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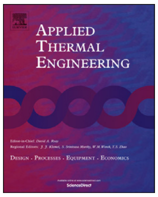

Research paper

Multi-objective and thermodynamic optimisation of a parabolic trough receiver with perforated plate inserts

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HIGHLIGHTS

- The study focuses on the use of perforated plate inserts in a parabolic trough receiver.
- Multi-objective and thermodynamic optimisation of the receiver is investigated.
- Influence of Reynolds numbers, fluid temperature and insert geometry is presented.
- Pareto optimal solutions and optimal insert configurations are presented.
- Optimal Reynolds at which entropy generation is a minimum is obtained and presented.

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ABSTRACT

In this paper, multi-objective and thermodynamic optimisation procedures are used to investigate the performance of a parabolic trough receiver with perforated plate inserts. Three dimensionless perforated plate geometrical parameters considered in the optimisation include the dimensionless orientation angle, the dimensionless plate diameter and the plate spacing per unit meter. The Reynolds number varies in the range $1.02 \times 10^4 \leq Re \leq 1.36 \times 10^6$ depending on the fluid temperature. The multi-objective optimisation was realised through the combined use of computational fluid dynamics, design of experiments, response surface methodology and the Non-dominated Sorted Genetic Algorithm-II. For thermodynamic optimisation, the entropy generation minimisation method was used to determine configurations with minimum entropy generation rates.

1. Introduction

Heat transfer enhancement in heat exchangers and in other thermal applications is of significant importance. Not only does it result in energy savings but has other benefits depending on the application under consideration such as heat exchanger weight and size reduction, reduction in device temperatures and reduction in the temperature difference between process fluids.

In parabolic trough receivers, heat transfer enhancement has potential to reduce absorber tube circumferential temperature gradients [1,2] and also reduce absorber tube temperatures thus lower receiver thermal loss and improved receiver thermal performance [3–5]. Moreover, as parabolic trough systems with high optical efficiencies and high concentration ratios become feasible [6,7], high heat fluxes and high absorber tube temperature gradients will result. As such, improved heat transfer performance will be essential to minimise absorber tube temperature gradients as well as improve the performance and reliability of the receiver at these high concentration ratios. More still, an increase in concentration ratios leads to increased entropy generation rates due to the increased finite temperature differences as concentration ratios increase [8,9]. As such, heat transfer enhancement can also act to minimise the entropy generation in the receiver. For these reasons, heat transfer enhancement in parabolic trough receivers has received considerable attention in the last few decades.

Passive heat transfer enhancement techniques are widely researched and applied in many industrial applications since they require no direct power input as compared to active techniques. Several researchers have applied some of the passive heat transfer enhancement techniques to improve the performance of parabolic

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Nomenclature

A	area, m^2
A_a	collector's projected aperture area, m^2
a_c	collector aperture width, m
A_r	absorber tube's projected area, m^2
Be	Bejan number
C_{2p}	inertial resistance factor, m^{-1}
c_p	specific heat capacity, J kg^{-1} K^{-1}
C_R	concentration ratio
d	perforated plate diameter, m
d_{gi}	glass cover inner diameter, m
d_{go}	glass cover outer diameter, m
d_{ri}	absorber tube inner diameter, m
d_{ro}	absorber tube outer diameter, m
DNI	direct normal irradiance, W m^{-2}
f	Darcy friction factor
h	heat transfer coefficient, W m^{-2} K^{-1}
h_w	wind heat transfer coefficient, W m^{-2} K^{-1}
I_b	direct solar radiation, W m^{-2}
k	turbulent kinetic energy per unit mass, m^2 s^{-2}
L	receiver length, m
Nu	Nusselt number
$N_{s,en}$	entropy generation ratio = $S_{gen}/(S_{gen})_o$
P	pressure, Pa
p	perforated plate spacing, m
Pr	Prandtl number
q''	heat flux, W m^{-2}
r	radial position, m
Re	Reynolds number
S_{gen}	entropy generation rate due to heat transfer and fluid friction, W K^{-1}
S'_{gen}	entropy generation rate per unit meter W m^{-1} K^{-1}
$(S'_{gen})_H$	entropy generation due to heat transfer per meter, W m^{-1} K^{-1}
$(S'_{gen})_F$	entropy generation due to fluid friction per meter, W m^{-1} K^{-1}
S_m	momentum source term
T	temperature, K
u,v,w	velocity components, m s^{-1}
v	volume, m^3
v_w	wind velocity, m s^{-1}
u_i,u_j	averaged velocity components, m s^{-1}
u_i',u_j'	velocity fluctuations, m s^{-1}
x_i, x_j	spatial coordinates, m
x,y,z	Cartesian coordinates
y^+	dimensionless wall coordinate
$-\rho\overline{u_i'u_i'}$	Reynolds stresses, N m^{-2}
∇p	pressure drop, Pa
Δm	perforated plate thickness, m

Greek letters

α	absorber tube absorptivity
α_p	permeability of the perforated plate, m^2
$\sigma_{h.t}$	turbulent Prandtl number for energy
β	plate orientation angle, °
δ_{ij}	Kronecker delta
ξ	emissivity
φ_r	collector rim angle, °
ρ	density, kg m^{-3}
ϱ	collector reflectance
λ	fluid thermal conductivity, W m^{-1} K^{-1}
η_o	optical efficiency, %
τ_g	glass cover transmissivity
τ_w	wall shear stress
θ	receiver angle, °
μ	viscosity, Pa s
μ_t	turbulent viscosity, Pa s
μ_τ	friction velocity, m/s
ν	kinematic viscosity, m^2 s^{-1}

Subscripts

amb	ambient state
f	fluid
gi	inner glass cover wall
go	outer glass cover wall
i, j, k	general spatial indices
max	maximum value
o	reference case (plain absorber tube - no inserts)
ro	absorber tube outer wall
ri	absorber tube inner wall
sky	sky temperature
t	turbulent
w	wall

Superscripts

–	mean value
~	dimensionless value
'	fluctuation from mean value

trough receivers. Reddy et al. [10] numerically analysed a receiver with various porous and longitudinal fin geometries. Ravi Kumar and Reddy [11] investigated the performance of the receiver with a porous disc. Different angles of orientation, porous disc heights and distances between the consecutive discs were considered. Muñoz and Abánades [2] analysed an internally helically finned absorber tube to improve the thermal performance of the receiver and minimise the temperature gradients in the receiver's absorber tube. Recently Cheng et al. [12] analysed the heat transfer enhancement of parabolic trough receivers using unilateral longitudinal vortex generators. In these studies, the potential for improved heat transfer performance in receivers with heat transfer enhancement is demonstrated.

Most heat transfer fluids used in parabolic trough receivers decompose rapidly at temperatures above 400 °C [13,14], leading hydrogen permeation in the receiver's annulus space which exacerbates receiver heat loss. Therefore, heat transfer enhancement mechanism in the receiver's absorber tube should avoid any hot spots and absorber tube surface modification should be done while taking into account likely thermal stresses. Therefore, use of tube inserts appears to be a sure way of avoiding temperature hotspots and thermal stress in the absorber tube. Porous media or perforated inserts present several benefits when compared with solid inserts such as lightweight, low fluid friction and potential for forcing uniform flow distribution [15]. In this study, the use of perforated plate inserts for heat transfer enhancement in a parabolic trough receiver is investigated.

However, besides improving heat transfer performance, heat transfer enhancement techniques also result in an increase in fluid friction. Therefore, to optimise the performance a particular heat