Development and Validation of Flat-Plate Collector Testing Procedures

Report for April, 2007

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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 seventh report of this activity.

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A paper based on the research related to collector testing was prepared for the American Solar Energy Society meeting in Cleveland in July. A copy of the paper is appended.

1. Available Testing Days

In considering alternative geographic locations to conduct outdoor tests in accordance with ASHRAE 93, it is of interest to estimate the effect of uncontrolled climatic weather conditions on the ability to meet the criteria listed in Tables 1 and 2. ISIS irradiance data[2] are available for several locations within the United States. For the following analysis 1 minute data are generated by interpolation from the provided 3 minute data. The following ISIS measurements are used for the calculations:

Table 1: ISIS [5] measurements

Variable	Symbol
Beam radiation normal to sun	I_{bn}
Diffuse radiation on a horizontal surface	I_d
Solar zenith angle	θ_z

The beam radiation on a horizontal plane I_{bn} is then given by

$$I_b = I_{bn}\cos(\theta_z) \tag{1}$$

The *total* irradiance on a *horizontal* plane, I, is the sum of the diffuse radiation on a horizontal plane measured by ISIS and the beam radiation on a horizontal plane from Eq. (1):

$$I = I_b + I_d \tag{2}$$

Knowing total, beam, and diffuse radiation on a horizontal plane, the Liu and Jordan model as described by Duffie and Beckman[3] can be used to calculate the total radiation on a tilted surface, I_T, with tilt angle β:

$$I_T = I_b R_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I\rho_g\left(\frac{1-\cos\beta}{2}\right) \tag{3}$$

where R_b is the ratio of beam radiation on the tilted surface to the beam radiation on a horizontal surface:

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{4}$$

While the solar zenith angle, θ_z, is provided by ISIS, the incidence angle of the beam radiation upon the tilted surface, θ, must be calculated. The incidence angle is a function of the declination, δ, the latitude, φ, the surface tilt angle, β, the surface azimuth angle, γ, and the hour angle, ω,, as in Eq. 8.

$$\begin{aligned}\cos\theta = {} & \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma \\ & + \cos\delta\cos\phi\cos\beta\cos\omega \\ & + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega \\ & + \cos\delta\sin\beta\sin\gamma\sin\omega\end{aligned} \tag{5}$$

The declination is calculated as a function of the day of year. The latitude for each ISIS station is known, the tilt angle and the azimuth angle can be set arbitrarily, and the hour angle is a function of the solar time of day in hours:

$$\omega = solar\ time \cdot 15° \tag{6}$$

The ground reflectance depends on the location of the tilted surface. Typical values are between 0.3 and 0.7. At this point all required information to calculate the total irradiance on a tilted surface is known.

For a fixed test mount Eq. (3) is used to calculate the irradiance normal to sun at the test site. For an altazimuth mount, Eq. (3) can be simplified since the total irradiance upon the collector plane is equal to the total irradiance normal to the sun. Therefore the term R_bI_b is equal to the beam radiation normal to the sun I_{bn} which is directly reported by ISIS. The variable β can be replaced by θ_z in case of a surface normal to the sun. The relation for the total irradiance on a surface normal to the sun is then:

$$I_n = I_{bn} + I_d\left(\frac{1+\cos\theta_z}{2}\right) + I\rho_g\left(\frac{1-\cos\theta_z}{2}\right) \tag{7}$$

The diffuse fraction *df* is defined as the ratio of the total diffuse irradiance upon the surface and the total irradiance upon the surface.

$$df = \frac{\left(1 - I_b R_b\right)}{I_T} \tag{8}$$

To evaluate the number of days suitable for outdoor testing during a certain time period, a *suitable test day* must be defined first. As shown in Report 2 Chapter 3, the length of a test period depends on the type of test mount used and the collector time constant. If the collector time constant is less than 5 minutes, which is typical for glazed flat plate collectors, the *data period* is fixed for a 5 minute period. Additionally for the *pre-data period*, 15 minutes are required with a fixed mount and 5 minutes with an altazimuth mount. Since it is desirable to conduct more than one test per day, a day is considered to be a suitable test day if the environmental conditions meet the requirements for a minimum total period of three hours.

For both types of outdoor test mounts, a test condition check is sequentially performed for the total irradiance normal to sun, diffuse fraction, and variation of irradiance upon the collector plane. First, the average[1] value of the total irradiance normal to sun must be greater than 790 W/m^2. Next, the diffuse fraction must be less than 20%. These two conditions are checked throughout the test period. The difference between the maximum and minimum solar irradiance upon the collector plane must be less than 64 W/m^2 during any 10 minute interval within the test period.

These test condition checks have been conducted for the years 2003 through 2005 for four locations within the United States using the ISIS data. The parameters presented in **Table 2** have been used for all calculations with the resulting average number of suitable days for outdoor testing shown in **Table 3**. Clearly, there are more opportunities to test

[1]The standard does not specify which time period is to be used to determine the average value.

solar collectors in Albuquerque and Salt Lake City than in Madison and Sterling. The presented numbers represent an upper limit for the number of days available for testing. The numbers are further restricted by weekends, and variation in other uncontrolled parameters such as wind speed and ambient temperature. The fact that for the fixed test mount measurements must be taken symmetric to solar noon according to ASHRAE 93 will further reduce the number of test days for this mount significantly.

Table 2: Parameters for calculations

Variable	**Value**
Ground reflectance	0.5
Azimuth angle	0° (south)
Tilt angle	50.5°

Table 3: Number of test days per year

	Fixed	Altazimuth
Sterling, VA	75	95
Madison, WI	87	115
Salt Lake City, UT	148	181
Albuquerque, NM	198	228

2. Calibration of RTD sensors

The collector thermal peformance tests require that the difference between the collector fluid inlet and outlet temperatures be measured at high precision in order to keep the uncertainty of the heat loss coefficient to a reasonable value. Class A 100 ohm platinum resistance temperature detectors (RTD) are used. The resistance of a platinum sensor varies with temperature. The following equation relates resistance and temperature for the used probes:

$$T = T_0 + \frac{1}{\alpha}\left(\frac{R_{RTD}}{R_0} - 1\right) \tag{1.9}$$

R_{RTD} is the measured resistance of the RTD sensor; the RTD sensors are made for use with the European standard curve (DIN 43760). This fact defines the following parameters for the used RTDs:

Table 4: RTD parameters

Variable	Description	Value
R_0	Reference resistance	100 ohm
T_0	Reference temperature	0 °C
α	Coefficient temperature curve	0.00385 (°C)$^{-1}$

IEC standard 751 defines the following accuracies for class A sensors:

$$\Delta T = \pm\left(0.15 + 0.002\left|T\right|\right) \tag{1.10}$$

where ΔT is the tolerance for the temperature measurement and $|T|$ is the absolute value of the true temperature value, both in°C. Eq. (1.10) has been used to generate Table 5 showing the tolerances for the temperature range of interest for solar collector testing.

Independent of these specifications the manufacturer has certified the calibration of the RTDs with a calibration uncertainty of 0.3°C in the range of -30°C to 500°C.

The accuracy for absolute temperature measurements required by ASHRAE 93 is ±0.5°C. Therefore, the specifications of IEC standard 751 (Table 5) for class A RTD sensors and the manufacturer's calibration information allow to conduct the temperature measurements in accordance with ASHRAE 93.

The accuracy of the temperature difference measurements required by ASHRAE 93 is ±0.1°C. Temperature differences are not measured directly but calculated as the difference between two absolute temperature values in the actual test setup. This means that the accuracy requirement for temperature difference measurements can not be met with the IEC standard 751 specifications or the manufacturer calibration.

In order to achieve higher accuracies for the temperature measurements, the RTD sensors have been calibrated over the range of 5°C to 95°C in order to obtain higher accuracies. The calibration has shown that all RTD sensors can achieve a standard deviation from a linear calibration curve of ±0.007°C by using the calibration coefficients rather than the standard European curve coefficient α. This shows that the RTD sensors are suitable also for temperature difference measurements with two RTD sensors. The uncertainty in temperature measurements will be increased by the instruments and instrument setup used to measure the resistance of the RTD sensors.

Table 5: Tolerances for Class A RTD sensors

Temperature [°C]	Tolerance [±°C]
-25	0.20
-20	0.19
-15	0.18
-10	0.17
-5	0.16
0	0.15
5	0.16
10	0.17
15	0.18
20	0.19
25	0.20
30	0.21
35	0.22
40	0.23
45	0.24
50	0.25
55	0.26
60	0.27
65	0.28
70	0.29
75	0.30
80	0.31
85	0.32
90	0.33
95	0.34
100	0.35

[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.

[2] Integrated Surface Irradiance Study (ISIS) Network, http://www.srrb.noaa.gov/isis/index.html

[3] J. A. Duffie, W. A. Beckman, “Solar Engineering of Thermal Processes”, 3rd ed., ISBN-10 0-471-69867-9, Wiley, 2006

ALTERNATIVE METHODS FOR PERFORMANCE TESTING OF SOLAR THERMAL COLLECTORS

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ABSTRACT

This paper summarizes and compares test methods for rating the performance of solar thermal collectors used by three standards. Test results of an alternative test method have been compared to those obtained by the standard methods. An uncertainty analysis to compare the quality of the test results of the test methods is presented. It has been shown that the feasibility of conducting outdoor tests depends strongly on location. Climatic conditions at different locations are evaluated to quantify the feasibility of outdoor testing at different geographic locations. In addition indoor test methods are investigated with the goal of significantly reducing the time, effort and the climate dependence of performance testing of solar collectors.

1. INTRODUCTION

Testing and certification of solar thermal collectors is important to assure installations meet performance expectations. Unfortunately, thermal performance testing of collectors in accordance with the existing test standards is difficult and resource intensive. Current test standards allow both indoor tests and outdoor tests. Indoor tests require an expensive solar irradiance simulator; in addition translating measured performance to outdoor conditions can be problematic since the spectral distribution of irradiance simulators may not duplicate terrestrial irradiance. In theory, outdoor tests can be conducted with modest cost under natural solar irradiance; however, the test conditions defined by the standards restrict the availability of suitable times for conducting outdoor tests, depending on the conditions at the test site.

This paper will briefly introduce the test methods used by alternative test standards. The feasibility of outdoor tests in accordance with actual test standards will be evaluated by determining the number of suitable test days on the basis of solar irradiance measurements. An alternative indoor test method that does not require a solar simulator is suggested. The results of the alternative test methods are compared to the results from outdoor tests.

2. COLLECTOR TIME CONSTANT TEST

The collector time constant is a measure of the thermal response time of a collector. Knowledge of the response time is important for setting an appropriate time period for the thermal efficiency test. It is also useful for determining an appropriate period to average and report the experimental data that are collected during the test.

The collector time constant is experimentally determined in accordance with ASHRAE Standard 93 in two steps. First, the collector is exposed to the sun and the collector inlet temperature is adjusted to the ambient temperature. After steady state conditions have been achieved, the solar irradiance is abruptly reduced by shading the collector with an opaque shield. The collector inlet and outlet temperatures are continuously observed. The collector time constant is determined as the time, τ, needed for the temperature difference between the collector outlet and inlet to decrease to a fraction of $1/e \approx 0.368$ of its initial value. Steady state conditions according to ASHRAE 93 are described in section 3.3 of this paper.

The ISO Standard 9806-1 uses basically the same test procedure except that the difference between collector outlet and ambient temperatures is measured instead of difference between the outlet and inlet temperatures. First, the collector is shielded from the sun until steady state conditions are achieved. Then the shield is removed abruptly and then measurements are taken until the second steady state is reached. The collector time constant is determined as the time, τ, needed for the temperature difference between the collector outlet and the ambient to increase to the initial value plus a fraction of 0.632 of the difference between initial and final value. Steady state conditions are defined to be achieved as soon as the outlet temperature of the collector does not vary more than ±0.05 °C per minute. The EN Standard 12975-2 recommends exactly the same method as the ISO Standard 9806-1, but the determination of the time constant is optional.

All three standards have in common that the flow rate through the collector is the same as used for the thermal efficiency tests and the inlet temperature is approximately equal to the ambient temperature. According to ASHRAE 93, the inlet temperature must be within ±1°C of the ambient temperature; the ISO and EN standards do not define values for the allowed inlet temperature range. A minimum solar irradiance upon the collector plane of 790, 800, and 700 W/m^2 is required by the ASHRAE, ISO and EN standards, respectively.

3. EFFICIENCY TEST

3.1 Thermal Efficiency Equations

The instantaneous efficiency of a solar thermal collector, η_g, is defined as the ratio of the useful energy gain of the collector, Q_u, and the solar irradiance, G_t, upon the gross collector area, A_g. The useful energy gain can be calculated as the product of the mass flow rate of the heat transfer fluid, its specific heat and the difference between collector outlet temperature T_o and inlet temperature T_i:

$$\eta_g = \frac{\dot{Q}_u}{A_g G_t} = \frac{\dot{m} C_p (T_o - T_i)}{A_g G_t} \quad (1)$$

The useful energy gain of a solar thermal collector can be described by the Hottel-Whillier equation [4]:

$$\dot{Q}_u = A_a \left[G_t F_R (\tau\alpha)_e - F_R U_L (T_i - T_a) \right] \quad (2)$$

where F_R is the collector heat removal factor, $(\tau\alpha)_e$ is the effective transmittance absorptance product, U_L is the collector overall heat loss coefficient, and T_a is the ambient temperature. Combining Eqs. (1) and (2) results in the following relation for the collector efficiency:

$$\eta_g = \frac{\dot{Q}_u}{A_g G_t} = \frac{A_a}{A_g} \left[F_R (\tau\alpha)_e - F_R U_L \frac{T_i - T_a}{G_t} \right] \quad (3)$$

$(\tau\alpha)_e$ is a function of incidence angle upon the collector plane and F_R and U_L are temperature dependent. If the efficiency tests are performed at near normal incidence conditions $(\tau\alpha)_e$ should be constant. If F_R and U_L are assumed to be constant in the range of temperatures obtained during testing, a straight line will result when η_g is plotted against $(T_i-T_a)/G_t$. The intercept of this line is $(A_a/A_g)F_R(\tau\alpha)_e$ and the slope is $(A_a/A_g)F_RU_L$. These two parameters effectively characterize the performance of a solar thermal collector operating under near normal incidence conditions. The required measurements are the efficiency and ratio $(T_i-T_a)/G_t$ at steady state conditions.

3.2 Test Method

Every combination of η_g and the ratio $(T_i-T_a)/G_t$ is called a "data point". ASHRAE Standard 93 requires 16 data points at 4 different inlet temperatures and prescribes two alternative methods to determine the inlet temperature distribution. The efficiency curve is derived from the measured data points by using a least-squares fit. The result of an efficiency test is presented qualitatively in Fig. 1.

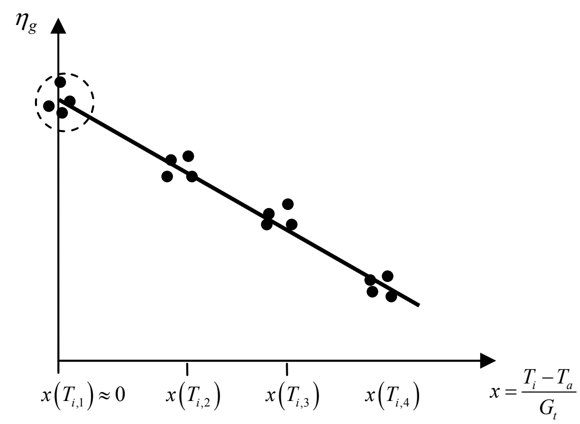

Fig. 1: Data points and resulting efficiency curve (line).

3.3 Test Conditions

ASHRAE Standard 93 defines the required test conditions including those conditions required to achieve steady state. One category of test conditions prescribed in the standard is explicit requirements for environmental conditions as shown in Table 1. The second category of conditions relates to limits on variability. Because Eq. (3) does not account for any transient effects, collector performance tests must be performed at steady state conditions. Table 2 lists the maximum allowed variation of key variables from ASHRAE Standard 93 to assure steady state conditions are attained.

TABLE 1: ABSOLUTE LIMITS

Variable	Absolute Limits
Total solar irradiance normal to sun	Minimum 790 W/m^2
Fraction of diffuse radiation	Maximum 20%
Wind speed	2.2 m/s < wind sp. < 4.5 m/s for maxim. of 10min and 2 τ
Incidence angle modifier	98% < value for normal incidence < 102%

TABLE 2: MAXIMUM VARIATION

Variable	Maximum variation
Total solar irradiance upon aperture plane	±32 W/m^2 for maxim. of 10min and 2τ
Ambient temperature	±1.5°K
Volume flow rate	±2 % or ±0.005 gpm[1)]
Inlet temperature	±2 % or ±1 °K[1)]

[1)] The *greater* one of both listed variations must be applied

4. FEASIBILTY OF EFFICIENCY TESTS

4.1 Inlet Temperature Distribution for Efficiency Tests

ASHRAE 93 efficiency tests are conducted for four distinctly different collector inlet temperatures. ASHRAE 93 specifies two methods to determine these temperatures. The lowest inlet temperature is set to the ambient temperature at the test site in both methods. The highest inlet temperature is defined based either on the manufacturer's recommended maximum operating temperature or on specified efficiencies achieved during the tests. For both methods, the inlet temperature distributions can require temperatures above 130°C for typical flat-plate or tubular collectors. This is impractical when testing with water and far higher than the temperatures obtained in real operation.

The ISO Standard 9806-1 recommends a maximum inlet temperature of 70°C if water is used as heat transfer fluid. The SRCC Standard 100-05 states that maximum temperature is usually chosen to be 70°C above ambient temperature. The European Standard EN 12975-2 distinguishes the types of collectors by their application and defines the maximum inlet temperature to be based on the collector type. EN 12975-2 recommends using inlet temperatures of 15°C, 60°C, 70°C, and 90°C for applications that include swimming pools, domestic hot water heating, district heating and process heating. The required inlet temperature distribution for the ASHRAE 93 standard should be revised to a simpler alternative that results in practical inlet temperatures below 100°C.

4.2 Collector Test Mounts

There are three basic types of collector test mounts. A *fixed mount* and an *altazimuth mount* for outdoor tests and an *indoor test mount*. A fixed mount requires both the tilt angle and the azimuth angle to remain constant during the test. An altazimuth mount automatically orients the collector surface normal to the beam radiation throughout the test period. An indoor test mount usually consists of the solar simulator and a rack for the collector. Both are adjustable in tilt. These types of test mounts are not defined explicitly in the ASHRAE Standard 93 but referred to for the definition of different requirements.

4.3 Time Effort

A complete set of thermal efficiency tests requires 16 data points. The efficiency for one data point is calculated from measurements taken over a *data period*. Steady-state conditions (Table 2) must be maintained throughout the data period. Only data taken during the *data period* are used to calculate the efficiency for each data point. In addition to maintaining steady-state conditions during the *data period* steady-state conditions must also be maintained during a defined time interval prior to the data period, here called the *pre-data period*. A test period as defined in ASHRAE 93 contains both the *pre-data* and the *data periods*. The situation is visualized in Fig. 2.

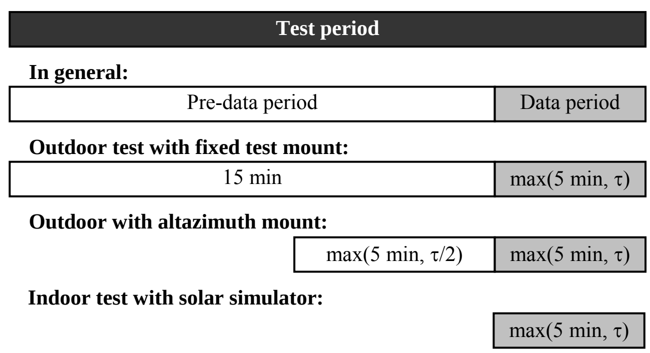

Fig. 2: Data and pre-data period for the efficiency tests (τ = collector time constant)

The required duration of the pre-data period depends on the test mount used. For outdoor tests with a fixed test mount, the *pre-data period* is 15 min (independent of the required collector time constant measurement); for outdoor tests with an altazimuth mount, the *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 mount and the greater of a 5 minute interval or the collector time constant.

Pre-data periods have a large influence on the overall time required for a collector test. In fact, the *pre-data period* dominates the total time consumed for conducting a single outdoor fixed-mount test. Assuming a collector time constant less than 5 minutes (typical for flat plate collectors), the *data period* during which the efficiency measurements are recorded would be 5 minutes 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* alone with the measurements taken during this period not directly contributing to the archived test results. *Pre-data periods* that are substantially longer than the collector time constant likely do not increase the quality of the test results.

4.4 Available Testing Days

In considering alternative geographic locations to conduct outdoor tests in accordance with ASHRAE 93, it is of interest to estimate the effect of uncontrolled climatic weather conditions on the ability to meet the criteria listed in Tables 1 and 2. ISIS irradiance data [5] are available for several locations within the United States. For the following analysis 1 minute data are generated by interpolation from the provided 3 minute data. The following ISIS measurements are used for the calculations:

TABLE 3: ISIS [5] MEASUREMENTS

Variable	Symbol
Beam radiation normal to sun	I_{bn}
Diffuse radiation on a horizontal surface	I_d
Solar zenith angle	θ_z

The beam radiation on a horizontal plane I_{bn} is then given by

(4) $$I_b = I_{bn}\cos(\theta_z)$$

The *total* irradiance on a *horizontal* plane, I, is the sum of the diffuse radiation on a horizontal plane measured by ISIS and the beam radiation on a horizontal plane from Eq. (4):

(5) $$I = I_b + I_d$$

Knowing total, beam, and diffuse radiation on a horizontal plane, the Liu and Jordan model as described by Duffie and Beckman [4] can be used to calculate the total radiation on a tilted surface, I_T, with tilt angle β:

(6) $$I_T = I_b R_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I\rho_g\left(\frac{1-\cos\beta}{2}\right)$$

where R_b is the ratio of beam radiation on the tilted surface to the beam radiation on a horizontal surface:

(7) $$R_b = \frac{\cos\theta}{\cos\theta_z}$$

While the solar zenith angle, θ_z, is provided by ISIS, the incidence angle of the beam radiation upon the tilted surface, θ, must be calculated. The incidence angle is a function of the declination, δ, the latitude, φ, the surface tilt angle, β, the surface azimuth angle, γ, and the hour angle, ω,, as in Eq. 8.

(8) $$\begin{aligned}\cos\theta = &\sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma \\ &+\cos\delta\cos\phi\cos\beta\cos\omega \\ &+\cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega \\ &+\cos\delta\sin\beta\sin\gamma\sin\omega\end{aligned}$$

The declination is calculated as a function of the day of year. The latitude for each ISIS station is known, the tilt angle and the azimuth angle can be set arbitrarily, and the hour angle is a function of the solar time of day in hours:

(9) $$\omega = solar\ time \cdot 15°$$

The ground reflectance depends on the location of the tilted surface. Typical values are between 0.3 and 0.7. At this point all required information to calculate the total irradiance on a tilted surface is known.

For a fixed test mount Eq. (6) is used to calculate the irradiance normal to sun at the test site. For an altazimuth mount, Eq. (6) can be simplified since the total irradiance upon the collector plane is equal to the total irradiance normal to the sun. Therefore the term $R_b I_b$ is equal to the beam radiation normal to the sun I_{bn} which is directly reported by ISIS. The variable β can be replaced by θ_z in case of a surface normal to the sun. The relation for the total irradiance on a surface normal to the sun is then:

(10) $$I_n = I_{bn} + I_d\left(\frac{1+\cos\theta_z}{2}\right) + I\rho_g\left(\frac{1-\cos\theta_z}{2}\right)$$

The diffuse fraction *df* is defined as the ratio of the total diffuse irradiance upon the surface and the total irradiance upon the surface.

(11) $$df = \frac{(1 - I_b R_b)}{I_T}$$

To evaluate the number of days suitable for outdoor testing during a certain time period, a *suitable test day* must be defined first. As shown in Fig. 2, the length of a test period depends on the type of test mount used and the collector time constant. If the collector time constant is less than 5 minutes, which is typical for glazed flat plate collectors, the *data period* is fixed for a 5 minute period. Additionally for the *pre-data period*, 15 minutes are required with a fixed mount and 5 minutes with an altazimuth mount. Since it is desirable to conduct more than one test per day, a day is considered to be a suitable test day if the environmental conditions meet the requirements for a minimum total period of three hours.

For both types of outdoor test mounts, a test condition check is sequentially performed for the total irradiance normal to sun, diffuse fraction, and variation of irradiance upon the collector plane. First, the average[1] value of the total irradiance normal to sun must be greater than 790 W/m^2. Next, the diffuse fraction must be less than 20%. These two conditions are checked throughout the test period. The difference between the maximum and minimum solar irradiance upon the collector plane must be less than 64 W/m^2 during any 10 minute interval within the test period.

These test condition checks have been conducted for the years 2003 through 2005 for four locations within the United States using the ISIS data. The parameters presented in Table 4 have been used for all calculations with the resulting average number of suitable days for outdoor testing shown in Table 5. Clearly, there are more opportunities to test solar collectors in Albuquerque and Salt Lake City than in Madison and Sterling. The presented numbers represent an upper limit for the number of days available for testing. The numbers are further restricted by weekends, and variation in other uncontrolled parameters such as wind speed and ambient temperature. The fact that for the fixed test mount measurements must be taken symmetric to solar noon according to ASHRAE 93 will further reduce the number of test days for this mount significantly.

TABLE 4: PARAMETERS FOR CALCULATIONS

Variable	Value
Ground reflectance	0.5
Azimuth angle	0° (south)
Tilt angle	50.5°

TABLE 5: NUMBER OF TEST DAYS PER YEAR

	Fixed	Altazimuth
Sterling, VA	75	95
Madison, WI	87	115
Salt Lake City, UT	148	181
Albuquerque, NM	198	228

5. INCIDENCE ANGLE MODIFIER TEST

5.1 Introduction

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

[1]The standard does not specify which time period is to be used to determine the average value.

The results of the thermal efficiency tests appear qualitatively as shown in Fig. 1. The efficiency has been measured at four different inlet temperatures but all tests are at approximately normal incidence. The purpose of the incidence angle modifier test is to determine the efficiency of the collector at a fixed inlet temperature and different incidence angles. The Standard prescribes that the collector inlet temperature must be maintained at ambient temperature during the tests. For the example shown in Fig. 1, the efficiency tests have to be repeated for the point where the collector inlet temperature, T_i, equals the ambient temperature, T_a, (highlighted with a dashed line circle in Fig. 1). Performing tests at these conditions and varying the incidence angles lead to results as shown in Fig. 3. For a typical flat plate collector, the thermal efficiency decreases as the incidence angle increases.

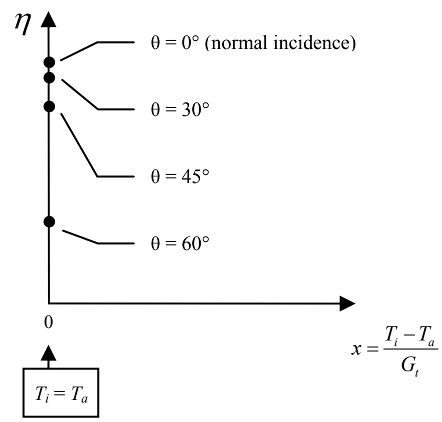

Fig. 3 Thermal efficiencies at different incidence angles

The incidence angle modifier is defined as the ratio of the efficiency to the efficiency at the same operating conditions but with normal incidence radiation:

$$K_{\tau\alpha}(\theta) = \frac{\eta(\theta)}{\eta_{normal}} \quad (12)$$

The Standard assumes that for non-concentrating collectors, Eq. (13) can be used to describe the incidence angle dependence of the incidence angle modifier (ASHRAE Standard 93-2003, Eq. (8.18)).

$$K_{\tau\alpha} = 1 - b_o\left(\frac{1}{\cos(\theta)} - 1\right) \quad (13)$$

b_0 is assumed to be constant, so plotting $K_{\tau\alpha}$ with respect to the term in parenthesis in Eq. (13) results in a straight line. The slope of this line is the coefficient, b_0, which is called the *incidence angle modifier coefficient* and generally a positive number. As soon as b_0 is determined, the incidence angle modifier for all angles can be calculated by Eq. (13).

5.2 Testing Methods

The ASHRAE 93-2003 Standard describes two methods for measuring the collector incidence angle modifier (ASHRAE 93-2003: 8.3.4.1). The incidence angle modifier is not measured directly but rather derived from a series of thermal efficiency measurements, performed as described above. Both methods for measuring the collector incidence 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 incidence 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 incidence angle is adjusted to 0, 30, 45, and 60 degrees by varying the tilt angle of the collector. This method necessarily assumes that the collector loss coefficient does not depend on the collector tilt, contrary to collector theory [4]. For every incidence 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.

All test conditions for thermal efficiency tests described above also apply for the incidence angle modifier tests with one exception: the allowed range for the incidence angle modifier is replaced by an allowed range for the incidence angle upon the collector plane. The incidence angle must be maintained within ± 2.5° of the incidence angle the actual test is conducted for. For collectors with an asymmetric response to variation in incidence angle, the test must be conducted for different directions.

ISO 9806-1 describes the same two methods as introduced above to experimentally determine the incidence angle modifier. However, the introduction of the incidence angle modifier coefficient b_0 is not used. ISO 9806-1 and EN 12975-2 provide a method to determine the incidence angle modifier curve if the fluid inlet temperature can not be set to the ambient temperature. EN 12975-2 also uses the two described test methods. However, only one measurement at an incidence angle of 50° is required.

6. UNCERTAINTY ANALYSIS

The uncertainty analysis for the thermal efficiency tests has been performed based on the accuracy requirements of the ASHRAE 93. For the solar irradiance measurements the minimum accuracies presented in Table 6 are prescribed. The 95% estimate of the bias in the measurement is determined by using the RSS (root-sum-square) combination to be 2.9% [8].

ASHRAE 93 (Ch. 6.2.2) requires temperature and temperature difference measurements with the accuracy and precision values provided in Table 7. The resulting uncertainty values are ±0.54°C for the temperature measurements and ±0.15°K for the temperature difference measurements.

TABLE 6: IRRADIANCE MEASUREMENTS

Characteristics	Maximum change in response
Ambient temperature	± 1%
Spectral distribution	± 2%
Nonlinearity	± 1%
Incidence angle	± 1%
Tilt angle	± 1%

TABLE 7: TEMPERATURE MEASUREMENTS

	Accuracy	Precision
Temperature	± 0.5°C	± 0.2°C
Temperature Difference	± 0.1°C	± 0.1°C

ASHRAE 93 also prescribes accuracies for the measurements of mass flow and the instrumentation. The uncertainty contribution of the accuracies of the data recording process is considered to be small compared to individual measurements; therefore, instrumentation uncertainties are neglected in the following uncertainty analysis. Table 8 summarizes the uncertainty values.

TABLE 8: UNCERTAINTY OF MEASUREMENTS

Variable	Uncertainty
Solar irradiance	± 2.9 %
Inlet, outlet, ambient temperatures	± 0.54°C
Temperature differences inlet – outlet, inlet - ambient	± 0.15°K
Mass flow rate	± 1.0 %

The uncertainty information in Table 8 has been used to calculate the following propagated uncertainty [7] of the measured collector parameters during an outdoor test conducted in Madison, WI for a one-cover solar collector.

$$(A_a/A_g)F_R(\tau\alpha)_e = 0.615 \pm 0.0090\ (\pm 1.5\%)$$
$$(A_a/A_g)F_R U_L. = 4.14 \pm 0.234\ (\pm 5.7\%)$$

7. EFFECT OF UNCERTAINTY ON SIMULATIONS

Collector efficiency parameters are used to predict the performance of collectors. TRNSYS [9] has been used to evaluate the effect the uncertainty in the parameters have on the results of performance simulations. The annual fraction of energy provided by the solar collector in a combined water heating system has been calculated for three cases:

1. Efficiency parameters $(A_a/A_g)F_R(\tau\alpha)_e$ and $(A_a/A_g)F_RU_L$ given by the test results
2. Highest $(A_a/A_g)F_R(\tau\alpha)_e$ with lowest $(A_a/A_g)F_RU_L$. (best case)
3. Lowest $(A_a/A_g)F_R(\tau\alpha)_e$ with highest $(A_a/A_g)F_RU_L$. (worst case)

The highest and lowest collector efficiency parameter values are taken from the uncertainty analysis in Section 6 of this paper. The tank volume is 0.3 m^3. The simulation is performed for collector areas of 2.5 and 5 m^2, the mass flow rate is held constant at 0.0111 kg/s-m^2. The results of the simulations are listed in Table 9. The uncertainty in the collector parameters is seen to have a relatively small effect on the estimated annual system performance.

TABLE 9: ANNUAL FRACTIONS

Case	Annual fraction 2.5m^2	Annual fraction 5m^2
Result values	64.50 %	95.72 %
Best case values	65.86 %	96.25 %
Worst case values	63.13 %	94.82 %

8. COMBINED INDOOR AND OUTDOOR TEST

8.1 Introduction

As climatic conditions limit the period of time suitable for outdoor collector testing in accordance with ASHRAE 93 and as it is desirable to reduce the overall time effort necessary for the collector tests, alternative test methods should be evaluated. One opportunity to decrease the dependence on climatic conditions is indoor testing. Symons [6] has described and conducted indoor tests for determining the overall heat loss coefficient of a solar flat-plate collector. This test method does not need a solar irradiance simulator. Instead, hot water is circulated through the collector and the temperature drop is measured. From this information, the overall heat loss coefficient, U_0, can be calculated. The coefficient U_0 is based on the mean fluid temperature in the collector. The heat loss parameter $(A_a/A_g)F_RU_L$ can also be determined from these test results if the calculation is based on the fluid temperature at the collector inlet instead of the mean fluid temperature.

If $(A_a/A_g)F_RU_L$ can be determined by an indoor test, the number of required outdoor tests can be reduced by 16. The incidence angle modifier test still must be performed outdoors to experimentally determine the incidence angle modifier coefficient b_0; however, the parameter $(A_a/A_g)F_R(\tau\alpha)_e$ can be derived from the incidence angle modifier tests alone without additional tests, as one or two of the tests determine the efficiency at normal incidence.

8.2 Test Setup and Calculations

The indoor test to determine $(A_a/A_g)F_RU_L$ has been performed running hot water through the array at different inlet temperatures and the same flow rate used during the outdoor tests. A fan is used to move air across the collector and the local air speed measured at 7 positions 10 cm above the collector surface. The average wind speed across the collector was estimated to be 2.2 m/s. The ceiling temperature of the test room has been found to be constant and slightly above the ambient room temperature. The variables presented in Table 10 are measured during the tests with the same equipment used for the outdoor tests.

During the indoor test, the irradiance G_t upon the collector plane is approximately zero, so Eq. (2) can be written as

$$\frac{A_a}{A_g}F_RU_L = \frac{\dot{m}C_p\left(T_i - T_o\right)}{A_g\left(T_i - T_a\right)} \tag{14}$$

The thermal loss parameter $(A_a/A_g)F_RU_L$ is calculated from steady state time periods of 3.5 minutes in duration using Eq. (14). A time period was considered steady state if the 10 seconds average values of volume flow rate, inlet temperature, outlet temperature and ambient temperature remained within the limits listed in Table 10.

TABLE 10: INDOOR TEST VARIABLES

Variable	Description
T_i	Collector inlet temperature
T_o	Collector outlet temperature
T_a	Ambient temperature
$\dot{V}$	Volume flow of water through the collector
A_g	Collector gross area

TABLE 11: STEADY-STATE CONDITIONS

Variable	Allowed variation
Inlet, outlet, ambient temperature	±0.2 K
Volume flow rate	±1.0 %

For time periods that met the steady state requirements defined above, $(A_a/A_g)F_RU_L$ was calculated by averaging the measured variables over 3.5 min and using these average values in Eq. 15. The results are presented in Table 12.

TABLE 12: INDOOR TEST RESULTS

Inlet - ambient temperature [°K]	Inlet – outlet temperature [°K]	F_RU_L [W/m^2-K]
33.3	1.8	4.49 ±0.38
45.2	2.4	4.39 ±0.28
26.4	1.3	4.09 ±0.47
37.2	2	4.48 ±0.34
44.6	2.4	4.47 ±0.28
44.6	2.3	4.27 ±0.28

8.3 Uncertainty Analysis

The accuracies for the measurements are equal to those for the outdoor tests, as the same equipment has been used (Table 8). The average propagated uncertainty has been calculated [7] to be

$$(A_a/A_g)F_R U_L. = 4.37 \pm 0.3390 \ (\pm 7.8\%)$$

The uncertainty of the precision error contribution can be reduced by averaging of repeated measurements. As a result, the uncertainty of the indoor test results may be lower than that presented above and closer to the uncertainty of the outdoor test results (±5.7%). The absolute values are within the uncertainty range of the outdoor tests.

9. CONCLUSIONS

The ASHRAE 93 test method has been compared to the methods described in ISO 9806-1 and EN 12975-2. The results of the comparison (not presented in this paper) have shown that all three standards use the same principle for determining the thermal efficiency. EN 12975-2 additionally offers a transient test method. All three test standards allow indoor tests with an irradiance simulator. However, the required equipment is expensive and the effect of the spectral distribution provided by the solar simulator on measured collector performance remains an issue. The feasibility of conducting solar thermal collector tests in accordance with ASHRAE 93, as related to the number of suitable days available for testing, depends strongly on the climatic conditions of the test site. Variation in wind speed and ambient temperature and the requirement of symmetric measurements additionally reduce the number of test days calculated here. Northern climates are particularly unsuitable for solar collector tests, even though solar systems can be operated effectively in northern climates. As a result, the development of alternative test methods with higher feasibility and lower costs is desirable.

Determining the heat loss of the collector with an indoor test can reduce the necessary outdoor tests by 16. The uncertainty of the test results is similar, 7.8% for the indoor test vs. 5.7% for the outdoor test. The uncertainty of the indoor test results can be decreased by repeated measurements and increasing the temperature difference, achievable by lowering the flow rate or increasing the surrounding air velocity.

One issue relating to indoor testing is that reduced thermal losses during the test could occur both as a result of improved collector design and as a result of a poor conductance between the fluid and the collector plate, which reduces the collector efficiency. A combination of indoor and outdoor testing may be a viable approach to reduce the time and expense associated with performance testing of solar thermal collectors.

10. NOMENCLATURE

A_a	Collector aperture area
A_g	Collector gross area
C_p	Specific heat of heat transfer fluid
F_R	Collector heat removal factor
G_t	Total irradiance per area upon collector plane
$\dot{m}$	Mass flow rate through collector
$\dot{Q}_u$	Useful energy gain
T_a	Ambient temperature
T_i	Temperature of heat transfer fluid at collector inlet
T_o	Temperature of heat transfer fluid collector outlet
U_L	Overall heat loss coefficient
η_g	Collector efficiency with respect to gross area
$(\tau\alpha)_e$	Effective transmittance absorptance product

11. ACKNOWLEDGMENTS

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