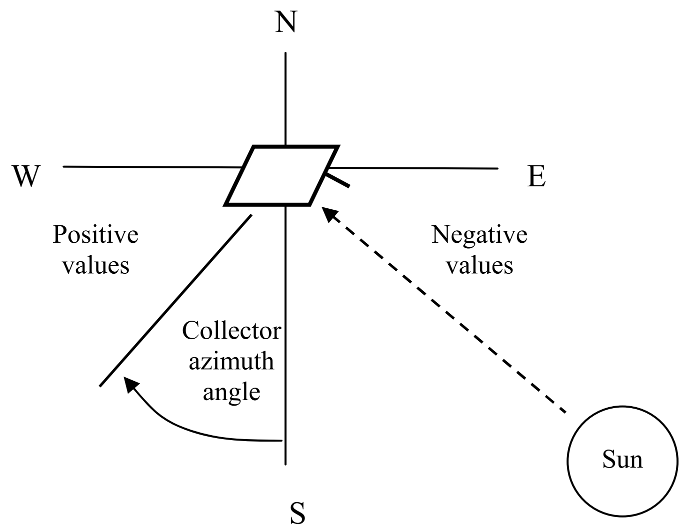

Figure 14 Collector orientation for incident angle modifier tests

The following set of equations allows calculating the azimuth angle based on this information. All equations are taken from Duffie and Beckman (2006).

$$B = (n-1)\cdot(360/365)\ [\text{deg}] \tag{7}$$

$$E = 229.2\ [\text{min}]\cdot\begin{pmatrix} 0.000075 + 0.001868\cdot \text{Cos}(B) - 0.032077\cdot sin(B) \\ -0.014615\cdot \text{Cos}(2\cdot B) - 0.04089\cdot sin(2\cdot B) \end{pmatrix} \tag{8}$$

$$soltime - standtime = \left(4\ [\text{min/deg}]\cdot(L_{st} - L_{loc}) + E\right)[\text{min}] \tag{9}$$

$$\omega = 15\ [\text{deg/h}]\cdot(soltime - 12_h) \tag{10}$$

$$\begin{aligned} \delta = {} & 0.006918 - 0.399912\cdot \text{Cos}(B) + 0.070257\cdot sin(B) \\ & -0.006758\cdot \text{Cos}(2\cdot B) + 0.000907\cdot sin(2\cdot B) \\ & -0.002679\cdot \text{Cos}(3\cdot B) + 0.00148\cdot sin(3\cdot B) \end{aligned} \tag{11}$$

$$\theta_z = arccos\left(cos(\phi)\cdot cos(\delta)\cdot cos(\omega) + sin(\phi)\cdot sin(\delta)\right) \tag{12}$$

$$\theta = arccos\begin{pmatrix} sin(\delta)\cdot sin(\phi)\cdot cos(\beta) \\ -sin(\delta)\cdot cos(\phi)\cdot sin(\beta)\cdot cos(\gamma) \\ +cos(\delta)\cdot cos(\phi)\cdot cos(\beta)\cdot cos(\omega) \\ +cos(\delta)\cdot sin(\phi)\cdot sin(\beta)\cdot cos(\gamma)\cdot cos(\omega) \\ +cos(\delta)\cdot sin(\beta)\cdot sin(\gamma)\cdot sin(\omega) \end{pmatrix} \tag{13}$$

$$\gamma_S = \mathrm{Sign}(\omega) \cdot ABS\left(arccos\left(\left(\frac{cos(\theta_z) \cdot sin(\phi) - sin(\delta)}{sin(\theta_z) \cdot cos(\phi)} \right) \right) \right) \tag{14}$$

$$\gamma_A = -(\gamma - \gamma_S) \tag{15}$$

The parameters for these equations are listed below.

Table 3 Parameter for collector orientation during $K_{\tau\alpha}$ test

Symbol	*Description*	*Value for MATC test facility*
N	Day of year (1…365)	The test day is the n^{th} day of the year. Test date → n
Soltime	Solar time (noon is defined by the zenith of the sun)	
standtime	Standard time of local time zone	Use the time in the middle of the data period. During daylight saving time subtract 1 h from local clock time.
L_{st}	Standard meridian for local time zone	90.0°
L_{loc}	Longitude of the location	89.4°
Ω	Hour angle	
Δ	Declination of the sun	
Φ	Latitude	
θ_z	Zenith angle, angle between beam radiation and horizontal plane	
Β	Slope or tilt, angle between collector and horizontal	50.5°
Θ	Incidence angle, angle between beam radiation and collector plane	0°, 30°, 45°, 60°
Γ	Collector azimuth angle, deviation from north-south orientation, east negative, west positive.	
γ_S	Solar azimuth angle, deviation from north-south orientation, east negative, west positive.	
Γ	Alternative collector azimuth angle, deviation from north-south orientation, east negative, west positive.	

For the given purpose the shaded cells in the third column of the table are calculated, all other data must be provided to determine a collector azimuth angle for a collector incident angle modifier test. The following example shows how a complete incident angle modifier test could be performed at Nov. 22 for the parameters given in **Table 4**. The times are chosen arbitrarily, except for the zero degree test (Test 2).

Table 4 **Example collector orientation**

Test number	*Solar time*	*Standard time*	*Incident angle*	*Solar azimuth*	*Collector azimuth*	*Alt. collector azimuth*
Test 1	11:30	11:14	30	-8	24	-40
Test 2	12:00	11:44	(0)[1)] 13	0	32	-32
Test 3	12:30	12:14	45	8	60	-44
Test 4	13:00	12:44	60	15	86	-56

[1)] Test at 0° incidence angle not possible with a fixed collector tilt of 50.5° at Nov. 22 (minimum 13°)

At this day, the zenith angle reaches its minimum (at solar noon) at about 63°. This means that a collector with a tilt fixed to 50.5° can not be orientated in a way that the incident angle reaches 0°. The situation is shown in Figure 15. In such a situation the collector should be orientated facing the sun at solar noon for the test at 0° incident angle. For this example the achieved incident angle at solar noon is 13°.

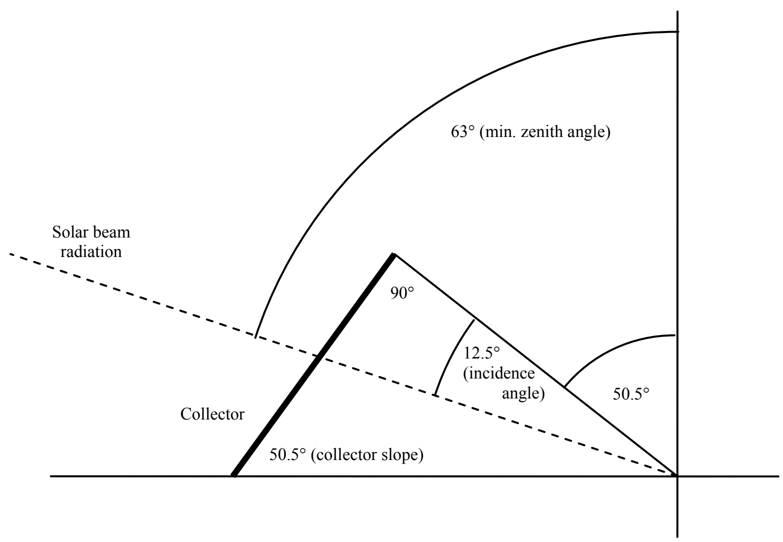

Figure 15 Incident angle and zenith angle

4.3 Conclusion

As soon as the required azimuth angles for the four incidence angle modifier tests are calculated, a normal thermal efficiency test must be performed. The proper azimuth angles will be provided by a set of tables or a program. All incidence angle modifier tests must be performed at ambient temperature. If the ambient temperature is below 0°C (32°C), these tests cannot be performed with water as heat transfer fluid.

[1] *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