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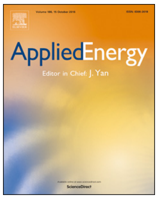

Exergy analysis of the focal-plane flux distribution of solar-thermal concentrators

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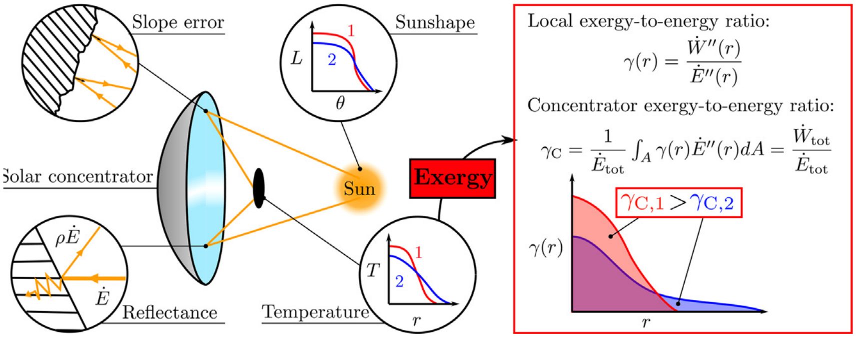
HIGHLIGHTS

- Breakdown of exergy effect of different optical errors presented for the first time.
- Slope error found more important than sun shape, mirror reflectivity or rim angle.
- Method is applicable to all concentrated solar power (CSP) systems.

GRAPHICAL ABSTRACT



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ABSTRACT

As concentrating solar power systems push towards higher temperatures and lower costs, it is critical that losses of overall system performance can be attributed correctly to the appropriate source. Up to now, this has been poorly done for the case of optical errors, since applicable methods do not exist to quantify how much different imperfections contribute to reducing the upper-bound efficiency of the overall system. Here, the exergy impact of varied optical design parameters—slope error, rim angle, mirror reflectance and sun-shape—is calculated for the first time. Slope error is shown to have the strongest impact. Also, dishes with rim angles significantly wider than the conventional 45° are shown to yield the best overall energy conversion. The resulting analysis method, broadly applicable in concentrating solar power, enables a new approach to quantitative optical system design.

1. Introduction

Concentrating solar thermal power (CSP) systems make use of mirrors to concentrate solar radiation onto a receiver, where radiation is converted to heat which can then be stored and later converted to electricity in a power cycle. Heat from such systems can alternatively be used to drive industrial processes. Although 4.8 GW of commercial CSP plants are now operational globally, the relatively high levelised cost of electricity (LCOE) from these plants remains as the main barrier to broader adoption of the technology. Together with reduction of system capital and operating costs, improvement of the overall system efficiency is a key factor to reducing LCOE, and will be essential for CSP to maintain its high current learning rates [1].

Maximising the efficiency of CSP systems requires that losses and irreversibilities in the whole energy transformation process be minimised. Thermodynamic irreversibilities are inherent to all heat-transfer processes, but can be identified, quantified and reduced through the use of exergy analysis [2]. Numerous recent works apply exergy analysis to thermal systems, including in design of power cycles [3] and CSP receivers [4], for the selection of CSP heat transfer fluids [5], in the

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Nomenclature

A	area
B	geometric factor
C	concentration ratio
CSR	circumsolar ratio
E	energy
f	focal length
G	irradiance
L	radiation intensity
$\dot{q}''$	heat flux
$\dot{q}$	heat rate
R_{in}, R_{out}	inner and outer radius (of a radial bin)
T	temperature
r	radius
S	entropy
W	work

Greek letters

γ	local exergy-to-energy ratio
γ_C	whole-collector exergy-to-energy ratio
σ	Stefan-Boltzmann constant/slope error
$\varkappa_1$, $\varkappa_2$	parameters in Buie sunshape
ϕ	azimuth angle (polar coordinates)
ρ	mirror reflectance
θ	angle
ω,Ω	solid angle
δ	dilution factor
$\chi(\delta)$	entropy irreversibility factor

Subscripts

0	ambient environment
s	source
e	effective temperature of radiation
ar	angular range – pillbox sun shape
opt	locally optimised
dish	dish (reflector)
aur	aureole (beyond the solar disc)
tot	total, in the focal plane
target	flux target (for ray tracing)
rim	rim (angle)
rec	receiver (for isothermal case)
cav	for isothermal cavity
g	geometric
Buie	Buie sunshape
j	radial bin index, $j \in [1,N_{\mathrm{bins}}]$
i	ray index $i \in [1,N_{\mathrm{rays}}]$
ar	angular range
P	Petela (Eq. (1))
b	black-body
em	emission

Modifiers

$\dot{x}''$	flux
$\dot{x}$	rate
$\bar{x}$	normalised

optimisation of CSP/coal hybrids [6], in design of hybrid concentrating photovoltaic-thermal (CPV-T) collectors [7], and in the off-design evaluation of molten-salt CSP systems [8]. A recent review of exergy analysis applied to solar thermal systems was provided by Kalogirou et al. [9], and an earlier review applied to renewable energy more general was provided by Hepbasli [10]. Gholamalizadeh and Chung [11] recently presented a breakdown of the exergy losses in a dish-Stirling system based on assumptions of uniform concentration at the aperture and an isothermal cavity.

A key unresolved issue for exergy analysis of CSP systems, however, is the treatment of radiation within these systems. The exergy of emitted radiation is relatively well understood, and in the case of the sun is closely approximated by the exergy of black body radiation [2,12]. As this radiation spreads out through space, its flux reduces but exergy is not lost, since in principle the radiation can be re-concentrated to its original condition, resulting in the familiar thermodynamic limits on concentration [13,14]. However, once radiation passes through imperfect optical systems with scattering, such as the earth's atmosphere and real mirrors, the radiation becomes 'diluted' and the exergy-to-energy ratio of the radiation is no longer conserved. This fact has received very little attention in CSP literature. Most authors use the exergy-to-energy ratio for black-body solar radiation as the input to their system and neglect these mirror and atmospheric effects completely [5,15–17], with the result that exergy destruction is attributed to the receiver [9] when in actual fact much of the destruction has taken place upstream, in the collector. Apart from the issue of dilution, there is also very little work looking at how exergy of radiation varies with the spatial and angular distribution of radiation throughout a CSP system.

In this paper, we first provide a little more background on the exergy of radiation and the exergy available as heat at the focal plane of a collector. We describe a model for a physically realistic paraboloidal dish, and then show that, using our model, we can link the exergy calculated at the focal plane to several different parameters associated with the collector, independent of the design of the receiver.

1.1. The exergy of radiation

In designing and optimising devices that convert solar radiation into useful work, an important problem is how to estimate the maximum output achievable by such devices. This requires us to be able to estimate the exergy which is carried by the solar radiation, and how that exergy is affected by the various design parameters as the radiation passes through the device. This surprisingly complex question has been reviewed recently [16,18–21] as well as previously [22]; selected results are summarised below, considering the case of unpolarised light only.

For black-body radiation inside an enclosed cavity at temperature T_b, the exergy to energy ratio γ of radiation in the cavity can be obtained using the Petela equation,

$$\gamma = \gamma_P\left(\frac{T_0}{T_b}\right), \quad \text{where } \gamma_P(x) = 1-\frac{4}{3}x + \frac{1}{3}x^4 \tag{1}$$

This equation can be derived from the radiation pressure, energy and entropy within the cavity, together with the usual definition of exergy in a closed system [23,24]. Other formulations for γ have been suggested [25,26] but suffer limitations in their application [19,27–29]. Calculated using Eq. (1), the exergy-to-energy ratio of extra-terrestrial (undiluted) solar energy is $\gamma = 0.93$ [30] ($T_b = 5800$ K, $T_0 = 300$ K).

Radiation is 'diluted' (relative to black-body radiation) when it is emitted by a real (non-black) surface, or when is scattered off its course or absorbed when travelling through a participating medium, or when it is reflected by non-specular or partly-absorbing surfaces [22,23,30–33]. The local fluxes of energy $\dot{E}''$ and entropy $\dot{S}''$ of diluted black body radiation passing through an elemental area $\mathbf{dA}$ can be determined in general by integrating the incident radiation over solid