Towards standard performance analysis for parabolic trough collector fields

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Abstract – The performance of a solar collector field is the main layout criterion for solar thermal power plants. Different kinds of models of varying complexity used to describe collector performance, in general on the basis of simplified efficiency equations, and differing nomenclature and methodology shall be replaced by a more general approach.

Based on an analysis for possible trough collector configurations, a set of nomenclature and definitions is presented with the intention to respect existing references and standards for solar technologies. The strategy is to use preferably properties and parameters of the collector and its components that can be measured and compared between different types of systems. Measurement devices and configurations are proposed.

The paper proposes a common methodology to assess the technical data of parabolic trough collectors, which are required by technology developers, system designers as well as financing institutions and policy makers to predict the performance of parabolic trough solar fields. It includes results from a SolarPaces working group on standardization of collector efficiency descriptions.

1. Objectives

The intention to impartially compare the solar energy output of different solar parabolic trough configurations requires standardized and well-documented models to describe solar collector efficiency. Initial requirement for the approach is a standard nomenclature and methodology to be used when assessing the technical data of parabolic trough systems.

Implementation of these nomenclature and methodology will help project developers to know what they can really expect of a solar field by correctly interpreting test reports from collector design developers and test centers.

Where possible, the definitions and formula are selected such that they are compatible with other solar technologies (concentrating, non-concentrating, thermal, and photovoltaic).

Existing established textbooks and international standards on solar thermal technology form the basis of the work [1-13].

2. Nomenclature

2.1 Symbols

A	aperture area orthogonal to the optical axis	m^2
b	aperture width of the trough collector	m
C	concentration ratio	-
c_p	specific heat capacity	kJ / kg K
c_{wind}	wind speed dependence of heat loss coefficient [11]	Ws / m^3K^2
d	absorber tube diameter	m
E	Solar irradiance (E_b beam direct, E_g global, E_d diffuse), normal irradiance	W / m^2
f	focal length	m
F, F_R	heat loss factor for calculations based on fluid temperature	-
F'	collector efficiency factor, for $T = T_m$ [1]	-
G	collector solar irradiance on the aperture area (G_b beam direct, G_g global (hemispherical), G_{dif} diffuse) [6], $G = E \cdot \cos\theta$	W / m^2

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h	massic enthalpy	kJ / kg
K	coefficient of heat transfer [7] temperature dependent heat loss coefficient of the absorber to the ambient	W / m^{2}K
K^*_{edge}	coefficient of heat transfer at receiver edges	W / K
l	aperture length of the reference area	m
P	energy flow	W
q_m	mass flow	kg / s
Q	energy	J
t	time	s
T	temperature	°C, K
T_a	ambient temperature	°C, K
T_m	mean fluid temperature $= \frac{1}{2}(T_{in} + T_e)$	K
T^*	reduced temperature difference $(T-T_a)/G$	m^{2}K / W
T^*_m	reduced mean temperature difference $(T_m - T_a)/G$	m^{2}K / W
v_{wind}	air speed	m / s
$\alpha, \alpha(\lambda)$	(spectral) absorptance for AM1.5 [13]	-
β	collector tilt angle [5]	°
γ	intercept factor (capture fraction)	-
γ_S	orientation angle, collector azimuth angle (North-south = 0°)	°
$\varepsilon, \varepsilon(\lambda)$	(spectral) hemispherical emittance for AM1.5 [13]	-
η	efficiency	-
θ	angle of incidence [5], longitudinal	°
κ_θ	incidence angle modifier factor (also IAM)	-
λ	wavelength	nm
$\rho_S, \rho_S(\lambda)$	(spectral) specular reflectance for AM1.5 [13], within 25 mrad	-
σ, σ_{total}	standard deviation (rms) of the beam spread [2]	mrad
$\sigma_{Boltzmann}$	Stefan-Boltzmann constant	W / m^{2}K^4
$\tau, \tau(\lambda)$	(spectral) transmittance for AM1.5 [13]	-
Φ_r	rim angle of the parabola	°
ϕ	latitude of test site [5]	°
χ	cleanliness factor	-
ψ	net area factor	-
ψ_{rec}	net area factor, ratio of absorber area to maximum absorber area, due to bellows and support	-
ω	solar hour angle [5]	°
ω_c	collector rotation angle	°

Indices

0	without thermal losses
a, amb	referring to ambient
abs	referring to the absorber
b	referring to beam radiation (E_b, G_b direct irradiance)
coll, loop, field	referring to one collector, one loop, the solar field
e, exit, out	at the outlet
geo	referring to lost radiation due to the geometry of the component (shading, blocking, end-losses, gaps)
gross	gross values, for aperture including gaps and frames, see definition below
in	at the inlet
net	net values, for aperture excluding inactive area (gaps, frames, ..), see definition below
nom	nominal values, for aperture given by the manufacturer, see definition below
opt	referring to optical losses (reflectance, transmittance and their incidence angle modifiers)
peak	referring to peak irradiance 1000 W/m^2 (AM1.5) perpendicular to the aperture area
pip	referring to solar field piping
rec	referring to the receiver
refl	referring to the (primary) concentrating reflector
shading	referring to shading between different collectors
standard	referring to standard conditions

2.2 Terminology

absorber	component absorbing the concentrated radiation and converting it into heat (e.g. absorber tube)
absorber area	active area of the receiver associated to a collector area, $\pi d_{abs} l$ for tubes
angle of incidence (longitudinal)	angle between collector optical axis and incident sun beam projected into the symmetry plane
angle of incidence (transversal)	angle between incident sun beam projected into the plane perpendicular to the longitudinal collector axis and collector optical axis (tracking offset)
aperture	entry plane delimited by the borders of the collector, in general perpendicular to the optical axis
blocking	effect that the reflected radiation does not reach the receiver due to structural obstacles
collector	entity of modules connected mechanically and having one heat transfer fluid entry and one heat transfer exit (also known as SCA)
collector azimuth angle	angle between collector rotation axis (for tilted collector projected onto the ground) and north-south-direction (also: orientation angle)
collector optical axis	collector symmetry line orthogonal to focal line and aperture plane
collector rotation angle	rotation angle of the collector optical axis around the rotation axis, ($0° =$ horizontal east/south for collector axis north-south / east-west respectively, $90°$ = zenith)
collector rotation axis	pivot axis of the collector, in most cases parallel to the focal line
concentrator, reflector, mirror	collector component redirecting the sun beam towards the receiver (primary concentrator)
facet	mirror element (also known as line concentrating device)
heat transfer fluid	short: HTF. Fluid transporting the absorbed energy from the receiver to other parts of the plant (e.g. thermal oil, water/steam, molten salt, ionic fluid, …)
intercept factor	fraction of reflected radiation which is intercepted by the receiver [1], (also: capture fraction)
land coverage	or packing density: ratio of nominal collector aperture area and the ground occupied (typical for troughs: 30%)
longitudinal	parallel to the collector rotation axis
module	collector unit between adjacent pylons, comprising reflector, its supports, and receiver (also known as SCE, solar collector element)
nominal power	collector output power, which can be achieved at design irradiation orthogonal to the aperture plane, at layout operation temperature
peak efficiency	ratio of peak power to the incident solar power at $G_b = 1000$ W/m^2 for given T_m
peak optical efficiency	theoretical efficiency without thermal and geometrical losses of the receiver
peak power	collector output power, which can be achieved at $G_b = 1000$ W/m^2 of beam irradiance orthogonal to the aperture plane for given T_m
pylon	collector support on the ground
receiver	Unit of the absorber with its housing, mounting elements and bellows, insulation and possibly secondary optical elements (also known as HCE, heat collecting element)
rim angle	in a cross section of the parabolic concentrator, the angle between the aperture plane normal and the line connecting the focus and the edge of the parabola
shading	effect that radiation does not reach the primary reflector due to structural obstacles or neighboring collectors
tilt angle	angle between horizontal ground and collector rotation axis (usually towards the equator)
tracking angle	collector rotation angle required to keep the sun beam in parallel to the symmetry plane of the parabolic trough concentrator ($0°$ = horizontal east/south for collector axis north-south / east-west respectively)
tracking offset	difference between the collector rotation angle and the tracking angle, = transversal angle of incidence
transversal, perpendicular	in a direction orthogonal to focal line and symmetry line (across the aperture)

2.3 Further definitions

Collector efficiency is defined by the ratio of useful power P_{coll} and incident solar power onto the collector $\eta_{coll} = P_{coll} / A_{coll} \cdot G_b$. In order to compare results, the reference collector area shall be defined with the net collector aperture area A_{net} including only the active area projected to the collector aperture plane, thus excluding mirror gaps.

The net collector aperture area A_{net} is the sum of projected mirror area, without mirror gaps, plus the non-overlapping part of the active area of the associated receiver tube in case of transparent backside (e.g. vacuum tube). Gross collector aperture area A_{gross} is the aperture area delimited by the outer borders of the considered collector, including possible gaps and frames. The nominal collector aperture area A_{nom} can be a value given by the manufacturer, which can be used for collector evaluation. The net area factor ψ_{refl} is introduced for the ratio of A_{net} / A_{nom} to correct the optical efficiency value accordingly. The definitions for net and nominal aperture area shall be applicable for all multiples of collector modules, collectors, rows, loops or fields.

As irradiance G_b onto the collector aperture area shall be considered the direct solar irradiance onto the collector area (beam irradiance corrected by the cosine factor) for the prevailing angle of incidence θ:

$$G_b = E_b \cdot \cos \theta \tag{1}$$

The term Direct Normal Irradiance (*DNI*, in W/m^2) is widely used for the beam irradiance E_b onto a surface perpendicular to the sunrays. The annual integral of this value is the annual direct normal irradiation (also *DNI*, but in kWh/m^{2}a or in MJ/m^{2}a or kWh/m^{2}d) referring to an area, which is two-axis-tracked to the sunbeam. Together with the characterizing geographical data (latitude) this value gives an estimation of the expected energy intercepted by the solar collector over a year. For more detailed analyses the irradiance data has to be available in hourly resolution, or even finer, and multiplied with $\cos\theta$ for every time step. G_b includes the momentary cosine corrections for the irradiance, see above.

The ideal concentration ratio of a trough collector shall be defined by the ratio of aperture width and absorber tube diameter $C_{ideal} = b/d$. The geometric concentration ratio is widely used and takes the whole absorber circumference into account: $C_{geo} = b/(\pi d)$. The average optical concentration ratio shall be defined as the ratio of the (gross) aperture width to the length of absorber tube circumference arc within the concentrator rim-angle. $C_{opt} = C_{geo} \cdot 180°/\phi$.

The cleanliness factor χ is defined by the ratio of optical efficiency in certain dirty conditions and the optical efficiency with the same optical element in unsoiled, clean condition. This factor can be applied to single components (mirror, receiver), or to the whole collector.

Specular reflectance is the reflectance measured within an acceptance angle of 25 mrad.

The coordinate system of a parabolic trough has been defined (right-handed):

z: pointing from the vertex of the parabola to the focus

y: pointing parallel to the symmetry axis of the parabola, orientation arbitrary, e.g. from the drive to the end

x: pointing from the vertex of the parabola across the parabola, orientation in order to have a right-handed system

Origin: located in the vertex of the reflecting parabola (for backside reflecting mirrors: backside of the reflector), so that the reflector parabola is given without any offset as $z=x^2/4f$, and the focal line is given by $x=0$, $z=f$.

Standard conditions shall refer to peak irradiance perpendicular to the aperture plane, at 25°C ambient temperature, and mean collector fluid temperature T_m.

Design point conditions include information about the design irradiance and angle of incidence for a specific date, e.g. $E_b = 800$W/m^2, 21st of June, $T_a = 25$°C, at the design point mean collector fluid temperature T_m. The solar multiple is the ratio of thermal output of the solar plant divided by the power plant thermal input in the design point.

3. Formulation of steady state trough collector efficiency

Efficiency is the ratio of useful energy output and energetic input into a system. The efficiency is the product of several factors describing individual elements and properties of the system. The definition of the efficiency should be usable for modeling and for measuring efficiency of collectors, collector rows, and collector fields. Efficiency shall be modeled for the components of the collector the reflector and the receiver and their energetic interaction.

The efficiency of the collector is described by the ratio of the useful Power P to the irradiated power $G \cdot A$. As a convention we propose to use the net area A_{net} defined above for the calculation of the irradiation. Furthermore the angle of incidence of the solar radiation onto the collector aperture is taken into account, by multiplying the direct normal irradiance E_b with the cosine of the angle of incidence θ, $G_d = E_d \cdot \cos\theta$. Peak efficiency is defined for $G_{b,peak} = 1000$W/m^2 of perpendicular irradiance onto the aperture area.

The useful power P_{coll} is the increase in enthalpy $q_m(h_e - h_{in})$ of the heat transfer fluid during its pass through the receiver. The fact that P_{coll} is lower than the incoming irradiation is obvious and can be attributed to several loss mechanisms. For the systematic modeling these losses shall be ordered according to their type and according to the collector component and e.g. its material properties. Some of the losses are proportional to the irradiance, like reflective losses, others are dependent on the collector temperature, like thermal losses.

The useful power of a collector P_{coll} is given by the energy balance on the absorber:

$$P_{coll} = P_{abs} - P_{th,loss} \tag{2}$$

With the absorbed power from solar radiation $P_{abs} = G_b \cdot A_{net} \cdot \eta_0$ (3)

The optical efficiency η_0 (collector efficiency for T_m-T_a=0) of the collector is the product of all optical collector performance factors listed below. It is variable with the angle of incidence θ.

$$\eta_0 = \eta_{opt,refl}(\theta) \cdot \eta_{geo,refl}(\theta) \cdot \gamma(\theta,\sigma) \cdot \eta_{opt,rec}(\theta) \cdot \eta_{geo,rec}(\theta) \tag{4}$$

All factors include the reduction of the factor due to $|\theta| > 0$, but not due to the cosine reduction of the beam irradiance.

However peak optical efficiency $\eta_{0,peak}$ shall be the optical efficiency for perpendicular irradiance ($\theta =0$, $\kappa=1$, $\eta_{endloss}=\eta_{shading}=1$), ideally clean optical elements ($\chi=0$), and without geometric losses ($\eta_{geo,refl}=\psi_{rec}=1$).

$$\eta_{0,peak} = \eta_{opt,refl} \cdot \gamma(\theta,\sigma) \cdot \eta_{opt,rec} \tag{5}$$

3.1 Optical collector performance

Only part of the incident solar energy on the aperture area is absorbed by the absorber. This fraction is the overall optical collector performance. In order to be able to analyze the effect of properties of individual components, this value shall be split into the product of efficiency factors, which are attributed to single components and physical effects.

3.1.1   Attenuation properties of the concentrator

The attenuation properties of the concentrator include mirror reflectance, mirror cleanliness factor, and the incidence angle modifier factors for both. The incidence angle modifier for dusty surfaces $\kappa_{\chi refl}(\theta)$ decreases stronger than the one of clean components $\kappa_{\rho s,refl}(\theta)$, so it might be considered separately.

$$\eta_{opt,refl} = \rho_{s,refl}\, \chi_{refl}\, \kappa_{\rho s,refl}(\theta)\, \kappa_{\chi refl}(\theta) \tag{6}$$

3.1.2   Geometrical properties of the concentrator

The geometrical properties of the concentrator include the geometric incidence angle modifier factor due to structural shading and blocking, end-losses, and shading from neighboring collectors.

$$\eta_{geo,refl} = \kappa_{geo,refl}(\theta)\, \eta_{endloss}(\theta)\, \eta_{shading}(\omega_c,\theta)\, \psi_{refl} \tag{7}$$

$$\eta_{endloss}(\theta) = 1 - \frac{f}{l} \cdot \left(1 + \frac{b}{48 f^2}\right) \cdot \tan\theta \quad [1], [2] \tag{8}$$

3.1.3   Intercept factor of the reflected radiation at the receiver

The intercept factor γ of the reflected radiation at the receiver is in complex dependence of all geometric imperfections of the sun-beam and the concentrator, e.g. sun shape, tracking error and twist, geometric accuracy, and its incidence angle modifier factor. It can be determined with ray-tracing approaches or with flux mapping around the receiver. Its value never reaches unity and its effect may not be neglected in any kind of collector efficiency analysis. Its dependence on collector properties has been presented by [2] and others.

$$\gamma(\theta,\sigma_{total}) \tag{9}$$

3.1.4   Attenuation properties of the receiver

Attenuation properties of the receiver are given by receiver glass transmittance, absorber absorptance, receiver cleanliness factor, and receiver incidence angle modifier factor.

$$\eta_{opt,rec} = \tau_{rec}\, \alpha_{rec}\, \chi_{rec}\, \kappa_{\tau \alpha rec}(\theta)\, \kappa_{\chi rec}(\theta) \tag{10}$$

3.1.5   Geometrical properties of the receiver

The relevant geometrical property of the receiver is the net area factor of the receiver (e.g. due to bellow shadowing). It also varies with the angle of incidence, due to relative location of receiver mounts (shields) and concentrator gaps or other end-effects.

$$\eta_{opt,rec} = \psi_{rec}\, \kappa_{geo,rec}(\theta)$$

3.2 Incidence angle modifier factor

For the incidence angle modifier factor the following model has been used previously [2], [11],[12]:

$$\kappa_i(\theta) = 1 - b_{0,i} \cdot \left(\frac{1}{\cos\theta} - 1 \right) \text{ for } \theta < \arccos(b_0 / (1 + b_0)) \tag{11}$$

This single-parameter approach is helpful in view of the difficulty to obtain good testing data with all parameters constant except for the angle of incidence.

The angular dependence of several of the incidence angle modifier factors might be neglected, setting $b_{0,i}=0$ for practical reasons.

$\kappa_{\text{geo,rec}}(\theta)$ can probably not be modeled with the function type from equation (11), because it includes the effects of the relative position of receiver edges and reflector gaps.

3.3 Thermal collector performance

3.3.1 Thermal properties of the receiver

The thermal losses of the collector can be modeled using the local absorber temperature with the approach

$$P_{\text{th,loss}} = A_{\text{net}} K(T) (T_{\text{abs}} - T_a) \tag{12}$$

A 1st order dependence of the heat transfer coefficient K from the mean temperature difference is used as empirical model.

$$K(T) = K_0 + K_1 (T_{\text{abs}} - T_a) \tag{13}$$

The coefficients in equation (13) will be determined by least square fit to experimental data. Due to the radiative losses at elevated temperatures (especially for unprotected absorbers), a 3rd order polynomial might be applied.

$$K(T) = K_0 + K_1 (T_{\text{abs}} - T_a) + K_2 (T_{\text{abs}} - T_a)^2 + K_3 (T_{\text{abs}} - T_a)^3 \tag{13a}$$

A more theoretical, simplified approach might be used in order to have the absorber emittance integrated in the model for the thermal loss coefficient [1] and a further term for the constructive elements at the absorber and glass supports. It suffers from the fact that the emittance depends of the spectral range and the absorber temperature.

$$K(T) \approx K^*_{\text{edge}} /A_{\text{net}} + \varepsilon\, \sigma_{\text{Boltzmann}}\, A_{\text{abs}} /A_{\text{net}} (T_{\text{abs}}^3 + T_{\text{abs}}^2 T_a + T_{\text{abs}} T_a^2 + T_a^3) \tag{13b}$$

$$P_{\text{th,loss}} \approx \varepsilon\, \sigma_{\text{Boltzmann}}\, A_{\text{abs}} (T_{\text{abs}}^4 - T_a^4) + K^*_{\text{edge}} (T_{\text{abs}} - T_a) \tag{12b}$$

These models are valid for the receiver and shall be referred to the net collector aperture area A_{net}. The receiver specific heat losses referring to the absorber area of the receiver is approached by $K_{\text{rec}} = K\, C_{\text{geo}}\, l_{\text{net}}/l_{\text{rec}}$. It might be relevant to give the length specific thermal losses of the receiver with a reference to the receiver length in W/m: $K'_{\text{rec}} = K_{\text{rec}}\, \pi d_{\text{abs}} = K\, b\, l_{\text{net}}/l_{\text{rec}}$. It is important to note that the heat transfer coefficient does not depend on irradiance, but only on the temperature in the absorber, which, however might be increased due to the heat resistance between absorber and fluid. This aspect is important for testing purposes and reflected in the heat loss factors.

From the energy balance of the collector

$P_{\text{coll}} = G_b \cdot A_{\text{net}} \cdot \eta_0 - P_{\text{th,loss}}$ follows [1]

$$\frac{P_{coll}}{A_{net}\, G_b} = \eta_{coll} = F' \cdot \eta_0 - F' \cdot K(T) \cdot \frac{T_m - T_a}{G_b} \tag{14}$$

with $K(T) = K_0 + K_1 (T_m - T_a)$ and the collector efficiency factor $F' = K_{\text{fluid-amb}} / K_{\text{abs-amb}}$ which enables to use the mean fluid temperature values instead of absorber temperature values in the heat balance.

This formulation is in agreement with the models given in [1], [2], [5], and others. Most authors do not explicitly introduce the temperature dependence of the heat loss coefficient, but rather use ranges for the validity of a linear efficiency equation. However we consider it important to reflect the non-linearity of the heat loss in this coefficient. By modeling the heat losses from the absorber surface, T^4 terms are introduced for radiative losses. But given the situation, that the heat loss coefficient is composed of convective terms (influenced by wind speed), conductive terms (to mounts and supports) and radiation terms for the heat transfer from absorber to envelope, we propose to continuously work with the 2nd order approach for evacuated receivers. A future change for $K(T)$ to a higher order polynomial of the mean temperature difference is unaffected. The irradiance should not be included as parameter in the heat loss coefficient, see references.

3.3.2 Convective losses influenced by air speed

Additional thermal losses can be detected at increased wind speed. This is accounted for with a linear approach.

$$P_{\text{th,loss,wind}} \approx c_{\text{wind}} \, v_{\text{wind}} \, (T_{\text{abs}} - T_a) \tag{15}$$

More precise models can be derived from air speed dependent Nusselt numbers. Wind effects might be quite difficult to quantify from collector tests.

3.3.3 Thermal properties of the connection piping

Specific thermal losses of the connection and header piping are taken into account, if included in the energy balance:

$$P_{\text{loss,pip}} = K_{\text{pip}} \, (T_{\text{m}} - T_a) \, l_{\text{pip}} \, \pi \, d_{\text{pip}} \tag{16}$$

3.4 Full collector model

A full collector model is derived from [11] and [18], including gains from diffuse irradiance G_d, and wind effects as convective losses, but omitting thermal capacity and sky temperature dependence. Wind dependence on the optical efficiency is included in η_0.

$$\frac{P_{coll}}{A_{net}} = F' \cdot \eta_0 \cdot G_b + F' \cdot \eta_{opt,rec} \cdot \psi_{rec} \cdot \frac{G_d}{C_{geo}} - F'K_0 \cdot (T_m - T_a) - F'K_1 \cdot (T_m - T_a)^2$$
$$- F'c_{Wind} \, v_{wind} \cdot (T_m - T_a) - K_{pip} \frac{l_{pip} \pi d_{pip}}{A_{net}} (T_m - T_a) \tag{17}$$

For the irradiated collector in steady state conditions the efficiency is given as

$$\eta = \frac{P_{coll}}{A_{net} G_b} = F' \cdot \eta_0 - (F'K_0 + F'c_{Wind} \, v_{wind} + K_{pip} \frac{l_{pip} \pi d_{pip}}{A_{net}}) \cdot \frac{(T_m - T_a)}{G_b} - F'K_1 \cdot \frac{(T_m - T_a)^2}{G_b} \tag{18}$$

The non-focused collector loses energy according to

$$\frac{P_{coll}}{A_{net}} = F' \cdot \eta_{opt,rec} \cdot \psi_{rec} \cdot \frac{G_{global}}{C_{geo}} - (F'K_0 + F'c_{Wind} \, v_{wind} + K_{pip} \frac{l_{pip} \pi d_{pip}}{A_{net}}) \cdot (T_m - T_a)$$
$$- F'K_1 \cdot (T_m - T_a)^2 \tag{19}$$

The gains of the receiver from non-concentrated radiation are significant for heat loss measurements during daytime and have to be taken into account.

For non-steady-state test conditions the thermal capacitance terms have to be added to these equations.

3.5 Reference to previous models

The definition of the optical efficiency remains basically unchanged with reference to other texts (e.g. $\eta_{opt} = \eta_0 = \rho_S \, \tau \, \alpha \, \gamma$), but it includes now a more detailed division for the collector components and their properties. The incidence angle modifier factor in previous models is now divided into several factors assigned to specific effects. Previously it included in some cases also the cosine losses due to the one-axis tracking. $IAM = \kappa_\theta = \Pi \, \kappa_{i,\theta} \, (\cos \theta)$.

One previous collector model included the collector efficiency variation in a temperature dependent offset:
$$\eta_{\text{coll}} = \kappa_\theta \, (\eta_0 - B \, (T - T_a)) - C \, (T - T_a)/G - D \, (T - T_a)^2/G$$

Recent collector studies e.g. by Sandia and for EUROTROUGH, applied simpler 2nd order equations of the format $\eta = \eta_0 - b_1 \, (T - T_a) - b_2 \, (T - T_a)^2$ for constant irradiance successfully [14].

Ray-Tracing codes usually model the geometric and intercept factors and may set the attenuation factors to 1. Such models are quite relevant in order to determine intercept factors and geometrical properties over the full parameter range of the angle of incidence and the collector tracking angle.

4. Measuring collector performance

4.1 Testing conditions

The thermal power delivered by a collector (or a module, a loop, a field) is determined from the increase in enthalpy flow of inlet to outlet $P_{coll} = q_m \, (h_e - h_{in}) = q_m c_p|_T \, (T_e - T_{in})$ with the average specific heat capacity

$$c_p \Big|_{T_{in}}^{T_e} = \frac{h(T_e) - h(T_{in})}{T_e - T_{in}} = \frac{1}{T_e - T_{in}} \int_{T_{in}}^{T_e} c_p(T) dt \tag{20}$$

for which the properties of the test fluid have to be exactly known.

Performance results of steady state tests at constant solar irradiation G_b follow, according to Equation (18) a parabola of the form

$$q_m c_p|_T (T_e - T_{in}) / (A_{net} G_b) = \eta = \eta_0{}' - c_1{}' \, T^*_m - c_2{}' \, G_b \, T^{*2}_m \; \underline{= c_3{}' \, G_b{}^2 \, T^{*3}_m - c_4{}' \, G_b{}^3 \, T^{*4}_m} \tag{21}$$

$c_i{}'$ are the condensed coefficients of Equation (18), which can be found from test results by means of multiple parameter least square fitting. 2nd order will be most practical for evaluation in most cases.

A promising method to determine the coefficients K_i is proposed in Equation (19) with a non-focused collector fed with hot fluid, because it does not include the measurement uncertainties of variation of irradiance.

η_0 can be determined approximately at lowest oil temperature when $T\text{-}T_a \approx 0$. The peak optical efficiency $\eta_{0,peak}$, which excludes receiver edge losses, cannot be assessed experimentally without additional geometric correction factors.

Reliable results for η_0 can be expected only, if the effects of soiled mirrors and receivers can be minimized with a rigorous washing program.

Only on the basis of a well-known data-set for η_0 and the coefficients K_i, the incidence angle modifier functions $\kappa_{\rho s,refl}(\theta) \cdot \kappa_{geo,refl}(\theta) \cdot \kappa_{\tau\alpha rec}(\theta) \cdot \gamma(\theta, \sigma_{total})$ can be determined for the clean collector. Note that it seems difficult to experimentally distinguish the individual effects of reflectance, geometry and intercept. Sun shape and beam spread play a significant role, but should be studied separately.

Further parameters can be evaluated only from geometrical considerations ($\eta_{endloss}(\theta)$, $\eta_{shading}(\omega_c,\theta)$, ψ_{refl}, $\kappa_{geo,rec}(\theta)$), optical models ($\gamma(\theta,\sigma_{total})$, $\kappa_{\rho s,refl}(\theta)$, $\kappa_{\tau\alpha rec}(\theta)$), reflectance and transmittance measurements ($\rho_{s,refl}$, χ_{refl}, $\kappa_{\rho s,refl}(\theta)$, $\kappa_{\chi refl}(\theta)$, τ_{rec}, α_{rec}, χ_{rec}, $\kappa_{\tau\alpha rec}(\theta)$, $\kappa_{\chi rec}(\theta)$), or different techniques (e.g. $\gamma(\theta,\sigma_{total})$) from flux mapping [17]).

4.2 Sensors

Temperature sensors to be used are PT100 resistance temperature transducers in 4-wire connection. Temperature sensors should be immersed into the heat transfer fluid, to the center of the tube. The probe location requires thermal insulation and protection from mechanical damage. The application of surface temperature sensors on the tube outside may be considered, if the thermal contact to the wall is good and if the measurement location is insulated sufficiently. For higher reliability of the measurements it is proposed to introduce two to three temperature sensors of the same type close together.

Flow rates of the heat transfer liquid should be measured with precision flow meters. For higher temperatures vortex flow meters showed good results for thermal oil. Fluid density at flow meter location has to be known, a pair of temperature sensors should be installed at a maximum of 1 m downstream of the flow meter.

Global irradiance is measured with a Pyranometer, first class (ISO 9060, 9846, 9847). Beam irradiance is measured with a Pyrheliometer, first class (ISO 9059, 9060).

16-bit A/D converters are required, in particular for the differential temperature measurements.

Further details will be worked out at a later stage of the work.

5. Conclusions and Outlook

The resulting set of terminology and equations is the result of the authors' discussion in a working group and their experience from the field of parabolic trough technology. Although the intention was to include as many previous information sources as possible it is unavoidable that some work has not been included, and that there are contradictory elements with respect to other publications and minor inconsistencies with respect to existing hot water collector standards [6], [11].

The definitions of the net collector reference area and aperture irradiance form the basis of the approach. The optical efficiency has been subdivided in many factors in order to be able to compare collector components according to their specific properties. This should also allow a more detailed and quantified view to those collector properties, which still give room for improvement of collector performance. In the scope of testing these factors may have to be rearranged.

The thermal losses are modeled with reference to the ambient temperature. Heat transfer coefficients are referring to the net collector area in order to avoid confusion with the receiver area. For the effect of irradiance on collector heat balance the reduced mean temperature difference of the measurable fluid temperature is used. The resulting efficiency equations are based on mean collector fluid temperature and therefore do not require corrections for different fluids or different flow regimes other than calculation of the appropriate collector efficiency factor F'.

Further work is anticipated on measuring and reporting collector performance. The work of the group is intended to continue and aims further definitions and standards in this field.

Readers are invited to submit their comments to the authors.

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