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Influence of thermal losses on the incidence angle modifier factorization approach

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ABSTRACT

Solar thermal applications for industries must be designed to operate at high temperature levels; however, the thermal dependency of the accuracy of the incidence angle modifier factorization has not been sufficiently analyzed. In this study, the annually delivered energy based on both factorized and non-factorized incidence angle modifier values were compared with each other. The integration was conducted for a typical meteorological year in Seville and Stockholm. Four collector types were considered: evacuated tube collector, MaReCo collector, Fresnel collector, and CCStaR collector. Thermal process parameters were shown to have an influence on the error made by the factorization approach; however, within the economically viable temperature range of an industrial heat application, this influence is not significant.

1. Introduction

The industry sector with its high and constant energy demand shows a remarkable potential for the integration of solar thermal technologies. The temperature requirements of such processes mainly range from 60 °C to 260 °C and can be provided by adapted versions of conventional low- (non-concentrating) or high- (concentrating) temperature collectors (Kalogirou, 2003).

With the quasi-dynamic testing method (QDT), the current international standard ISO 9806:2013 allows assessment of the performance of a collector in a wide range of designs (Eq. (1)).

$$\dot{q} = \eta_{0,b} \cdot K_b(\theta_T, \theta_L) \cdot G_{bT} + \eta_{0,d} \cdot K_d \cdot G_{dT} - c_6 \cdot u \cdot G - c_1(\vartheta_m - \vartheta_a) - c_2(\vartheta_m - \vartheta_a)^2 - c_3 \cdot u \cdot (\vartheta_m - \vartheta_a) + c_4 \cdot (E_L - \sigma_b \cdot T_a^4) - c_5 \cdot \frac{d\vartheta_m}{dt} \quad (1)$$

One challenge in this respect is to account for the frequent complex response to different angles of incidence that can be observed especially for concentrating technologies. The regulatory body in this field has addressed this problem by incorporating the factorization method proposed by McIntire (1982). Instead of measuring the incidence angle modifier (IAM) for every point on the collector hemisphere, measurements are carried out only for some angles along the symmetry planes of the collector (longitudinal and transversal planes). The IAM is then approximated by the product of the corresponding transversal and longitudinal IAM values for any arbitrary angle:

$$K_b(\theta_T, \theta_L) = K_b(\theta_T, 0) \cdot K_b(0, \theta_L) \quad (2)$$

where K_b is the IAM at the incidence angle θ, with its projected angles θ_T and θ_L. In further studies on the performance assessment of Fresnel collectors, θ_L was replaced by θ_i, the angle between the sun position vector and the transversal plane of the collector (Bernhard et al., 2008; Heimsath et al., 2014; Horta et al., 2008) (Fig. 1); and, better results were obtained when θ_i was applied (Hertel et al., 2015).

Obviously, the IAM surface constructed by factorization is only a simplified form of the true surface and, therefore, causes errors when it comes to annual energy predictions. Studies have been conducted to quantify this error. Rönnelid et al. and Mertins compared the numerical result from factorization with the experimental annually delivered energy for a CPC installation in Stockholm, Sweden (Rönnelid et al., 1997) and a Fresnel installation in Hughade, Egypt and Faro, Portugal (Mertins, 2009). In a study by Rönnelid, the factorization approach overestimated the real energy output by 4–5% at an average process temperature of 56 K, while Mertins mentioned an underestimation of 2.4% (Hughade) and 3.7% (Faro) at an average temperature of 300 K. Pujol-Nadal (2014), Pujol-Nadal et al. (2015) evaluated the error in case of the CCStaR collector when factorization was applied in the $\theta_T - \theta_L$ domain. Other studies by Horta and Osório (2014), Bernhard et al. (2008), and Heimsath et al. (2014) considered a pure numerical analysis of the optical part of the energy equation

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Nomenclature

$\Delta\vartheta$	$\vartheta_m - \vartheta_a$ (K)
$\Delta\vartheta_{max}$	stagnation temperature difference, $\dot{q}^{opt} = \dot{q}^{th}$ (K)
Δt	simulation time step (s)
α_0	absorptance at normal incidence (–)
α_1	decreasing error development parameter (–)
α_2	increasing error development parameter (–)
α_c	rotation about longitudinal collector axis (rad)
β_c	rotation about transversal collector axis (rad)
δ	Kronecker delta function
ε	relative factorization error (–)
$\eta_{0,b}$	optical efficiency of a collector regarding direct solar irradiance (–)
$\eta_{0,d}$	optical efficiency of a collector regarding diffuse solar irradiance (–)
Ω	steradian (sr)
ω	interval on polar coordinate grid
ϕ	azimuth angle (°)
σ	collector operation indicator (–)
θ	incidence angle on the aperture plane with reference to collector normal (°)
θ_i	angle between the sun vector on the aperture and transversal planes of the collector (°)
θ_L	longitudinal incidence angle (°)
θ_T	transversal incidence angle (°)
θ_z	zenith angle (°)
ϑ_a	ambient or surrounding air temperature (K)
ϑ_m	mean temperature of heat transfer fluid (K)
ϑ_{op}	maximum operating temperature according to the manufacturer (K)
ϑ_{stg}	maximum annual stagnation temperature (K)
σ	combined variance of Gaussian distribution to model scattered specular reflection (mrad)
c_1	heat loss coefficient at $(\vartheta_m - \vartheta_a) = 0$ (W/(m^2 K))
c_2	temperature dependence of the heat loss coefficient (W/(m^2 K^2))
c_3	wind speed dependence of the heat loss coefficient (J/(m^3 K))
c_4	sky temperature dependence of the heat loss coefficient (–)
c_5	effective thermal capacity (J/(m^2 K))
c_6	wind dependence in the zero loss efficiency (s/m)
DNI	direct normal irradiance (W/m^2)
E_L	long wave irradiance ($\lambda > 3$ μm) (W/m^2)
G	hemispherical solar irradiance (W/m^2)
G_{bT}	beam direct solar irradiation on the tilted collector surface plane (W/m^2)
G_{dT}	diffuse solar irradiation on the collector plane (W/m^2)
K_b	incidence angle modifier for direct solar irradiation (–)
K_d	incidence angle modifier for diffuse solar irradiation (–)
G'_b	incidence angle modifier with reference to direct beam irradiation DNI
$\dot{q}$	specific thermal power (W/m^2)
$\bar{q}$	annually integrated specific heat (W/m^2)
T	upper bound of time interval (number of time steps per year)
t	time (s)
u	surrounding air speed (m/s)
wh	working hours (h)

Abbreviations

CCStaR	Concentrating Collector with Stationary Reflector
ES	east–west installation
ETC	evacuated tube collector
QDT	quasi-dynamic testing method
IAM	incidence angle modifier
NS	north–south installation
TMY	typical meteorological year
SWEC	Spanish Weather for Energy Calculation
IWEC	International Weather for Energy Calculation

Indices

FAC	based on factorization approach
RT	based on ray tracing results for every point on the hemisphere
opt	refers to optical terms
th	refers to thermal terms (heat losses)
i	spatial iteration index (rows)
j	spatial iteration index (columns)
k	temporal iteration index

in the case of Fresnel collectors to determine the accuracy of factorization when applied in different angle domains ((θ_T, θ_L) and (θ_T, θ_i)). In addition Hertel et al. (2015) analyzed the same annual error by comparing the existing factorization models with each other at different latitudes. In all of these studies, the thermal part of the energy equation was neglected. Since a poorly approximated IAM value affects only the optical term of the energy equation, it might seem reasonable to neglect thermal effects such as the process temperature. However, in the view of an annual energy balance, increasing heat losses due to elevated process temperatures can possibly change the significance of the errors made on the energy gain side. We could not find any previous study on this topic to the best of our knowledge. In the view of constantly increasing demand of industrial solar thermal applications, the study of the influence of the process temperature on the factorization approach was considered a relevant research topic.

2. Mathematical model

The temperature influence on the IAM factorization error might be counterintuitive. To illustrate this effect, a simplified form of the QDT model from Eq. (1) was considered. Diffuse irradiation, thermal capacity, and wind effects are not taken into account:

$$\dot{q} = \underbrace{\eta_{0,b} \cdot K'_b(\theta) \cdot DNI}_{\dot{q}^{opt}} - \underbrace{(c_1 \cdot \Delta\vartheta + c_2 \cdot \Delta\vartheta^2)}_{\dot{q}^{th}} \quad (3)$$

where DNI is the direct normal irradiance, $\Delta\vartheta$ is the difference between ambient temperature and mean temperature of the heat transfer fluid $\vartheta_m - \vartheta_a$. The equation can be regarded as composed of two separate parts: the optical part $\dot{q}^{opt}$ and the thermal part $\dot{q}^{th}$, where $\dot{q}^{th}$ is the only temperature dependent term.

When it comes to annual energy integration of Eq. (3), the IAM $K'_b(\theta)$ plays an important role, as it reflects how the collector responds to different sun angles. This behavior can be fairly complex and is best illustrated with a surface of IAM values over all possible angle pairs that define a sun vector in the collector hemisphere. The most popular domains are the spaces spanned by the projected angles (θ_T, θ_L) or (θ_T, θ_i) respectively; Fig. 1 shows the angle definitions. In this study, this IAM surface was obtained numerically. A simulation was conducted for each of the four collector geometries that are presented in Section 3. We run the simulation for all possible (θ_T, θ_i) tuples with an increment of 5°