# A Solar Collector Model for TRNSYS Simulation and System Testing

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Bengt Perers
Chris Bales

INTERNATIONAL ENERGY AGENCY
Solar Heating & Cooling Programme

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by

Bengt Perers* and Chris Bales*

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*Solar Energy Research Center SERC
Högskolan Dalarna
Dept. of Energy, Environment and Construction
781 88 Borlänge
Sweden

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# 1 Background

To be able to decouple a system test from the local unpredictable and variable weather at the test site, a collector emulator is proposed and described here. "*It is normal that the weather is abnormal"* as the Swedish Grand Old Man and Entrepreneur Gunnar Wilson says.

To be able to make a system test without the unpredictable influence of the actual weather during the test, it has become common to use an electric heater in the collector loop of the system instead of a solar collector to generate a "simulated" controlled thermal power output from the collector.

An intermediate step, that is not dealt with here, could be to use the real collector and an inexpensive solar simulator based on standard mass produced lamps.

This description will be focused on the electric heater alternative and modelling of the electric power input to the collector loop based on data from a separate quasistationary thermal collector test described in CEN 12975 [2].

# 2 Description of the Collector Model

## *2.1 Validity of the Model*

The proposed dynamic collector model is based on well validated sub models for solar thermal collectors and general heat transfer. The model is based on the "Hottel-Whillier-Bliss" equation for flat plate solar collectors [3].

The main new thing of the proposed collector model is a complete set of simple correction terms that extends the model to almost all collector designs and weather types and also to dynamic operating conditions in a system. The choice of correction terms has also been selected, so that the extremely fast and simple to use, Multiple Linear Regression, can be used for evaluation of dynamic collector test data.

The total model (equation (5) below) has been validated against measurements on collectors in test rigs under well controlled operating conditions, both outdoors and indoors in solar simulators and data from in situ measurements and in real collector loops in different system types.

The model can be described as a compromise or a design freeze to an accuracy level that is a compromise between error level and costs for the test rig, sensors, measurements and evaluation. In the future and for special purposes more elaborate models are and will be available if needed.

## *2.2 The Collector Model Derivation in Mathematical Terms*

The derivation of the model and relation to previous steps in collector modelling for standardised testing is described below. The equations are given as much as possible in standard solar nomenclature also closely connected to the formulation in the CEN standard. A more elaborate description including evaluation of test data is given in [11].

**The collector model for the present "old" stationary test methods:**
As a background we start to describe the stationary or steady-state collector model in the present standards. This model has been widely used both in testing (ISO 9806-1 [6] and ASHRAE 93-77 [1]) and for simulation. If expressed as useful output power of the solar collector per m² of aperture area, the basic equation for the stationary model for near normal incidence angle operation can be written as:

*equ.1:* $$P_{out} = F'(\tau\alpha)_{en}\, G - c_1\, (t_m - t_a) - c_2\, (t_m - t_a)^2$$

where

$F'(\tau\alpha)_{en}$ = Zero loss efficiency for global or total radiation at normal incidence [-]

$c_1$ *and* $c_2$ = Parameters that describe the temperature-dependent heat losses.

$G$ = The global or total solar radiation onto the collector plane [W/m²]. No corrections are made for the incidence angle or diffuse fraction of the incoming solar radiation.

$t_m$ = Arithmetic mean temperature between inlet and outlet temperature of the collector [$^o$C].

$t_a$ = Ambient air temperature close to the collector [$^o$C].

There are optional, additional separate test procedures, for the determination of incidence angle dependence (IAM) of the zero loss efficiency, here denoted $K_\theta(\theta)$ and the effective thermal capacitance of the collector, $c_5$ or $(mC)_e$ . The parameter $(mC)_e$ is not measured, but calculated by weighting the capacities of the collector components.

The full instantaneous equation based on all options in the present steady-state standards can be written as:

*equ. 2:* $$P_{out} = F'(\tau\alpha)_{en}\, K_\theta(\theta)\, G - c_1\, (t_m - t_a) - c_2\, (t_m - t_a)^2 - c_5\, dt_m/dt$$

*This is still a clear weather or indoor solar simulator model.* Only high irradiance levels are accepted in the test sequence, and thus only low diffuse fractions.

This model has no correction term for diffuse radiation. This is needed in most simulation programmes for long term performance calculations. The solar radiation must be divided into beam and diffuse radiation and a separate incidence angle correction has to be known for the diffuse radiation. No method for correction for non-stationary test conditions is described in the test procedure. Therefore very stable weather conditions are needed for each test point. Furthermore it is assumed that the incidence angle is near normal, so that incidence angle effects can be neglected. This limits the available outdoor testing time very much in variable climates and makes an outdoor test very expensive according to the existing stationary collector test standards.

**The new quasi-dynamic model for collector testing and now for emulation of collector loop output:**

In the new approach proposed here, the first term of equation (2) is divided into two parts, the zero loss efficiency for beam radiation and the diffuse radiation. $F'(\tau\alpha)_{en}\, K_{\theta b}(\theta)\, G$ is replaced by the sum:

*equ. 3:* $$F'(\tau\alpha)_{en}\, K_{\theta b}(\theta)\, G \;=\; F'(\tau\alpha)_{en}\, K_{\theta b}(\theta)\, G_b + F'(\tau\alpha)_{en}\, K_{\theta d}\, G_d\,.$$

*With:*

$K_{\theta b}(\theta)$ = Incidence angle modifier (IAM) for direct (beam) radiation [-]

$K_{\theta d}$ = Incidence angle modifier for diffuse radiation, a collector constant [-]

Note 1) The basic modelling of the IAM-dependence, $K_{\theta b}(\theta)$, is done with equation (4) below:

*equ. 4* $$K_{\theta b}(\theta) = 1 - b_0((1/\cos\theta_i) - 1)$$ as described in e.g. ASHRAE 93-77 [1]

Where:

$b_0$ = Incidence angle modifier parameter determined from collector test if this model is appropriate for the collector design.

$\theta_i$ = Incidence angle for the beam solar radiation onto the solar collector plane.

Note 2) In case of some other collector designs the incidence angle dependence of the zero loss efficiency, $K_{\theta b}(\theta)$, can not be accurately modelled by an equation. Instead a vector or in extreme cases a matrix with $K_{\theta b}(\theta)$ values for 10 angular degrees intervals, has to be determined in the collector test and used in the collector model. The extended collector test method, required here, is given as an option in the test standard ISO 9806-3 [7]. The test method is already validated for this case see [4] and [10].

Furthermore the wind-dependence is modelled by two correction terms added to equation (2). One term gives the effect on the zero loss efficiency ($- c_6\, u\, G$). This is significant for some plastic and rubber collectors with limited heat transfer in the absorber surface. The other term models the wind influence on heat losses ($- c_3\, u\, (t_m - t_a)$). After a final addition of the long-wave "thermal" (outside solar spectrum) irradiance dependence, of the heat losses, the collector model is complete.

The full collector model for the useful output power of the collector per m² is then written as:

*equ. 5:* $$P_{out} = F'(\tau\alpha)_{en}\, K_{\theta b}(\theta)\, G_b + F'(\tau\alpha)_{en}\, K_{\theta d}\, G_d - c_6\, u\, G - c_1\, (t_m - t_a) - c_2 (t_m - t_a)^2 - c_3\, u\, (t_m - t_a) + c_4\, (E_L - \sigma T_a^4) - c_5\, dt_m/dt$$

where

$u$ = Wind speed in (parallel to) the collector plane [m/s]

$E_L$ = Long wavelength radiation (outside solar spectrum) onto the collector plane [W/m$^2$]

The modelling of the long-wave irradiance dependence of the collector, is done in a similar way as described in the basic ISO 9806-3 [7], for testing of unglazed collectors, but here it is treated as a heat loss term $c_4\, (E_L - \sigma T_a^4)$. Note $T_a$ in degrees Kelvin [K]. All additions to equation (2) inserted in equation (5) are based on long agreed on solar collector and heat transfer theory.

The coefficients in equation (5) are explained below:

$F'(\tau\alpha)_{en}$ = Zero loss efficiency of the collector at normal incidence angle for the solar radiation onto the collector. [-]

$c_1$ = Heat loss coefficient at ($t_m$ - $t_a$) = 0 is modelled as F' $U_0$ [$Wm^{-2}K^{-1}$]

$c_2$ = Temperature dependence of the heat losses, equal to F' $U_1$ [$Wm^{-2}K^{-2}$]

$c_3$ = Wind speed dependence of the heat losses, equal to F' $U_u$ [$Jm^{-3}K^{-1}$]

$c_4$ = Long-wave irradiance dependence of the heat losses, equal to F' ε [-]

$c_5$ = Effective thermal capacitance, equal to $(mC)_e$ [$Jm^{-2}K^{-1}$]

$c_6$= Wind dependence of the zero loss efficiency, a collector constant [$sm^{-1}$]

All constants $c_1$ to $c_6$ can be derived from a standard collector test specified in the new European test standard ISO 9806-3 [7].

We are now preparing the collector model above for TRNSYS called Type 132 for biaxial and asymmetrical incidence angle modelling. This is needed for some extreme collector designs today and may be more common in the future. Type 132 is a joint IEA development. The new extended TRNSYS collector model Type 132 will be available from the authors at SERC University Dalarna Sweden http://emb.du.se/serc/serc.html during the spring 2003. The test method ISO 9806-3 [7] is already validated for this case, see [4] and [10].

**How to Use the Model for Different Collector Designs**

The collector model as described in equation (5) will, to our knowledge, cover most collector designs available on the market today (1999), except ICS collectors.

In an ICS collector the residence time of the fluid in the collector is often much longer than the prescribed averaging time of 5-10 minutes. Therefore the inlet and outlet temperatures will not reflect the internal energy content of the collector and an accurate thermal capacitance correction is not possible with the simplified capacitance term proposed here. With a more elaborate capacitance correction term this can be solved.

For unglazed collectors, the use of the full collector model is mandatory for best accuracy. For other collectors the parameters to be used and presented in the results, will in general be given by the T-ratio of the initial regression (parameter identification) at the test.

The T-ratio = (parameter value / standard deviation of parameter value) of the regression. The T-ratio should be greater than 2 for those parameters presented in the test results.

Still for all types of collectors, the use of $F'(\tau\alpha)_{en}$, $K_{\theta b}(\theta)$, $K_{\theta d}$ and the coefficients $c_1$, $c_2$, and $c_5$ are mandatory and they should be identified and used.

# 3 The Use of the Collector Model to Emulate the Collector.

There are three alternatives to control the solar collector emulator in a solar thermal system test according to equation (5):

## 3.1 Emulator Model Alternative 1

To use the collector model output directly (Pout in equation (5)) and measure and control the electric input $P_{electric}$ to the collector loop during test, to follow the calculated output Pout multiplied by the chosen collector area $A_{coll}$.

*equ. 6:* $P_{electric} = P_{out} * A_{coll}$

## 3.2 Emulator Model Alternative 2

In some cases for large collector areas the calculated power output may be larger than the available electric power from the grid on site. A 10 m² flat plate collector may give up to 10-20 kW of thermal power in an extreme short-term dynamic case. In this case a separate mixing device with the electric heater in a thermal accumulator (tank) has to be used to reach the desired power output. Then often the outlet temperature is controlled in a conventional test rig. The $t_{out}$ can then be derived as:

*equ. 7:* $t_{out} = t_{in} + P_{out} * A_{coll} / (V_{flow} * \rho * c_p)$

Where the variables and constants are as follows:

$t_{out}$ = Desired outlet temperature from collector emulator [$^oC$]

$t_{in}$ = Measured inlet temperature to the collector emulator [$^oC$]

$P_{out}$ = Calculated collector output (from Equation 3) [W/m²]

*Vflow* = Actual volumetric flow into the collector emulator [$m^3/s$]

$\rho$ = Density of the fluid in the collector loop at the flowmeter position/fluid temperature. [$kg/m^3$]

$c_p$ = Thermal capacitance of the collector fluid at the average temperature in the collector emulator $t_m$ [J/(kg*K)]

Where $t_m = (t_{out} + t_{in})*0.5$.

An iterative solution for $t_{out}$ and hence $t_m$ may be needed here for 100% accuracy. A typical value of $c_p$ at for example 50$^o$C will do for most practical conditions to determine Tout, Tm and $c_p$ for most collector fluids and operating conditions. Low-flow systems are more sensitive to this approximation as the temperature rise $(t_{out}-t_{in})$ is higher.

## 3.3 Emulator Model Alternative 3

Tout is here calculated directly from equation (5) by solving for Tout. A Matlab solution for equation (8) is available from Peter Kovacs at SP, Sweden www.sp.se . Then Tout can be controlled as in the examples above depending on the local electric grid conditions and available components and engineering knowledge. The equation (8) is an implicit solution for Tout in equation (5) above:

*equ. 8:* $T_{out} = f\,(G_b,\ G_d,\ t_m,\ t_a,\ u,\ E_L,\ dt_m/dt)$

# 4 Input Data Needed For the Collector Model During System Testing and Simulation

All the input data needed can be seen in Equation 5 plus either of equation (6), (7) or (8) depending on choice of thermal power control in the emulator. Three groups of data can be identified 1) Weather data 2) Collector Parameters 3) System data during system test.

## *4.1 Weather Input Data Needed for the Collector Model*

First a weather data base is needed with at least hourly weather data or preferably higher time resolution so that interpolation can be avoided during the test. Here the data period is crucial. The parameters needed are from equation (5):

$G_b$ = Direct or beam solar radiation in the collector plane [W/m$^2$]

$G_d$= Diffuse solar radiation in the collector plane including ground reflected radiation [W/m$^2$]

$T_a$ , $t_a$ = Ambient temperature (dry bulb) in [K] resp in[$^o$C]. ($t_a$ is often the standard meteorological for dry bulb temperature in [$^o$C] $T_a$=$t_a$+ 273.15 )

In case of an unglazed collector or some extreme (or bad) collector designs, further weather data are needed:
$u$ = Wind speed in (parallel to) the collector plane [m/s]
$E_L$ = Long wavelength radiation (outside solar spectrum) onto the collector plane [W/m$^2$]

These last variables are probably not a common requirement for collectors used in combisystems for domestic hot water and space heating purposes, so for combisystem testing and simulation they can be neglected in most cases.

## *4.2 Collector Input Data for Testing and Simulation:*

The parameters below from equation (5) that are relevant for the collector design:

$F'(\tau\alpha)_{en}$ = Zero loss efficiency of the collector at normal incidence angle for the solar radiation. [-]

$c_1$ = Heat loss coefficient at $(t_m - t_a) = 0$ is modelled as $F'\,U_0$ [Wm$^{-2}$K$^{-1}$]

$c_2$ = Temperature dependence of the heat losses, equal to F' $U_1$ [Wm$^{-2}$K$^{-2}$]

$c_3$ = Wind speed dependence of the heat losses, equal to F' $U_u$ [Jm$^{-3}$K$^{-1}$]

$c_4$ = Long-wave irradiance dependence of the heat losses, equal to F' ε [-]

$c_5$ = Effective thermal capacitance, equal to $(mC)_e$ [Jm$^{-2}$K$^{-1}$]

$c_6$ = Wind dependence of the zero loss efficiency, a collector constant [sm$^{-1}$]

$K_{\theta b}(\theta)$ = Incidence angle modifier (IAM) for direct (beam) radiation [-]

$K_{\theta d}$ = Incidence angle modifier for diffuse radiation, a collector constant [-]

(See paragraph 2.2 for a more detailed explanation of the IAM model).

### 4.3 System Input Data For the Model During Test and Simulation

The other input data are taken online from the system in test operation, from handbooks or from manufacturers' specifications:

$A_{coll}$ = Collector Aperture Area

$t_{in}$ = Inlet temperature to the emulator (or actually the collector) [$^{o}$C]

$V_{flow}$ = Volumetric flow in collector loop (Note: not in emulator internal loop if mixing is used) [$m^3$/s]

$\rho$ = Density of fluid in collector loop at temperature $t_{in}$ (as close as possible to the flow meter position) [kg/m3]

$c_p$ = Thermal capacitance of the collector loop fluid at $t_m$. From a handbook or preferably from manufacturer of the actual fluid mixture. [J/(kg*K)].

## 5 TRNSYS Collector Model Type 132

During the IEA SH&C Task 26 work a solar collector model Type 132, according to equation (3) above, has been developed for the system simulation program TRNSYS. This model and program was also used for all simulations for Combisystems within IEA Task 26. The model is still under further improvements, as an international "open source code" co-operation, to incorporate all options for incidence angle dependence in equation (5). A well developed version is already available for most standard collectors from the IEA Task 26 work. This and later updates of the TRNSYS model Type 132 can be obtained from SERC, Solar Energy Research Centre, http://emb.du.se/serc/serc.html at Dalarna University SWEDEN .

## 6 Acknowledgements

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