Energy xxx (2014) 1–12

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Minimum entropy generation due to heat transfer and fluid friction in a parabolic trough receiver with non-uniform heat flux at different rim angles and concentration ratios

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ARTICLE INFO

Article history:
Received 17 February 2014
Received in revised form
10 June 2014
Accepted 14 June 2014
Available online xxx

Keywords:
Concentration ratio
Entropy generation
Monte Carlo ray-tracing
Parabolic trough
Receiver
Rim angle

ABSTRACT

In this paper, Monte Carlo ray-tracing and computational fluid dynamics are used to numerically investigate the minimum entropy generation due to heat transfer and fluid friction in a parabolic trough receiver. The analysis was carried out for rim angles in the range 40°–120°, concentration ratios in the range 57–143, Reynolds numbers in the range 1.02×10^4–1.36×10^6 and fluid temperatures in the range 350–650 K. Results show existence of an optimal Reynolds number at any given combination of fluid temperature, concentration ratio and rim angle for which the total entropy generation is a minimum. The total entropy generation was found to increase as the rim angle reduced, concentration ratio increased and fluid temperature reduced. The high entropy generation rates at low rim angles are mainly due to high peak temperatures in the absorber tube at these low rim angles.

1. Introduction

Increasing world's population as well as increasing urbanisation rates are increasingly putting pressure on the available resources. This together with concerns of climate change due global warming means that available resources must be utilised in a sustainable way and with minimum impacts on the environment. As far as provision of clean and sustainable energy is concerned, several efforts by both governments and private entities have been directed towards development and deployment of clean and renewable energy systems.

Solar energy is one of the renewable energy sources that is widely available and has significant potential to provide a significant portion of the global energy needs. Many technologies have been developed for conversion of the sun's energy into useful forms, with concentrated solar power systems being the widely used for large-scale electricity generation [1]. Concentrated solar systems in use today include parabolic trough systems, solar dish, linear Fresnel systems and solar towers. The parabolic trough systems are the most commercially and technically developed systems in use today. They produce the largest share of electricity available from concentrated solar thermal systems today [2].

Several studies on analysis of parabolic trough collector systems are available in literature such as Refs. [3–12]. Research on parabolic trough systems entails almost every aspect of the technology ranging from development of highly reflective coatings for the collector, selective coatings for the receiver's absorber tube, development of heat transfer fluids, cost reduction measures and others [6,13,14].

The parabolic trough's linear receiver is a central component to the performance of the entire system. As such, the linear receiver has been the focus of several investigations regarding its thermal performance and how its performance can be improved [3,4,6,7,15–19]. The state and design of the receiver significantly affects the thermal performance of the systems.

In most studies on the performance analysis of parabolic trough receivers, the basis of analysis is mainly the first law of thermodynamics and therefore does not give an understanding of the quality of energy from the parabolic trough systems. Application of the second law is usually recommended if one is to understand the quality of energy from a given system and for the eventual thermodynamic optimisation of the thermal system and system components [20,21]. In the second law of thermodynamics, the entropy

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http://dx.doi.org/10.1016/j.energy.2014.06.063
0360-5442/

Nomenclature

a_c	collector's aperture width, m
A_a	collector's aperture area, m^2
A_r	projected absorber tube area, m^2
Be	Bejan number = entropy generated due to heat transfer/total entropy generated
C_1, C_2, C_μ	turbulent model constants
c_p	specific heat capacity, J kg^{-1} K^{-1}
C_R	concentration ratio
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
G_k	generation of turbulence kinetic energy due to mean velocity gradients, kg m^{-1} s^{-3}
h_w	wind heat transfer coefficient, W m^{-2} K^{-1}
k	turbulent kinetic energy, m^2 s^{-2}
L	length, m
p	pressure, Pa
Re	Reynolds number
S	modulus of the mean rate-of-strain tensor, s^{-1}
S_{ij}	rate of linear deformation tensor, s^{-1}
S_{gen}	Entropy generation rate due to heat transfer and fluid friction in the receiver, W/K
S'_{gen}	entropy generation due to heat transfer and fluid friction per unit length of the receiver, W/mK
S'''_{gen}	volumetric entropy generation, W m^{-3} K^{-1}
$(S'''_{gen})_F$	volumetric entropy generation due to fluid friction, W m^{-3} K^{-1}
$(S'''_{gen})_H$	volumetric entropy generation due to heat transfer, W m^{-3} K^{-1}
$S'''_{PROD,VD}$	entropy production by direct dissipation, W m^{-3} K^{-1}
$S'''_{PROD,TD}$	entropy production by turbulent dissipation, W m^{-3} K^{-1}
$S'''_{PROD,T}$	entropy production by heat transfer with mean temperatures, W m^{-3} K^{-1}
$S'''_{PROD,TG}$	entropy production by heat transfer with fluctuating temperatures, W m^{-3} K^{-1}
T	temperature, K
v	volume, m^3
v_w	wind velocity, m/s
$\dot{V}$	volumetric flow rate, m^3/s
u_i, u_j	time averaged velocity components, m s^{-1}
u',v',w'	velocity fluctuations, m s^{-1}
u_τ	friction velocity ($\mu_\tau = \sqrt{\tau_w/\rho}$), m s^{-1}
x_i, x_j	spatial coordinates, m
x,y,z	Cartesian coordinates, m
y^+	dimensionless wall coordinate
$-\rho\overline{u'_i u'_j}$	Reynolds stresses, N m^{-2}

Greek letters

$\hat{\alpha}$	absorber tube absorptivity
α	thermal diffusivity, m^2 s^{-1}
α_t	turbulent thermal diffusivity, m^2 s^{-1}
$\sigma_{h.t}$	turbulent Prandtl number for energy
σ_ε	Turbulent Prandtl number for ε
σ_k	Turbulent Prandtl number for k
δ_{ij}	Kronecker delta
ε	turbulent dissipation rate, m^2 s^{-3}
ξ	emissivity
η	turbulence model parameter = Sk/ε
η_c	collector thermal efficiency, %
φ_r	collector rim angle
ρ	density, kg m^{-3}
□	collector reflectivity
τ_g	glass cover transmissivity
τ_w	wall shear stress, N/m^2
θ	absorber tube circumference angular position, degrees
λ	fluid thermal conductivity, W m^{-1} K^{-1}
λ_{eff}	heat transfer fluid effective thermal conductivity, W m^{-1} K^{-1}
μ	viscosity, Pa s
μ_t	Eddy viscosity, Pa s
μ_{eff}	effective viscosity, Pa s
ν	Kinematic viscosity, m^2 s^{-1}

Subscripts

amb	ambient
c	collector
g	glass cover
inlet	absorber tube inlet
i, j, k	general spatial indices
sky	sky
t	turbulent
w	wall

Superscripts

$'$	fluctuation from mean value

generation rates are determined and the minimisation of the entropy generated improves the thermodynamic performance of the system components and the entire system. This method has been termed the entropy generation minimisation method [21]. Several researchers have applied the entropy generation minimisation method to the analysis and optimisation of engineering systems [8,22,23] as well as to heat transfer and fluid flow problems [24–27]. Moreover, the entropy generation minimisation method has been shown to be applicable to a wide range of engineering systems such as small-scale wood fired circulating fluidised bed adiabatic combustor as demonstrated in the study by Baloyi et al. [28], analysis of exergy recovery from the exhaust cooling in a DI diesel engine as demonstrated by Ghazikhani et al. [29] and in characterising the effects of fuel additives on exergy parameters of engines [30] and many others.

For parabolic trough systems, studies on entropy generation are not wide spread. An analytical method suggested by Bejan [21] for determining the entropy generation in solar collectors was adapted to concentrating collectors by Kalogirou [31]. In this method, the entropy generation is a function of the incident solar radiation, useful heat delivered to the user and the receiver heat loss. In our previous study [25], we showed that the entropy generation due to heat transfer and fluid friction inside the receiver's absorber tube gives nearly the same optimum flow rates as the analytical method [31]. The method used in our previous investigation [25] directly calculates the entropy generation using computational fluid dynamics according to the equations derived by Kock and Herwig [32].

In the analytical method for determining entropy generation in the parabolic trough collector [21,31], the effect of several collector parameters on entropy generation is not explicitly considered. Moreover, in our previous investigation [25], the effect of rim angles on entropy generation was not investigated and the heat flux profile used was an approximate one. Therefore, this study seeks to

Please cite this article in press as: Mwesigye A, et al., Minimum entropy generation due to heat transfer and fluid friction in a parabolic trough receiver with non-uniform heat flux at different rim angles and concentration ratios, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.06.063