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

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ABSTRACT

This paper compares the performance of three variations to a novel low-profile nanofluid-based direct absorption parabolic trough solar collector design. More specifically, we propose a steady state, three-dimensional model for the efficiency of such a collector subject to laminar flow. The model consists of a system of two partial differential equations describing the conservation of energy and momentum, and a radiative transport equation describing the propagation of radiation through the nanofluid. We non-dimensionalise the model revealing seven controlling dimensionless numbers: two describing different rates of thermal diffusion to advection, another two describing Newton cooling at the boundaries, and the remaining three describing black-body emissions at the boundaries. The system is solved via a modified Crank-Nicolson method which is optimised to cater for non-linearities in the radiative transport equation. A realistic parameter space exploration is conducted to investigate the optimal collector design variation.

1. Introduction

Energy consumption is a significant driver of economic growth [15]. Global solar energy demand 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 [22]. Currently, solar-thermal technologies produce more energy than solar voltaic technologies [10]. Solar-thermal technologies provide hot water to heat and cool space, and to generate high-temperature heat for industrial processes [18]. Whilst the global solar-thermal capacity continues to rise, recently, the rate of capacity increase has seen a decline (falling 14% in 2015 [18]). More innovation is needed if solar-thermal technologies are to see this recent trend reversed. The industrial process heat market is under-served with viable solar-thermal options [10]. A suitable solar collector needs to be efficient, cheap, and easily integrated into architectural designs [17]. In this study we design and model a new type of solar collector and optimise its efficiency.

Concentrating solar collectors use mirrors and lenses to focus solar radiation onto a receiver area which is typically much smaller than the aperture area. Low to medium-temperature concentrating collectors (<750 K [23]) can be used to power industrial heat processes, one such design is the parabolic trough solar collector (PTSC). PTSCs use a highly reflective parabolic trough to focus sunlight onto a cylindrical pipe receiver. Conventional PTSCs contain surface-based absorbers, i.e., incoming electromagnetic radiation is converted into thermal energy at the surface of the receiver. It is important to note that thermal losses occur at the surface, and this surface is the hottest part of a surface-based collector. Direct-absorbing parabolic trough solar collectors (DAPSCs) offer an alternative to the surface-absorbing collector design [20]. In a DAPSC, incoming electromagnetic radiation is absorbed volumetrically by the working fluid rather than at the surface of the collector. This results in cooler temperatures at the surface of the collector; in fact, Li et al. [10] show that by focusing incoming radiation, it is possible to achieve hotter temperatures at the centre of a volumetric receiver rather than at the surface. However, standard working fluids in a DAPSC are inefficient at absorbing sunlight due to their unsuitable optical properties—for example, Otanicar et al. [16] show that water only absorbs 13% of the available solar energy at a depth of 1 cm. This has led to the development of nanofluid-based direct absorption parabolic trough solar collectors (NDAPSCs). A nanofluid is a colloidal suspension of nanoparticles in a liquid medium. Theoretical and experimental studies show that nanofluids have enhanced optical properties for absorbing solar radiation over their base-fluids [10,16,20]; in a nanofluid, solar radiation is attenuated much faster due to the nanoparticles

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Nomenclature

R	receiver radius [m]
σ	Stefan's constant [kg s^{-1} K^{-1}]
L	receiver length [m]
$\bar{u}^*$	mean fluid velocity [m s^{-1}]
ν	kinematic viscosity [m^2 s^{-1}]
T^*	temperature [K]
G_s^*	incident radiative heat flux
ρ	density [kg m^{-3}]
k	thermal conductivity [W m^{-1} K^{-1}]
c_p	heat capacity [J kg^{-1} K^{-1}]
f_v	nanofluid particle volume fraction [–]
β_0, β_1	fitting parameters [–]
Pe	Peclet number [–]
Re	Reynolds number [–]
$\gamma, \varphi, \tau, \widehat{T}, \hat{\gamma}, \lambda$	dimensionless parameters [–]
ϵ	emissivity [–]
h	heat transfer coefficient
η	efficiency [–]

f	focal length [m]
W	aperture width [m]
Υ_T	transmittance [–]
Υ_R	reflectivity [–]
r^*	coordinate [m]
x^*	coordinate [m]
ϕ	coordinate [rad]

Subscripts

bf	base fluid
nf	nanofluid
I	inlet
A	ambient
a	aperture
s	sun
Bb	black body

absorbing and scattering radiation propagating through the nanofluid.

Several studies have modelled the efficiency of NDAPSCs. Khullar et al. [8] considered a two-dimensional model for the temperature and efficiency of an Al/Therminol® VP-1 NDAPSC subject to coupled radiative and diffusive heat transfer in an absorbing, emitting, and scattering medium under plug flow. They compared a numerical treatment of their model to experimental data for conventional (surface-based) concentrating parabolic solar collectors, while maintaining the same external conditions (i.e., ambient/inlet temperatures, wind speed, solar insolation, flow rate, concentration ratio, etc.). They observed that NDAPSCs can have 5–10% higher efficiency than conventional parabolic solar collectors. Menbari et al. [12] proposed a model for a CuO/Water NDAPSC subject to steady turbulent depth-dependent flow. They validated the model by comparing a finite difference solution for the temperature with experimental results. The experimental and numerical results revealed that the thermal efficiency of NDAPSCs improves by increasing the nanofluid flow rate. They also found that an increase in nanofluid particle volume fraction from 0.002% to 0.008% leads to a significant increase in thermal efficiency from 18% to 52%. O'Keeffe et al. [13] proposed a model for an Al/Therminol® VP-1 NDAPSC under a turbulent flow regime which included a power-law approximation for the solution to the radiative transport equation. An analytic expression for the radiative transport equation enabled the authors to non-dimensionalise the model and then use a realistic case study to explore the relative size of the dimensionless terms. Thus, they simplified the model by neglecting small terms to obtain an approximate analytical expression for the efficiency of an NDAPSC (in contrast to previous numerical/experimental studies [8,10]). Li et al. [10] compared the performance of a concentrating NDASC with the performance of a surface-absorbing concentrating solar collector demonstrating that both collectors could perform well, but that more research is needed on volumetric receivers. We note that the solar concentration method in Li et al.'s [10] collector used a combination of lens and compound parabolic reflectors to focus solar radiation onto the surface of a collector; while this method works quite well for surface-based solar collectors, it does not necessarily work as well for volumetric collectors. Ray tracing analysis shows that in a compound parabolic reflector, the concentrated incoming radiation is not always normal to the receiver [1]—the implications of this result are discussed in further detail in Appendix A.

O'Keeffe et al. [13] offer a comprehensive review of the literature surrounding the application of heat-mirrors to NDAPSCs. A heat-mirror is a selectively transmissive/reflective material that is highly transparent at short (solar) wavelengths, but highly reflective at long wavelengths. If the surface of a volumetric receiver is coated with a suitable heat-mirror, most of the incoming solar radiation is able to pass through the surface while the majority of the emitted black-body radiation is reflected off the surface and prevented from leaving the system [7,10,13,20]. Although selective absorbing surfaces are well developed and very successful commercially, selective transparent surfaces are comparatively underserviced by scientific literature [19]. Previous research suggests that heat-mirror coatings can improve the efficiency of an NDAPSC [7,10,20]. However, O'Keeffe et al. [13] show that this is not always the case: for lower temperatures an uncoated system may be more efficient. Also, as the solar concentration ratio increases, an uncoated NDAPSC becomes more efficient than an NDAPSC coated with a heat-mirror; at higher inlet temperatures, the concentration ratio required for an uncoated NDAPSC to be more efficient than a coated NDAPSC increases. In this paper we will explore if, and to what extent, these results also apply to a low-profile NDAPSC under laminar flow.

Fig. 1(i) illustrates a three-dimensional rendering of the novel collector design modelled in this paper, while this collector consists of a series of parallel collector tubes, in this paper we model one collector tube in isolation of the rest of the system. Fig. 1(ii) outlines three potential variations to the collector tubes: Collector (a) has no vacuum annulus, Collector (b) has a vacuum annulus but no heat-mirror coating, and Collector (c) has both a vacuum annulus, and a heat-mirror coating on the outer surface of the receiver tube to minimise radiative emissions from the glass surface. These three designs are similar in principle to the vacuum glass tube component of the collector proposed by Li et al. [10], with a few notable differences: (1) The width of the parabolic trough is maximised so that it is equal to the inner diameter of the vacuum glass tube in order to maximise the amount of concentrated solar radiation, (2) these tubes rotate to track the sun, while in Li et al.'s design [10] the tubes move linearly, and (3) this design does not incorporate lens or prisms, (i.e., the parabolic trough is the only mechanism for solar concentration) the lens in Li et al.'s design reduce that collector's optical efficiency by 10% and the lens/compound parabolic reflector combination does not focus incoming