Development and Validation of Flat-Plate Collector Testing Procedures

Report for February, 2007

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 fifth report of this activity.

This report is not a final report. The content of this report is therefore continuously reviewed and corrected if necessary. Corrected versions of the actual and preceding reports can be found on the UW Solar Energy Lab webpage:

http://sel.me.wisc.edu/research/coltest.html

[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

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1. Data analysis incidence angle modifier test

An incidence angle modifier test was performed on December 9, 2006. The desired incidence angles are achieved by adjusting the azimuth angle of the collector. Table 1 summarizes the sequences of testing conditions and the corresponding measured efficiencies. The efficiency as a function of incidence angle is plotted in Figure 1. Figure 2 shows the incidence angle modifier with respect to the incidence angle and Figure 3 shows the incidence angle modifier as a linear function of the term [-1 + 1 / cos(incidence angle)]. The incidence angle modifier coefficient, b_0, is estimated to be 0.179 based on the measurements. The test results are not in accordance with ASHRAE 93-2003, as the test conditions were not maintained within the allowed range over the required time period of 20 minutes. The test should be repeated if possible.

Table 1 Test setup incidence angle modifier test

Test No.	Incidence Angle [degree]	Start Time [local time]	End Time [local time]	Collector azimuth [degree west]	Efficiency
1	0	13:10:00	13:24:30	21.7	0.650
2	30	13:25:00	13:36:30	51.9	0.649
3	45	13:40:00	13:52:00	75.2	0.631
4	60	13:55:00	14:10:00	97.1	0.531

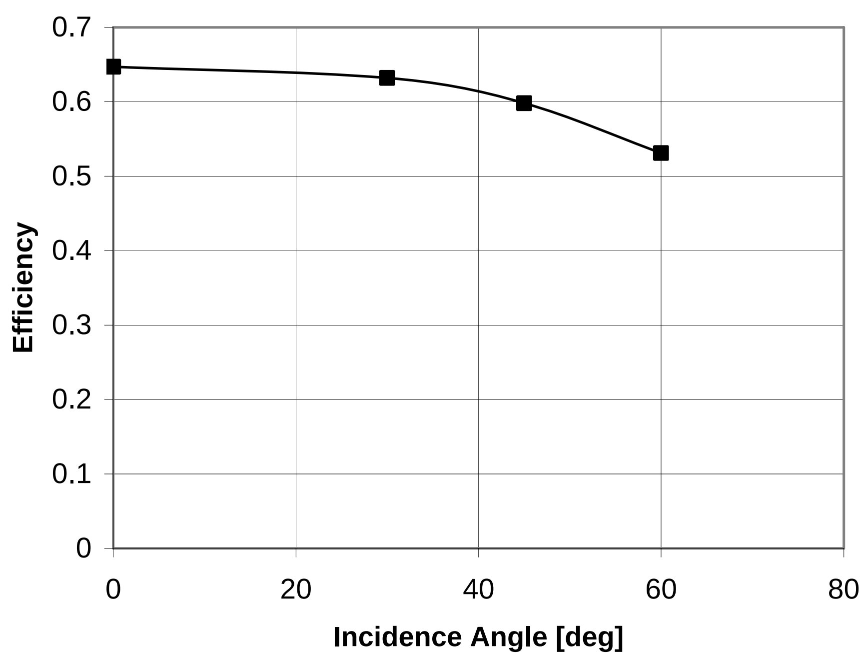

Figure 1 Incidence angle modifier test: efficiency vs. incidence angle

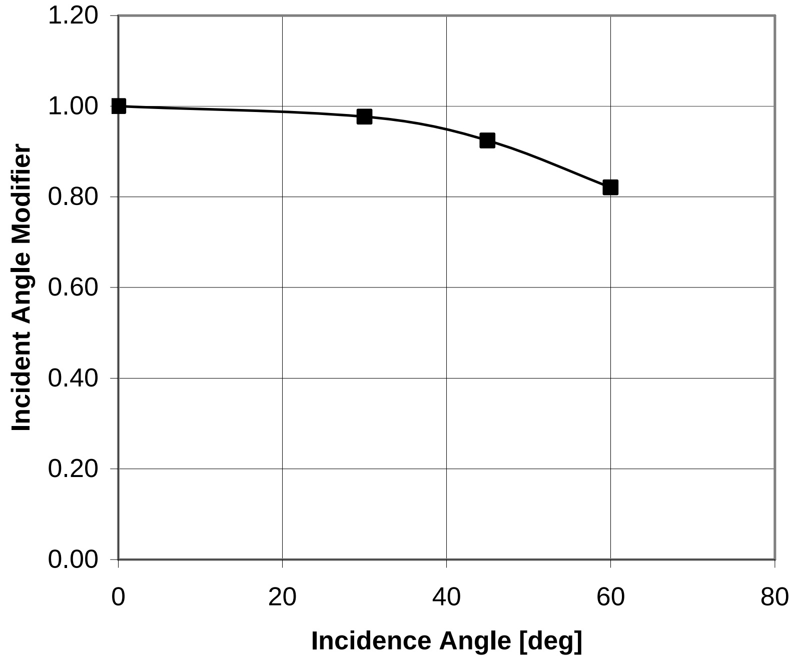

Figure 2 Incidence angle modifier test: incidence angle modifier vs. incidence angle

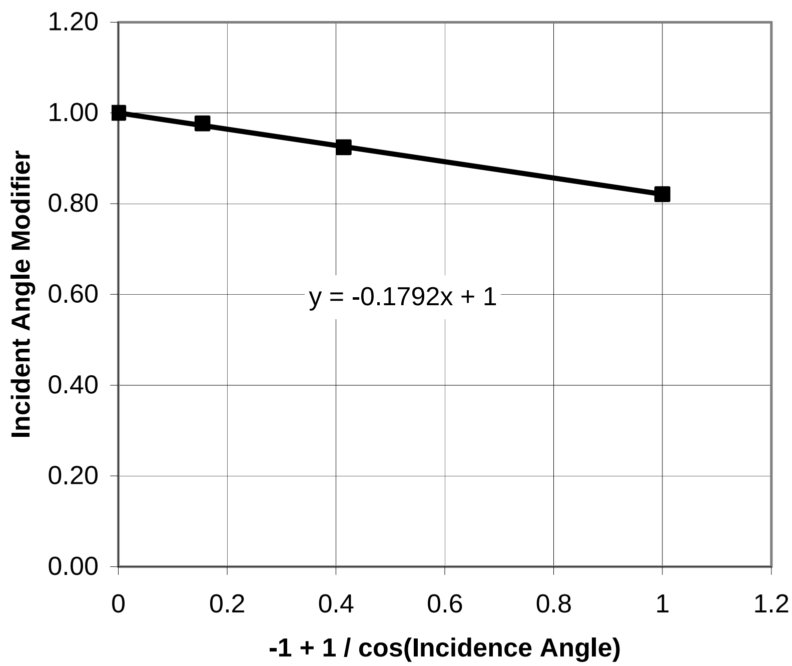

Figure 3 Incidence angle modifier test: incidence angle modifier as linear function

2. Closed loop design

2.1. Closed loop

A new test mount will be built at MATC. The major changes compared to the existing mount are that the heat transfer fluid will circulate in a closed loop, which allows use of heat transfer fluid alternatives that differ from water, e.g. ethylene glycol or propylene glycol. The test mount will be capable of tracking the sun, which allows maintaining normal incidence for tests throughout the day. Figure 4 shows a block diagram of the planned test loop, designed by Thomas Kaminski.

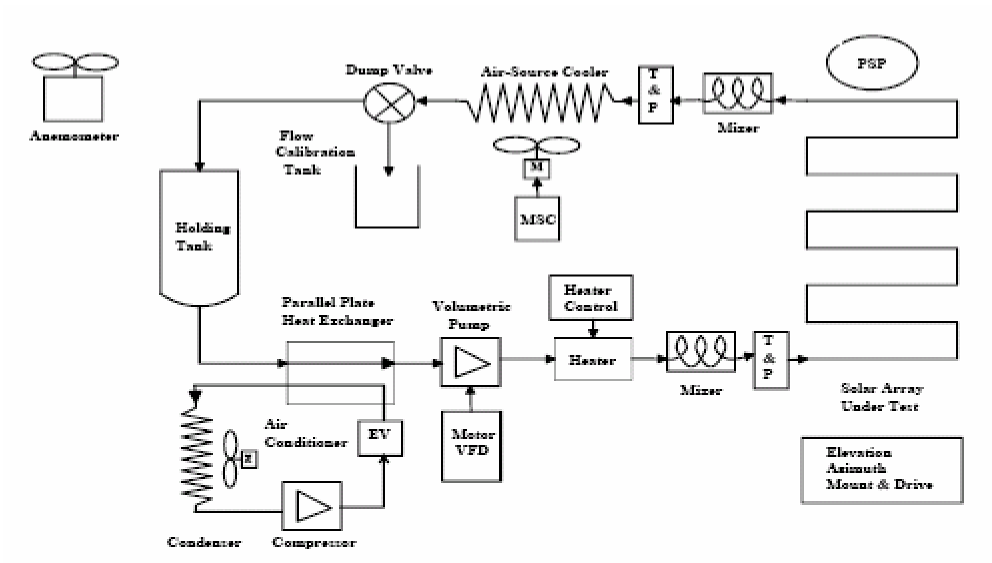

Figure 4 MATC solar collector test stand (closed loop), design by Thomas Kaminski

2.2. Heater

2.2.1. Required inlet temperatures

The collector tests must be conducted with four different inlet temperature levels. The inlet temperature levels are set to specified values above the ambient temperature at the test site. There is a concern with the time required to bring the fluid inventory in the test loop up to its operating temperature. Assuming that the heat losses of the test loop are lower than the rate of energy gain of the collector, the collector itself will be able to increase the temperature of the heat transfer fluid to the desired temperature levels. However, the heating power of the collector may be low compared to the heat capacity of the test loop resulting in delays at startup. Consequently electric heaters are integrated in the test loop, not only to control the collector inlet temperature precisely, but also to decrease the loop's transient time.

2.2.2. Heater power calculations

The maximum required heater power is defined by the following equation:

$$P_{max} = \frac{\sum_i (m_i c_i) \cdot \Delta T_{max}}{\Delta t_{max}} - P_{coll} + P_{loss} \quad (1.1)$$

where m_i and c_i are the mass and the specific heat of component i of the test system. ΔT_{max} is the maximum required temperature increase during testing and Δt_{max} is the maximum acceptable time period for the heat up process. P_{coll} represents the heat power provided by the collector and P_{loss} represents the heat losses of the test system to the ambient.

The maximum heating power is dictated by the largest increase in temperature, which is ΔT_{max} 80°C (144°F) above ambient temperature. In order to size the heater, a time period, Δt_{max}, of 20 minutes is assumed and the heat losses are neglected ($P_{loss} = 0$). In the worst case (test of solar collector with small area under low irradiance) the heat power contribution of the collector is negligible, so the P_{coll} is set to zero. The heat capacities will be determined in the next section.

$$\Delta T_{max} = 80°C \quad (1.2)$$

$$\Delta t_{max} = 20\,\text{min} \quad (1.3)$$

$$P_{coll} = 0 \quad (1.4)$$

$$P_{loss} = 0 \quad (1.5)$$

2.2.3. Test system heat capacity

The heat capacity of the test system is determined by the solar collector and the components of the test loop on the one side and the heat transfer fluid on the other side. The heat capacity of the collector has been determined for the maximum collector area that can be tested with the planned test mount based on typical values listed by SRCC[2]. At this time, the components of the test loop are not known, so their heat capacities can not be determined. They are included in the calculations by overestimating the heat capacity of the collector.

The heat capacity of the heat transfer fluid is the product of the volume, the density and the specific heat of the heat transfer fluid. Density and specific heat are known for water and a glycol water solution. The heat capacity of water will be used for the calculations as it is higher compared to the heat capacity of the solution and therefore results in a higher heater power. The volume of the heat transfer fluid depends on the fluid capacity of the collector and the fluid capacity of the test loop (piping and other components). The fluid capacity of the collector has been determined based on typical values listed by SRCC. The fluid capacity of the test loop is not known at present, so the results will be presented as a function of the fluid capacity of the test loop.

[2] Solar Rating and Certification Corporation (SRCC), Directory of SRCC Certified Solar Collector Ratings, http://www.solar-rating.org/SUMMARY/Dirsum_20070201.pdf

2.2.4. Results

Based on the parameters set before, the required heater power depending on the fluid capacity of the test loop has been calculated and is presented in Table 2 and Table 3.

Table 2 Required heater power for 80°C temperature increase within 20 minutes (SI units)

Fluid capacity of collector [liters]	Fluid capacity of other test loop components [liters]	Heater Power [kW]
6	5	3.3
6	10	4.9
6	20	8.0
6	30	11.1
6	40	14.2
6	50	17.3
6	100	32.8

Table 3 Required heater power for 80°C temperature increase within 20 minutes (English units)

Fluid capacity of collector [gal]	Fluid capacity of other test loop components [gal]	Heater Power [Btu/hr]
6	1.4	11,200
6	2.7	16,500
6	5.3	27,100
6	8.0	37,700
6	10.6	48,300
6	13.3	58,900
6	26.5	111,900

2.3. Air source cooler

An air (ambient) to liquid heat exchanger in will be used to cool the heat transfer fluid (air source cooler in Figure 4). In cases where the air source cooler cannot provide enough cooling power, it will be supported by a chiller (Figure 4). It is desirable to decrease the temperature of the heat transfer fluid from its temperature at the collector outlet to a temperature of 2.8°C below the required collector inlet temperature (Eq. (1.8)) in order to allow a precise adjustment of the collector inlet temperature to the required value by the heaters. To select the appropriate heat exchanger and fan, the capacitance rate of the heat transfer fluid, the required temperature decrease of the heat transfer fluid and the temperature of the ambient air must be provided.

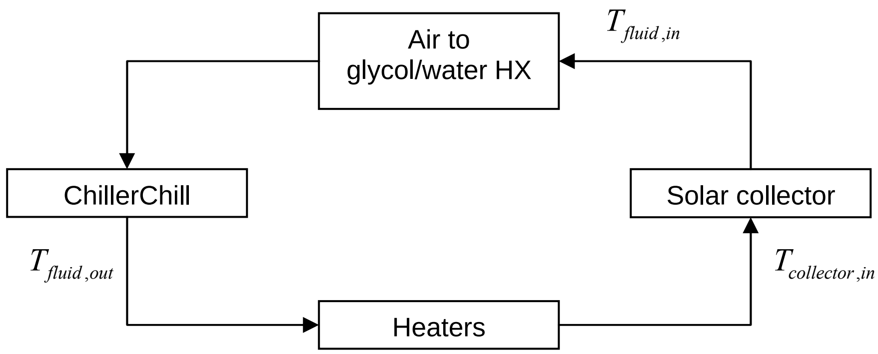

Figure 5 MATC test loop

$$\Delta T_{collector} = T_{fluid,in} - T_{collector,in} \tag{1.6}$$

$$\Delta T_{fluid} = T_{fluid,out} - T_{fluid,in} \tag{1.7}$$

$$\Delta T_{fluid} = \Delta T_{collector} + 2.8°C \tag{1.8}$$

The increase in temperature of the heat transfer fluid by the solar collector depends on the heating power of the collector and the capacitance rate of the heat transfer fluid. The air HX must provide the most cooling power when the collector produces the most heating power. This is the case at high irradiance and high collector efficiency (1,200 W/m^2 and 0.75 used for calculations). The new test mount is designed for panel dimensions up to 1.22 m (4 ft) width and 2.44 m (8 ft) length. So the maximum collector area that can be tested is 3.9 m^2 (32 ft^2). At these conditions the collector provides a heating power of 3.8 kW (13,000 Btu/hr).

The maximum collector area determines the maximum mass flow rate through the collector during the tests, as ASHRAE Standard 93-2003 recommends 0.02 kg/(s-m^2 collector area). Two heat transfer fluids will be used for testing, pure water and a propylene glycol water mixture with a concentration of 50% by volume. The capacitance rates for these fluids have been calculated.

Table 4 and Table 5 show the extreme conditions for the air heat exchanger. The first condition represents a test with the lowest expected ambient temperature and the lowest expected collector inlet temperature; these conditions provide the minimum air inlet temperature expected for the heat exchanger. The second condition represents a test with maximum expected ambient temperature and maximum collector inlet temperature which gives the maximum inlet temperature of the air HX. The temperature, $T_{fluid,in}$, represents the heat transfer fluid temperature at the air HX inlet, $\dot{C}_{fluid}$ is the capacitance rate of the heat transfer fluid, and ΔT_{fluid} is the required temperature decrease.

For the minimum ambient temperature case, the ΔT_{fluid} cannot be provided by the ambient air-to-liquid heat exchanger alone, as the inlet temperature of the collector is set equal to ambient temperature. This means that temperatures below the air inlet temperature are required. For both cases (maximum and minimum ambient temperature), the size or the cost of the heat exchanger might be the limitation for the cooling power of the air HX. The portion of the required temperature decrease that cannot be provided by the air HX will be provided by the air conditioner.

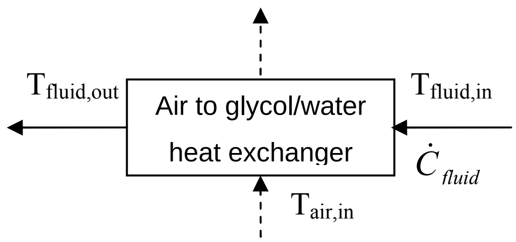

Figure 6 Air to glycol/water heat exchanger

Table 4 Conditions for air to glycol/water heat exchanger, SI units

Condition	Fluid	$T_{air,in}$ [C]	$T_{fluid,in}$ [C]	$\dot{C}_{fluid}$ [kJ/s-K]	ΔT_{fluid} [C]
Lowest ambient temperature	50% Glycol/Water	-23.4	-8.272	0.251	17.93
	Water	3	14.63	0.327	14.43
Highest ambient temperature	50% Glycol/Water	37.8	130.4	0.301	15.44
	Water	37.8	129.3	0.332	14.26

Table 5 Conditions for air to glycol/water heat exchanger, English units

Condition	Fluid	$T_{air,in}$ [F]	$T_{fluid,in}$ [F]	$\dot{C}_{fluid}$ [Btu/hr-F]	ΔT_{fluid} [F]
Lowest ambient temperature	50% Glycol/Water	-10.1	17.1	476.5	32.3
	Water	37.4	58.3	619.8	26.0
Highest ambient temperature	50% Glycol/Water	100.0	266.8	570.1	27.8
	Water	100.0	264.7	628.7	25.7

3. Comparison of solar thermal collector test standards

3.1. Unglazed collectors

3.1.1. Purpose and scope of compared test standards

The purpose of all compared test standards is to provide test methods for thermal solar collectors, including methods for the determination of the thermal efficiency. The following table summarizes the methods in current use for determining the thermal efficiency of a collector as well as the types of collectors and associated heat transfer fluids covered by the various standards.

Test Standard		**Scope**
ASHRAE 96	Test methods:	• Steady state • Outdoor and indoor
	Collectors:	• Flat plate • Unglazed
	Heat transfer fluids:	• Liquid
ISO 9806-3	Test methods:	• Steady state • Outdoor and indoor
	Collectors:	• Unglazed
	Heat transfer fluids:	• Liquid
	Exceptions:	• Collectors with integrated thermal storage unit • Collectors with phase change of heat transfer fluid
EN 12975-2: Chapter 6.1 (steady state)	Test methods:	• Steady state • Outdoor and indoor
	Collectors:	• Unglazed
	Heat transfer fluids:	• Liquid
	Exceptions:	• Collectors with integrated thermal storage unit • Tracking concentrating
EN 12975-2: Chapter 6.3 (dynamic)	Test methods:	• Dynamic • Outdoor
	Collectors:	• Glazed and unglazed • Nonconcentrating and concentrating[3]
	Heat transfer fluids:	• Liquid
	Exceptions:	• Collectors with integrated thermal storage unit

[3] The test method must be adjusted for the test of concentrating collectors.

3.1.2. Test conditions comparison

All standards prescribe test conditions for performing thermal efficiency tests. These test conditions determine how restrictive the test method is with respect to the test apparatus and the climatic conditions at the test site. The following table shows a comparison of the test conditions for the three test standards considered. All values are mandatory if not specifically noted otherwise.

Test conditions	ASHRAE 96	ISO 9806-3	EN 12975-2: Chapter 6.1 (steady state)	EN 12975-2: Chapter 6.3 (dynamic)	Comments
Test procedure					
Number of data points[4]	16 4 for each inlet temperature Symmetric pairs for fixed mount outdoor.	32 4 of each type (See Table 6.) Symmetric pairs for fixed mount outdoor.	18 2 of each type (See Table 7.) Symmetric pairs only if conditions allow.	Not applicable, as no single data points but continuous measurements throughout the day are taken.	Symmetric pairs mean that two measurements for the same collector inlet temperature are taken at times symmetric to solar noon. One efficiency value is measured before and one after solar noon.
Length predata period[5]	15 min outdoor	4*C/(mCp)[6] but minimum 15 min	4 collector time constants but minimum 15 min	Not applicable.	

[4] A data point is the pair of two values: the temperature difference irradiance ratio and the determined efficiency value for a data period. Based on all determined data points the efficiency curve of the collector is derived.

[5] The predata period is defined as the time period ahead to the data period. The measurements of the predata period are not used for the calculation of the efficiency, but to make sure that steady state conditions are achieved. The predata period is also called preconditioning period.

[6] C is the heat capacity of the collector. mCp is the heat capacitance flow rate of the heat transfer fluid.

Test conditions	**ASHRAE 96**	**ISO 9806-3**	**EN 12975-2: Chapter 6.1 (steady state)**	**EN 12975-2: Chapter 6.3 (dynamic)**	**Comments**
Length of data period[7]	5 min outdoor	15 min	4 time constants but minimum 15 min	Not applicable.	
Minimum amount of required test days	Fixed mount: 3 to 4 clear days Altazimuth mount: 2 clear days	Fixed mount: 6 to 8 clear days Altazimuth mount: 4 clear days	Fixed mount: 4 clear days Altazimuth mount: 2 clear days	4 to 5 days recommended (no nights) (see Table 8)	
Set points for controlled variables					
Inlet temperature distribution	4 inlet temperatures 1 with X within -0.02 to -0.15 C/(W/m2) 3 with X within 0.01 to 0.03 C/(W/m2)	See Table 6.	See Table 7.	3 inlet temperatures See Table 8 and Table 9. Hottest temperature depends on collector application.	X = (collector inlet temperature - ambient temperature) / Solar irradiance upon collector in °C/(W/m^2)
Mass flow rate	0.7 kg/s-m2 or manufacturer recommendation	0.4 kg/s-m2 or manufacturer recommendation	0.4 kg/s-m2 or manufacturer recommendation	0.02 kg/s-m2 or manufacturer recommendation	

[7] The data period is defined as the time period of which measurements are used to calculate the thermal efficiency.

Test conditions	ASHRAE 96	ISO 9806-3	EN 12975-2: Chapter 6.1 (steady state)	EN 12975-2: Chapter 6.3 (dynamic)	Comments
Allowed range of uncontrolled variables (absolute limits)					
Total solar irradiance on collector plane	Minimum 630 W/m2	Minimum 650 W/m2	Minimum 650 W/m2	Minimum 300 W/m2	
Incidence angle (angle between beam radiation and collector normal)	Maximum 30 deg	Maximum 30 deg	Maximum 30 deg	No requirement	
Wind speed	No minimum defined. Maximum 1.3 m/s	Minimum 1.5 m/s Maximum 4.0 m/s	Minimum 0.0 m/s Maximum 3.5 m/s	Minimum 0 m/s Maximum 3.5 m/s	
Ambient temperature	Min 15 C Max 38 C	Only variation limits defined (see Table 6).	Minimum dew point temperature.	Minimum dew point temperature	
Ambient temperature range between all data points	Maximum 10 K	No requirement defined.	No requirement defined.	No requirement defined.	This requirement
Wind speed	Average max 1.3 m/s	See Table 6.	See Table 7.	Average between 1 and 4 m/s	ASHRAE 96 uses surrounding air speed independent of direction while EN 12975-2 uses air speed parallel to collector. ISO 9806-3 does not specify which speed to use.

Test conditions	**ASHRAE 96**	**ISO 9806-3**	**EN 12975-2: Chapter 6.1 (steady state)**	**EN 12975-2: Chapter 6.3 (dynamic)**	**Comments**
Allowed variation of controlled and uncontrolled variables (steady state conditions)					
Inlet temperature	Not defined.	± 0.1 K	± 0.1 K	± 1 K	
Inlet flow rate	Not defined.	± 1 %	± 1 %	± 1 % at each day ± 10% between days	
Total solar irradiance on collector plane	Not defined.	± 50 W/m2	± 50 W/m2	No requirement (dynamic variable)	
Long wave irradiance on collector plane	Not defined.	± 20 W/m2	± 20 W/m2	No requirement (dynamic variable)	
Ambient temperature	Not defined.	± 1 K	± 1 K	± 0.5 K	
Air speed	Not defined.	± 10%	± 0.5 m/s	± 0.25 m/s	
Heat transfer fluid density	± 0.5% over fluid temperature range during test	± 1% over fluid temperature range during testing	± 1% over fluid temperature range during testing	± 1 % over fluid temperature range during testing	
Heat transfer fluid specific heat	± 0.5% over fluid temperature range during test	± 1% over fluid temperature range during testing	±1% over fluid temperature range during testing	± 1 % over fluid temperature range during testing	

3.1.3. Tables

Table 6 Minimum range of thermal performance test conditions, ISO Standard 9806-3, Table 1

Test point	Net irradiance G'' W/m²	Surrounding air speed, u m/s	$(T_{in} - T_a)/G''$ m² K/W	Efficiency
1	> 650	2 to 3	< 0,002	η_0
2	> 650	2 to 3		$0,8\eta_0$ to $0,6\eta_0$
3	> 650	2 to 3		$0,6\eta_0$ to $0,4\eta_0$
4	> 650	2 to 3		$< 0,4\eta_0$
5	> 650	< 1,5	< 0,002	
6	> 650	< 1,5		$< 0,5\eta_0$
7	> 650	3 to 4	< 0,002	
8	> 650	3 to 4		$< 0,5\eta_0$

Table 7 Range of thermal performance test conditions, EN 12975-2, British version, Table 7

Test point	Net irradiance Wm^{-2}	*Tm* (mean temperature) K	Air speed parallel to collector ms^{-1}
1	>650	$T_m = T_a \pm 3$ K	< 1
2	>650	$T_m = T_a \pm 3$ K	1,5 ± 0,5
3	>650	$T_m = T_a \pm 3$ K	3 ± 0,5
4	>650	$T_m = T_a + 0,5\ (\Delta t_{max}) \pm 3$ K	< 1
5	>650	$T_m = T_a + 0,5\ (\Delta t_{max}) \pm 3$ K	1,5 ± 0,5
6	>650	$T_m = T_a + 0,5\ (\Delta t_{max}) \pm 3$ K	3 ± 0,5
7	>650	$T_m = T_a + \Delta t_{max} \pm 3$ K	< 1
8	>650	$T_m = T_a + \Delta t_{max} \pm 3$ K	1,5 ± 0,5
9	>650	$T_m = T_a + \Delta t_{max} \pm 3$ K	3 ± 0,5

Table 8 Combination of inlet temperatures and weather conditions for test days, EN 12975-2, British version

Mean plate temperature	Clear sky	Partly cloudy
Ambient temperature ±3K	Day 1	Day 2
(Ambient + hottest temperature) / 2	Day 3	Day 3
Hottest temperature (see Table 9)	Day 4	Day 4

Table 9 Highest fluid temperature as a function of collector type, EN 12975-2, British version

Collector type	Hottest temperature (accuracy range not specified)
Domestic hot water preparation	Ambient temperature + 60 C
District heating	Ambient temperature + 70 C
Swimming pools	Ambient temperature + 15 C
Process heating	Ambient temperature + 90 C