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Modelling the efficiency of a nanofluid-based direct absorption parabolic trough solar collector

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ABSTRACT

In this paper we propose an approximate analytic solution to the steady state, three-dimensional model of the efficiency of a nanofluid-based direct absorption parabolic trough solar collector under a turbulent flow regime. The model consists of a system of equations: a partial differential equation describing the conservation of energy, and a radiative transport equation describing the propagation of radiation through the nanofluid. Writing the model in non-dimensional form leads to four controlling non-dimensional numbers, specifically one describing the relative importance of conduction and advection and three representing the heat loss to the surroundings. We use realistic parameter values to reduce the model further and show that two of the non-dimensional groups have a much lesser impact on the performance of the solar collector. Our reduced model suggests that the nanofluid's temperature rise is linear as it flows through the receiver. The resulting solution is used to investigate the efficiency of the collector and permits optimisation of design parameters such as particle loading, particle type, solar absorption characteristics of the fluid, receiver dimensions, the inlet temperature, and solar concentration ratio. Further analysis of the collector efficiency reveals an inequality that determines whether or not it is reasonable to incorporate a heat-mirror into the solar collector's design.

1. Introduction

The solar energy industry has experienced phenomenal growth in recent years due to both technological improvements, resulting in cost reductions, and government policies supportive of renewable energy development and utilisation (Timilsina et al., 2012). Global solar energy production is predicted to rise at a rate of 8.9% annually between 2012 and 2040, making it the fastest growing form of energy generation in the coming decades (U.S. Energy Information Administration, 2016).

Several types of solar collectors have been used to harness solar energy. The most common non-concentrating solar collectors are flat-plate black-surface absorbers and evacuated tubes. Flat-plate collectors consist of a dark flat-plate absorber and a working fluid which circulates through the system, extracting heat from the absorber plates. Evacuated tube collectors are composed of multiple evacuated glass tubes, each containing an absorber plate fused to a heat pipe (Mahjouri, 2004). A parabolic trough solar collector (PSC) is a solar concentrating system that uses a parabolic reflector to concentrate incoming solar radiation onto a metallic solar absorbing tube (which heats up as it absorbs solar radiation) (Kalogirou, 1996). Typically a working fluid flows through the pipe; as the pipe heats up this heat is transferred into the working fluid.

The solar collectors highlighted exhibit several shortcomings, such as: limitations on incident flux density, relatively high heat losses, and corrosion effects (Tyagi et al., 2009). Direct absorption solar collectors (DASCs) (Taylor et al., 2011) were first proposed in the mid-1970s as an alternative to surface absorbers. A DASC does not absorb incoming solar radiation with its surface; instead, the working fluid absorbs the incoming solar energy directly. Direct absorption parabolic trough solar collectors (DAPSCs) use parabolic mirrors to concentrate the incoming solar irradiance onto a transparent cylindrical reciever located on its focal line, as shown in Fig. 2a. Since the receiver area is much smaller than the aperture area, the rise in temperature is much greater than that of non-concentrating DASCs, and so DAPSCs can be used in a wider variety of applications. DAPSCs have proven to be useful in many industrial processes. Kalogirou (2003) identifies several industrial processes with favourable conditions for the application of solar energy such as: sterilising, pasteurising, drying, hydrolysing, distillation and evaporation, washing and cleaning, and polymerisation. In an industrial heating process, the operating temperature needs to be predictable, so accurate models for the working fluid's outlet temperature are useful.

While DASCs are a promising technology, standard fluids are

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Nomenclature

R	receiver radius [m]
h	Plancks constant $[\mathrm{m^2\,kg\,s^{-1}}]$
c	speed of light $[\mathrm{m\ s^{-1}}]$
Ω_S	solid angle of the sun [sr]
σ	Stefan's constant $[\mathrm{kg\,s^{-1}\,K^{-4}}]$
S_{Att}	attenuation coefficient [–]
k_B	Boltzmann constant $[\mathrm{m^2\,kg\,s^{-2}\,K^{-1}}]$
L	receiver length [m]
u	mean fluid velocity $[\mathrm{m\,s^{-1}}]$
ν	kinematic viscosity $[\mathrm{m^2\,s^{-1}}]$
T^*	temperature [K]
G_s^*	incident radiative heat flux
ρ	density $[\mathrm{kg\,m^{-3}}]$
k	thermal conductivity $[\mathrm{W\,m^{-1}\,K^{-1}}]$
c_p	heat capacity $[\mathrm{J\,kg^{-1}\,K^{-1}}]$
K_e	extinction coefficient $[\mathrm{m^{-1}}]$
f_v	nanofluid particle volume fraction [–]
D	nanoparticle diameter [m]
λ	wavelength [m]
n	refractive index [–]
$\varkappa_a$	absorption index [–]
J_0	spectral intensity at top of receiver $[\mathrm{W\,sr^{-1}\,m^{-1}}]$
P	radiative flux $[\mathrm{W\,m^2}]$
β_0,β_1	fitting parameters [–]
Pe	Peclet number [–]
Re	Reynolds number [–]
γ,φ,τ	dimensionless parameters [–]
ϵ	emissivity [–]
η	efficiency [–]
C_A	solar concentration ratio [–]
Υ_T	transmittance [–]
F	heat mirror solar transmittance [–]
Υ_R	reflectivity [–]
r^*	coordinate [m]
x^*	coordinate [m]
ϕ	coordinate [rad]

Subscripts

bf	base fluid
np	nanoparticle
nf	nanofluid
O	outlet
I	inlet
A	ambient
a	absorption
s	scattering
Sun	sun
A	incoming
B	outgoing
Bb	black-body

inefficient at absorbing sunlight due to their low absorptive properties (Otanicar et al., 2009). To overcome the poor absorption properties of conventional fluids, nanoparticle-laden fluids can serve as the absorbing medium in DASCs (Taylor et al., 2011). Unlike traditional DASCs, nanofluid-based direct absorption solar collectors (NDASCs) use a colloidal solution of nanoparticles to absorb incident sunlight. There is an ongoing debate as to whether or not nanofluids exhibit unusually enhanced thermophysical properties over their base fluids (Buongiorno et al., 2009; Myers et al., 2013; Myers et al., 2017). However, the presence of nanoparticles in the fluid leads to increased scattering and absorption of light compared to the particle-free liquid, which results in enhanced optical properties and thus an improvement in the efficiency of NDASCs when compared to DASCs (Lenert and Wang, 2012; Otanicar et al., 2010).

Gorji and Ranjbar (2017) offer an extensive review of the literature surrounding the use of nanofluids in DASCs. Table 4 from Gorji and Ranjbar (2017) presents a chronological summary of the literature around on low-flux nanofluid-based DASCs, includes 18 previous studies. Since the aim of this paper is to develop analytic expressions for the temperature and efficiency of DASCs, we will focus on the analytic studies presented by Gorji and Ranjbar. Of the articles mentioned, only three provide a fully analytical solution for the temperature of the nanofluid as it flows through the receiver: Cregan and Myers (2015), Lee and Jang (2015), and Turkyilmazoglu (2016). Cregan and Myers present the first fully analytic solution for the temperature of a low-flux NDASC; in their proposed model, they assume a laminar and plug flow through the receiver and apply a zero-flux boundary condition at the bottom of the receiver. Lee and Jang obtain an analytic solution to the temperature of a low-flux NDASC while considering a laminar and depth-dependent fluid flow, and again, a zero-flux boundary condition at the bottom of the receiver. Meanwhile, Turkyilmazoglu applies an isothermal boundary condition rather than a zero-flux boundary condition at the bottom of the collector, while assuming laminar and plug flow.

Returning our attention to DAPSCs, Khullar et al. (2012) consider a two-dimensional model for the temperature and efficiency of an Al/Therminol® VP-1 nanofluid-based DAPSC (NDAPSC) subject to coupled radiative and diffusive heat transfer in an absorbing, emitting, and scattering medium under plug flow. They compare a numerical treatment of their model with experimental data for conventional concentrating parabolic solar collectors, maintaining the same external conditions (i.e., ambient/inlet temperatures, wind speed, solar insolation, flow rate, concentration ratio, etc.). Khullar et al. (2012) observe that NDAPSCs have 5–10% higher efficiency than conventional parabolic solar collectors. Menbari et al. (2016) propose a model for a CuO/Water NDAPSC subject to steady turbulent depth-dependent flow. They validate the model by comparing a finite difference solution for the temperature with experimental results. Interestingly, the average axial nanofluid temperature rises almost linearly along the length of the receiver tube. Furthermore, the experimental and numerical results show that thermal efficiency of NDAPSCs improves by increasing the nanofluid flow rate. They also find that an increase in nanofluid particle volume fraction from 0.002% to 0.008% leads to an increase in thermal efficiency from 18% to 52%.

Analytical models for the performance of concentrating NDASCs are rare in the literature; moreover, analytic models for NDAPSCs are nonexistent. Table 5 from Gorji and Ranjbar (2017) provides a chronological summary of the literature on concentrating NDASCs. Of the seven studies mentioned, only one proposes a fully analytic solution for the temperature of the nanofluid as it flows through a receiver—Veeraragavan et al. (2012). Veeraragavan et al. assume laminar and plug flow through a two-dimensional channel of height 1 cm and apply a zero-flux boundary condition at the bottom of the receiver. This model excludes the effect of scattering due to the nanoparticles, and also assumes that the base fluid is a non-absorbing medium; moreover this model does not describe an NDAPSC; different types of concentrating systems must be modelled differently. The other six studies discussed in Table 5 from Gorji and Ranjbar (2017) are numerical and/or experimental.

In this paper we develop an approximate analytic solution to a three-dimensional model for the efficiency of an NDAPSC. The model consists of a system of partial differential equations describing the