On-site performance of solar collectors

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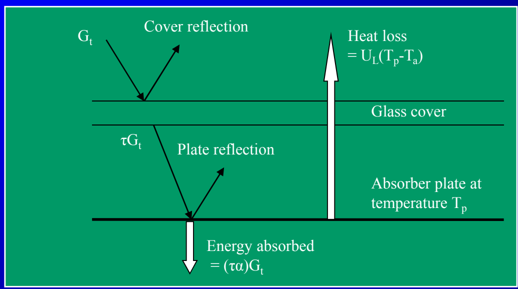
Collector Efficiency depends on:

- Collector construction
- Solar environment
  - radiation intensity,
  - diffuse fraction,
  - incidence angle.
- Ambient conditions
  - ambient temperature,
  - wind speed,
  - sky temperature
- Operating conditions
  - fluid inlet temperature,
  - fluid flow rate and thermal properties,
  - collector slope and orientation.

Useful energy collected from a flat plate collector



- In equation form it is given by:

$$Q_u = A_c\left[G_t(\tau\alpha) - U_L\left(T_p - T_a\right)\right] = \dot{m}c_p\left[T_o - T_i\right]$$

Useful energy collected from a flat plate collector

- by substituting inlet fluid temperature (T_i) for the average plate temperature (T_p):

$$Q_u = A_c F_R\left[G_t(\tau\alpha) - U_L\left(T_i - T_a\right)\right]$$

- Where F_R is the heat removal factor

Heat removal factor

- Heat removal factor is the ratio of the heat actually delivered to that delivered if the collector plate were at uniform temperature equal to that of the entering fluid.
- Equation:

$$F_R = \frac{\dot{m}c_p}{A_c U_L}\left(1 - \mathrm{Exp}\left[\frac{U_L F' A_c}{\dot{m}c_p}\right]\right)$$

Collector efficiency

- Finally, the collector efficiency can be obtained by dividing Q_u by (G_t A_c). Therefore:

$$\eta = F_R(\tau\alpha) - F_R U_L \frac{U_L(T_i - T_a)}{G_t}$$

PERFORMANCE OF SOLAR COLLECTORS

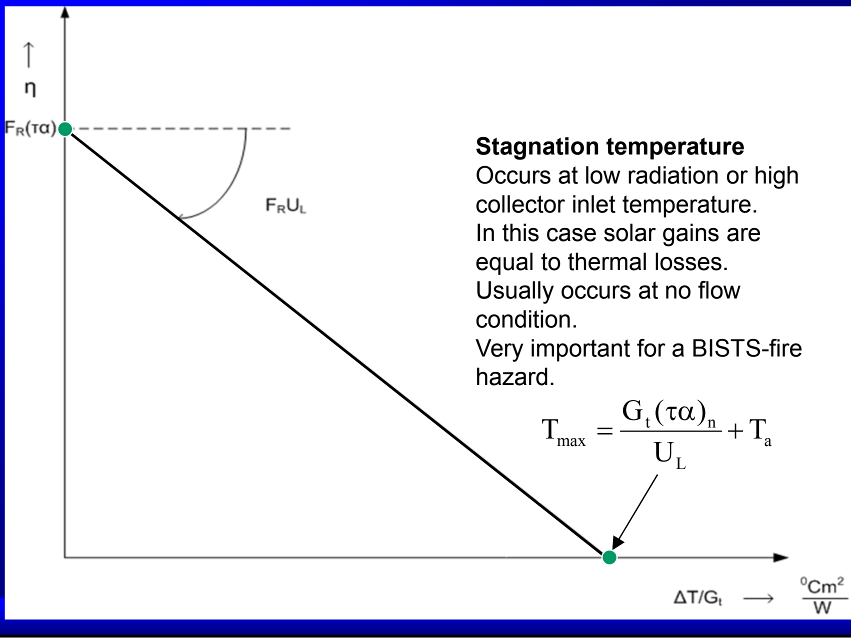
- The thermal performance of the solar collector is determined by:
  - Obtaining values of instantaneous efficiency for different combinations of incident radiation, ambient temperature and inlet fluid temperature.
  - Determining the incidence angle modifier.
  - Obtaining the transient thermal response characteristics of the collector (time constant).

Efficiency plots

- *For flat plate collectors:* The first-order equation plots as a straight line on a graph of efficiency versus the heat loss parameter $(T_i - T_a)/G_t$:
  - The intercept (intersection of the line with the vertical efficiency axis) equals to $F_R(\tau\alpha)$.
  - The slope of the line equals to $-F_R U_L$.

$$\eta = F_R(\tau\alpha) - F_R U_L \frac{U_L(T_i - T_a)}{G_t}$$

Efficiency curve for FPC



Stagnation temperature
Occurs at low radiation or high collector inlet temperature.
In this case solar gains are equal to thermal losses.
Usually occurs at no flow condition.
Very important for a BISTS-fire hazard.

$$T_{max} = \frac{G_t(\tau\alpha)_n}{U_L} + T_a$$

Second order equation for Thermal Efficiency

- In reality the heat loss coefficient U_L in performance equation is not constant but is a function of collector inlet and ambient temperatures. Therefore:

$$F_RU_L = c_1 + c_2(T_i - T_a)$$

- Applying above equation to the standard performance one we get:

$$Q_u = A_aF_R\left[(\tau\alpha)_nG_t - c_1(T_i - T_a) - c_2(T_i - T_a)^2\right]$$

Flat plate collector efficiency

- Therefore the efficiency can be written as:

$$\eta = F_R(\tau\alpha) - c_1 \frac{(T_i - T_a)}{G_t} - c_2 \frac{(T_i - T_a)^2}{G_t}$$

- According to EN12975-2:2006:

$$\eta = \eta_o - a_1 T_m^* - a_2 G (T_m^*)^2$$

  - Where reduced temperature difference is given by:

$$T_m^* = \frac{t_m - t_a}{G} \quad \text{and} \quad t_m = t_{in} + \frac{\Delta T}{2} = \frac{t_{in} + t_o}{2}$$

2. Incidence Angle Modifier Flat-plate collectors

- The above performance equations assume that the sun is perpendicular to the plane of the collector, which rarely occurs.
- For the glass cover plates of a flat-plate collector, specular reflection of radiation occurs on the collector glazing thereby reducing the (τα) product.
- The incident angle modifier is defined as the ratio of (τα) at some incident angle θ to (τα) at normal radiation $(\tau\alpha)_n$:

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

- Difficult to test on BISTS

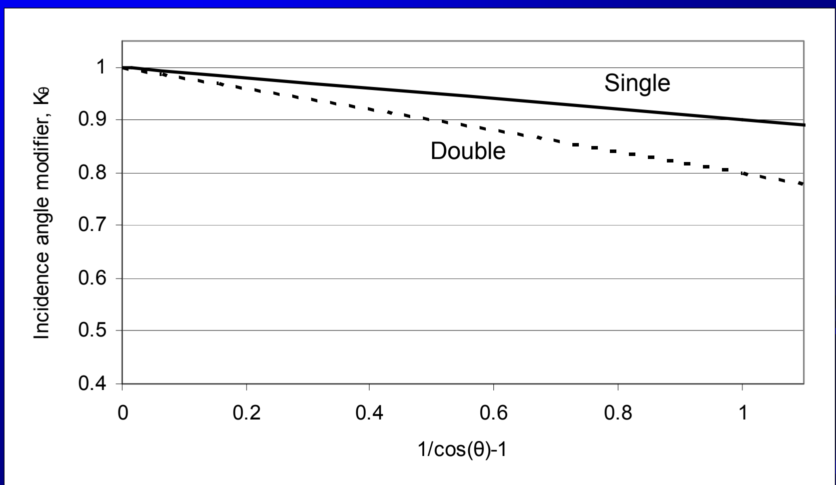
Second order equations for incidence angle modified

- A more general expression for the incidence angle modifier is a second-order equation given by:

$$K_\theta = 1 - b_o\left(\frac{1}{\cos(\theta)} - 1\right) - b_1\left(\frac{1}{\cos(\theta)} - 1\right)^2$$

- Second order equation is required for double glazed collectors.
- For single glass cover, a single-order equation can be used with b_o equal to 0.1 and b_1=0

Plot of incidence angle modifier against 1/cos(θ)-1 for two types of flat plate collectors



Efficiency equation by considering incidence angle modifier

- With the incidence angle modifier the collector efficiency equation can be modified as:

$$\eta = F_R(\tau\alpha)_n K_\theta - c_1 \frac{(T_i - T_a)}{G_t} - c_2 \frac{(T_i - T_a)^2}{G_t}$$

3. Collector Time Constant

- A last aspect of collector testing is the determination of the heat capacity of a collector in terms of the time constant.
- Whenever transient conditions exist, the performance equations given before do not govern the thermal performance of the collector since part of the absorbed solar energy is used for heating up the collector and its components.

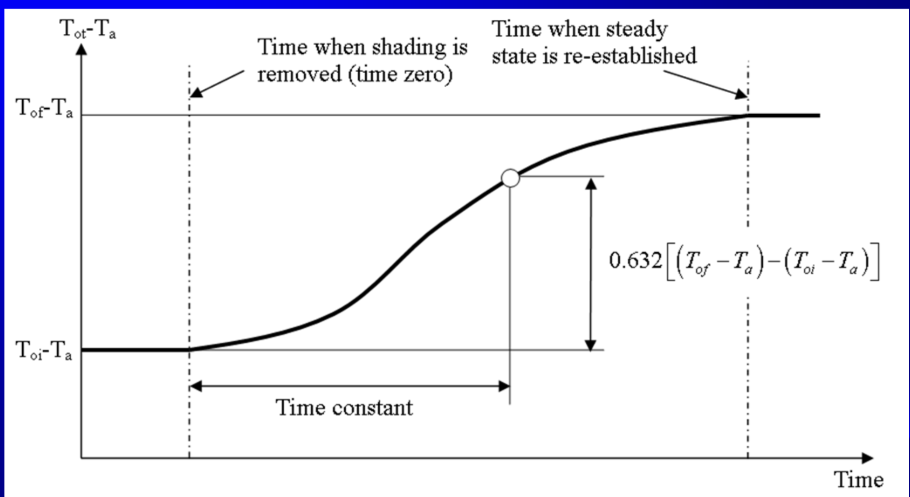
Collector time constant

- The time constant of a collector is the time required for the fluid leaving the collector to reach 63% of its ultimate steady value after a step change in incident radiation.
- Therefore the collector time constant is a measure of the time required for the following relationship to apply:

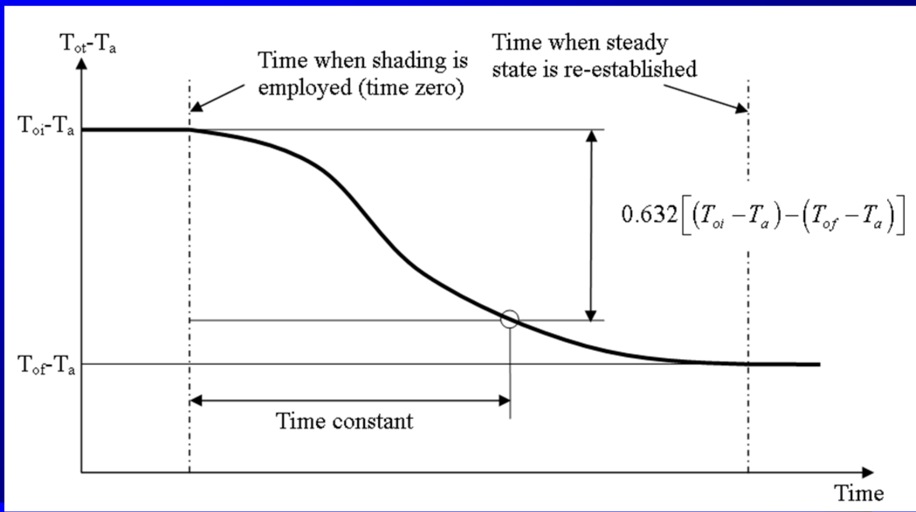
$$\frac{T_{ot} - T_i}{T_{oi} - T_i} = \frac{1}{e} = 0.368$$

- T_{ot} = Collector outlet water temperature after time t (°C)
- T_{oi} = Collector outlet initial water temperature (°C)
- T_i = Collector inlet water temperature (°C)

Time constant as specified in ISO 9806-1:1994



Time constant as specified in ASHRAE 93:2010



Collector stagnation temperature

- Stagnation temperature is the maximum temperature experienced by a collector at zero efficiency (heat gain=heat loss) or at no flow condition.
- By using second order collector performance equation and denoting $F_R(\tau\alpha)$ as η_o, then:

$$T_{stag} = T_a + \frac{-c_1 + \sqrt{c_1^2 + 4\eta_o c_2 G_t}}{2c_2}$$

- Or from the first order performance equation as:

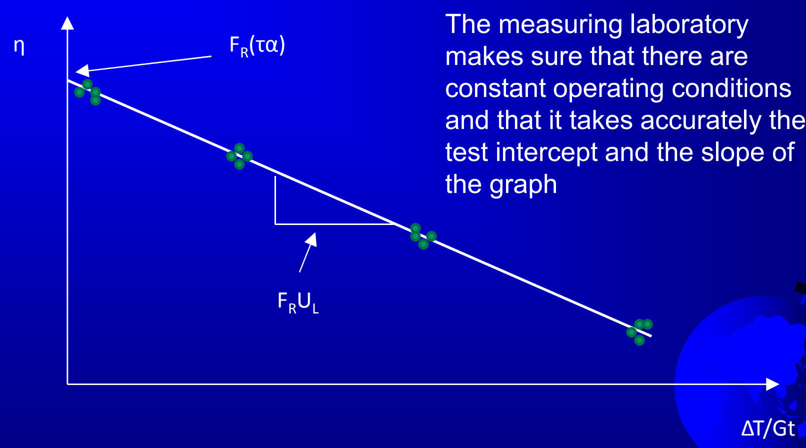
$$T_{stag} = G_t(\tau\alpha)/U_L + T_a$$

Practical way of carrying out the tests

- Mounting the collector on a specific structure to face the sun directly-serious problem for BISTS.
- Specific weather conditions as:

Parameter	Value or deviation from the mean
Available solar radiation	>800 W/m^2
Total solar irradiance variation	±50 W/m^2
Ambient air temperature	±1K
Wind speed	2-4 m/s
Fluid mass flow rate	±1%
Collector inlet fluid temperature	±0.1K
Minimum temperature rise in collector	1.5K

Experimental testing



The measuring laboratory makes sure that there are constant operating conditions and that it takes accurately the test intercept and the slope of the graph

Dynamic system testing

- For locations that do not have steady environmental conditions for long periods of time the transient or dynamic system test method can be used.
- This method is according to EN 12975-2:2006 and involves monitoring the transient response of a collector over a number of days, which include both clear and cloudy conditions.
- The performance data obtained from the dynamic method allows a more detailed characterization of the collector performance in comparison with the steady state method.

Dynamic system testing-equation

- After testing, the data collected over the wide range of operating conditions are fitted to a transient mathematical model of the collector performance.

$$Q_u = \eta_o\left[K_{\theta,B}G_B + K_{\theta,D}G_D\right] - a_0(\overline{T} - T_a) - a_1(\overline{T} - T_a)^2 - c\frac{d\overline{T}}{dt}$$

- Where η_o, a_0, a_1, c and the coefficients $K_{\theta,B}$ and $K_{\theta,D}$ are determined by the correlation of the test measured data.
- This equation is similar to the second order equation used for steady state testing with the addition of a transient term and incident angle modifiers for both beam $K_{\theta,B}$ and diffuse $K_{\theta,D}$ radiation.

Dynamic system testing-remarks

- An added advantage of the method is that the equipment required is the same as the steady state testing, which means that a test centre can have the same equipment and perform both steady state and dynamic testing at different periods of the year according to the prevailing weather conditions.
- The primary difference between the two methods is that in the dynamic method the data are recorded on a continuous basis over a day and averaged over 5-10 minutes.
- Is this method suitable for BISTS?

International standards

- **ISO 9806-1:1994**, Test Methods for Solar Collectors – Part 1: Thermal Performance of Glazed Liquid Heating Collectors Including Pressure Drop.
- **ISO 9806-2:1995**, Test Methods for Solar Collectors – Part 2: Qualification Test Procedures (next slide).
- **ISO 9806-3:1995**, Test Methods for Solar Collectors – Part 3: Thermal Performance of Unglazed Liquid Heating Collectors (Sensible Heat Transfer Only) Including Pressure Drop.
- **ANSI/ASHRAE Standard 93, 2010**, Methods of Testing to Determine the Thermal Performance of Solar Collectors.

Collector quality test methods
ISO 9806-2:1995

Series	Test
1	Internal pressure test for fluid channels
2	High temperature resistance
3	Stagnation temperature
4	Exposure test
5	External thermal shock
6	Internal thermal shock
7	Rain penetration
8	Freeze resistance test
9	Mechanical load with positive or negative pressure
10	Impact resistance
11	Final inspection

European standards
Collectors and complete systems

- **EN 12975-1:** Thermal solar systems and components - Solar collectors – Part 1: General Requirements
- **EN 12975-2:** Thermal solar systems and components - Solar collectors – Part 2: Test methods
- **EN 12976-1:** Thermal solar systems and components – Factory made systems – Part 1: General Requirements
- **EN 12976-2:** Thermal solar systems and components – Factory made systems – Part 2: Test methods
- **ENV 12977-1:** Thermal solar systems and components – Custom built systems – Part 1: General Requirements
- **ENV 12977-2:** Thermal solar systems and components - Custom built systems – Part 2: Test methods
- **ENV 12977-3:** Thermal solar systems and components - Custom built systems – Part 3: Performance characterization of stores for solar heating systems

Systems testing ISO standards

- **ISO 9459-1: 1993**-Solar heating - Domestic water heating systems. Part 1: Performance rating procedure using indoor test methods.
- **ISO 9459-2: 1995**-Solar heating - Domestic water heating Systems. Part 2: Outdoor test methods for system performance characterization and yearly performance prediction of solar-only systems.
- **ISO 9459-3: 1997**- Solar heating - Domestic water heating systems. Part 3: Performance test for solar plus supplementary systems.
- **ISO 9459-4: 1992**-Solar heating - Domestic water heating systems. Part 4: System performance characterization by means of component tests and computer simulation.
- **ISO 9459-5: 2007**-Solar heating - Domestic water heating systems. Part 5: System performance characterization by means of whole-system tests and computer simulation.

Solar Keymark

- Solar Keymark is given to collectors and systems which comply with the following standards:
  - EN12975: Thermal solar systems and components - Solar collectors.
  - EN12976: Thermal solar systems and components - Factory made systems.
  - ISO 9000/1 quality standards
- Solar Keymark is important for the European market because:
  - Products with the Keymark can only be used in national subsidization schemes.
  - In some EU countries it is necessary for all systems to have the keymark.
  - General public expects to see the «Solar Keymark» symbol in order to buy a solar system.

Centre for testing collectors and systems

Current status of standards concerning BISTS

- The subject is hardly touched….
- EN12975-2 states in scope:
  - Collectors that are custom built (e.g. roof integrated collectors that do not compose of factory made modules and are assembled directly on the place of installation) cannot be tested in their actual form for durability, reliability and thermal performance according to this standard. Instead, a module with the same structure as the ready collector may be tested. The module gross area should be at least 2 m^2. The test is valid only for larger collectors than the tested module.
- This will be replaced by ISO 9806:2 which states:
  - **Simulated roof:** construction using materials of a quality typical to that used in roofs, from roof structure to roof coverings.

➢ Furthermore the new standard states:

- The collector shall be mounted in the manner specified by the manufacturer. The collector mounting frame shall in no way obstruct irradiance on the collector, and shall not significantly affect the back or side insulation. Unless otherwise specified (for example, when the collector is part of an integrated roof array), an open mounting structure shall be used which allows air to circulate freely around the front and back of the collector. The collector shall be mounted such that the lower edge is not less than 0.5 m above the local ground surface. Currents of warm air, such as those which rise up the walls of a building, shall not be allowed to pass over the collector. Where collectors are tested on the roof of a building, they shall be located at least 2 m away from the roof edge.

➢ For air heating collectors/unglazed collectors

- Collectors designed to be mounted directly on standard roofing or wall material may be mounted over a simulated roof or wall section. In case of building envelope integrated collectors, a model consisting of a small scale collector placed on an artificial roof/wall should be prepared for the purpose of the tests.
- If mounting instructions are not specified, the collector shall be mounted on an insulated backing with a quotient of the materials thermal conductivity to its thickness of 1 $W/(m^2 \cdot K) \pm 0.3 W/(m^2 \cdot K)$ and the upper surface painted matt white and ventilated at the back.
  - NOTE Example material suited for the insulated backing is 30 mm of polystyrene foam.
- The performance of some forms of solar air heating collectors and unglazed collectors is a function of module size. If the collector is supplied in fixed units of area smaller than 1 m^2 then a sufficient number of modules should be linked together to give a test system gross area of at least 3 m^2. The biggest possible test sample size should be chosen.

➢ No mention of façade installation….

Potential problems for testing BISTS

- Generally large systems
- Because of integration on building - No way to follow sun.
- Difficult to measure incidence angle modifier
  - Maybe test a smaller module as normal
- Time constant – test on real system
- Need to specify a specific procedure so as the test to be done on-site.
  - Maybe in addition to testing a smaller unit as normally?

Need to include also:

- Detailed shading calculations
  - For the particular location and surrounding obstacles.
- Diffuse and reflected solar irradiance
  - From surrounding buildings
  - Affect isotropic sky model
- Noise measurements
  - Currently only air collectors are tested for that for the noise they produce and not for the noise transmitted into the building.
- Etc.…

Special committee

- Therefore I suggest to create a special committee to look into the subject:

1. Collect more information from existing standards
2. Suggest new testing procedures for BISTS

- Mainly WG1 activity but can be viewed across the Action.
- This will be an important contribution of the Action.

Thank you for your attention

Any Questions…,

Comments…

Suggestions….