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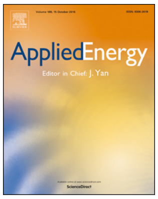

Thermal and mechanical analysis of a sodium-cooled solar receiver operating under a novel heliostat aiming point strategy

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HIGHLIGHTS

- A heliostat aiming strategy is developed using the simulated annealing algorithm.
- Detailed receiver thermomechanical models are used to identify optimum strategies.
- Heat flux profiles generated by the aiming strategy are input into receiver models.
- Peak heat flux can be lowered to $< 10\%$ that of a single centralised aiming point.
- Optimum target strategy exists to minimise spillage and maximise thermal performance.

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Simulated annealing
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Thermal performance
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ABSTRACT

The nature in which a solar receiver in a concentrated solar power plant interacts with an accompanying heliostat field plays a significant role in plant performance and economics. An appropriate heat flux distribution should help deliver maximum receiver thermal performance, while minimising mechanical damage – thereby maximising power production and reducing costs. The current work presents an investigation into the thermal performance and mechanical reliability of a sodium-cooled solar receiver operating under heat flux profiles generated by a novel heliostat aiming strategy. A modification of the HFLCAL model is used to generate heat flux profiles for individual heliostats in a representative plant, and simulated annealing optimisation techniques are used to produce a novel heliostat aiming strategy. The importance of giving consideration to receiver limitations under non-uniform thermal boundary conditions in the development of a heliostat aiming strategy is demonstrated in this study, with mathematical optical, thermal, and mechanical models used to complete the analysis. An investigation has been conducted for a point-in-time resulting in maximum thermal loading conditions, with theoretical modelling techniques used to calculate receiver tube temperatures for aiming strategy yielded heat flux profiles, thereby allowing for the determination of heat losses and mechanical reliability through creep-fatigue damage. Results show that the simulated annealing algorithm can significantly improve heat flux homogeneity on the receiver, potentially reducing peak heat flux to less than 10% that of a single aiming point strategy, given an appropriate spillage allowance and aiming point grid size. A satisfactory configuration of spillage allowance and aiming grid size exists so as to supply maximum power to the receiver, while uniformly distributing the incident heat flux in order to meet mechanical reliability requirements. Based on the receiver design and conditions simulated in the analysis, a grid constructed of more than 81 aiming points (receiver area coverage of 32.7%), and an additional spillage allowance of 10% allows the receiver to deliver maximum power output while retaining mechanical durability through a 30 year plant life cycle.

1. Introduction

The ability of concentrated solar power (CSP) systems to store thermal energy allows for dispatchable electricity, which greatly adds to the value of the technology relative to other renewable systems [1]. CSP is expected to play a significant role in the future energy mix, forecast to contribute 12% to global electricity production by 2050 [2]. The most critical challenge associated with CSP is the production of cost effective electricity. CSP has a high levelised cost of electricity (LCOE) relative to other power generation systems, hindering it's

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Nomenclature

A	area (m^2)
AK, ψ	annealing schedule functions
AM	aiming point matrix
A_n, a_n, B_n, b_n	Fourier coefficients
AT	annealing temperature
a	solar absorptivity
B	distance between elements (m)
C	cost function
$\cos\theta_i$	incident ray cosine factor
$\cos rcv$	receiver cosine factor
C_p	specific heat capacity (J/kg K)
D	heliostat slant range (m)
D_i, D_o	inner, outer diameter (m)
d	heliostat general dimension (m)
E	Young's modulus (GPa)
F	Fourier expression
F_{view}	view factor
f	function of
f_{att}	atmospheric attenuation factor
$G_{o,n}$	wall temperature functions
Gr	Grashof number
H, W	height, width (m)
H_t, W_s	tangential, sagittal image dimension
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	length (m)
L_{focal}	focal length (m)
$\dot{m}$	mass flow rate (kg/s)
n, N	number
n_d, N_d	actual, allowable fatigue cycles
Nu	Nusselt number
P	pressure (kPa)
P_{select}	selection probability
Pr	Prandtl number
Q	power (W)
Q''	heat flux (W/m^2)
R	random number
Re	Reynolds number
r_i, r_o	inside, outside radius (m)
S	solution space
Sp	spillage (%)
Δt_d, t_d	actual, allowable time (h)
T	temperature (K)

Greek symbols

α	material expansion coefficient (K^{-1})
β	air expansion coefficient (K^{-1})
δ	Stefan-Boltzmann constant (W/m^2 K^4)
ε	emissivity strain
η	efficiency
θ	circumferential position (rad)
μ	dynamic viscosity (Pa s)
ν	Poisson's ratio
ρ	density (kg/m^3)
σ, τ	normal, shear stress (MPa)
υ	kinematic viscosity (m^2/s)
Φ_{ast}	astigmatic error (mrad)
Φ_{bq}	beam quality error (mrad)
Φ_{eff}	effective error (mrad)
Φ_{sse}	surface slope error (mrad)
Φ_{sun}	sunshape error (mrad)
Φ_{track}	heliostat tracking error (mrad)

Sub/superscript

∞	ambient conditions
add	additional
aim	aiming point
$conv$	convection
el	element
$error$	convergence error
f	fluid
fc, mc, nc	forced, mixed, natural
h, n	home, neighbour
hel	heliostat
i	iteration (aiming strategy)
in	inlet
j	iteration (thermal model)
k	iteration (re-reflection)
l	losses
lam, $turb$	laminar, turbulent
max, min	maximum, minimum
net	net input
out	outlet/output
p	fatigue cycle type
q	creep loading condition
r, θ, z	radial, circumferential, axial
rad	radiation
rcv	receiver
ref, abs	reflection, absorption
s_i, s_o	inside, outside surface
th	thermal
t	tube
vM	von Mises

Abbreviations

CSP	concentrated solar power
DNI	direct normal irradiance
HTF	heat transfer fluid
SA	simulated annealing

competitiveness in the energy market. The delivery of CSP systems with a low LCOE valuation is a function of minimising costs and maximising the performance of components in the power plant.

Central receiver systems are expected to become the dominant CSP technology of the future, largely due to high temperature and solar concentration capabilities that can yield high-efficiency thermodynamic power cycles [3]. A central tower CSP plant uses a large number of automated heliostats to concentrate solar energy onto a receiver. The receiver converts concentrated solar energy into workable thermal energy via a heat transfer fluid (HTF). The HTF is then used to generate steam to drive a turbine and generate electricity. There are numerous receiver concepts which use solid/liquid/gaseous HTF [3], however the liquid tubular design has found favour throughout the history of CSP. Liquid tubular receivers use a bank of vertically aligned tubes to shuttle a HTF between inlet and outlet headers. The HTF temperature is increased when the tubes are receptive to concentrated sunlight from the heliostat field. Liquid tubular receiver design lends from traditional heat exchanger technology [4], and is relatively straightforward in design and operation when compared to gaseous volumetric receivers and solid particle receivers. The liquid tubular