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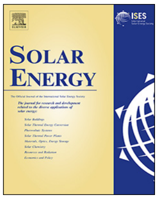

Time-dependent modelling of nanofluid-based direct absorption parabolic trough solar collectors

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ABSTRACT

In this paper we propose a time-dependent, three-dimensional model for 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 for conservation of energy, and a time-dependent radiative transport equation describing the propagation of solar radiation through the nanofluid. Writing the model in dimensionless form reveals four controlling dimensionless numbers: one describing the relative importance of conduction and advection and three describing the heat loss to the surroundings. Realistic parameter values are applied to reduce the model further and these indicate that two of the dimensionless groups have a much smaller impact on the performance of the solar collector. We use the resulting solution for the temperature to calculate an analytic expression for the collector's efficiency. This expression permits optimisation of design parameters such as particle loading, incoming radiative intensity, receiver dimensions, the inlet temperature, and solar concentration ratio.

1. Introduction

Global capacity for generating concentrating solar thermal power (CSP) increased by more than 40% per year on average between 2008 and 2012, which placed CSP amongst the fastest growing forms of energy generation (Ellabban et al., 2014). There are multiple ways to generate CSP, for example, Xie et al. (2011) numerically and experimentally study a point focus solar collector using high concentration Fresnel lens, however, parabolic trough systems have driven most of the recent CSP capacity growth (Sawin et al., n.d.). Surface-based parabolic trough solar collectors (SPSCs) are the predominant parabolic trough system design. SPSCs usually consist of a working fluid flowing through metallic pipes. These pipes heat up as they absorb incoming solar radiation, and this heat is then absorbed by the working fluid. Black-body emissions from the SPSC surface are a major source of inefficiency in this design since an SPSC's surface is the hottest part of the collector (Li et al., 2016). Direct-absorbing parabolic trough solar collectors (DAPSCs) are an alternative (albeit less popular) form of parabolic trough CSP production; in a DAPSC, the working fluid is heated volumetrically by incoming radiation rather than at the surface of the receiver. Martinopoulos et al. (2010) show experimentally that the efficiency of a translucent polycarbonate direct-absorbing solar collector can be similar to that of low-cost flat plate commercially available collector. Li et al. (2016) show that by focusing incoming radiation, it is possible for the surface of a DAPSC's receiver to experience lower temperatures than its center-line. Previous studies have compared the efficiencies of direct-absorption and surface-based solar collectors and hypothesise that direct-absorption solar collectors' lower surface temperatures could make them more efficient (Taylor et al., 2011; Khullar et al., 2012; Xu et al., 2015; Li et al., 2016; O'Keeffe et al., 2016, 2018a,b). However, conventional DAPSCs are limited because standard working fluids are inefficient at absorbing sunlight; for example, Otanicar et al. (2009) show that water only absorbs 13% of the available solar energy at a depth of 1 cm. Therefore, SPSCs outperform DAPSCs using standard working fluids. Theoretical and experimental studies show that nanofluids have enhanced optical properties for absorbing solar radiation over their base-fluids (Otanicar et al., 2009; Taylor et al., 2011). A nanofluid is a colloidal suspension of nanoparticles in a liquid medium. In a nanofluid, solar radiation is attenuated much faster due to the nanoparticles absorbing and scattering the solar radiation that propagates through the receiver. This has led to the development of nanofluid-based direct-absorption parabolic trough solar collectors (NDAPSCs).

Several studies model NDAPSCs in an attempt to better understand and predict their performance. Khullar et al. (2012) consider a steady-state two-dimensional model for the temperature and efficiency of an

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Nomenclature

R	receiver radius [m]
σ	Stefan's constant [kg s^{-1} K^{-4}]
L	receiver length [m]
u	mean fluid velocity [m s^{-1}]
T^*	temperature [K]
G_s^*	incident radiative heat flux [W m^{-2}]
ρ	density [kg m^{-3}]
k	thermal conductivity [Wm^{-1} K^{-1}]
c_p	heat capacity [J kg^{-1} K^{-1}]
f_v	nanofluid particle volume fraction [–]
G_m, A, B, 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 [–]
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

Al/Therminol® VP-1 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. Menbari et al. (2016) propose a steady-state 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. Xu et al. (2015), while comparing the performance of a medium-temperature (80–250 °C) NDAPSC to that of an SPSC, show that the NDAPSC's working fluid temperature distribution is more uniform than that of the SPSC's, and therefore, an NDASC can have greater efficiency than an SPSC within a preferred working temperature range. O'Keeffe et al. (2018a,b) consider a steady-state model for the temperature and efficiency of an Al/Therminol® VP-1 NDAPSC. Unlike Menbari et al. (2016) and Khullar et al. (2012), O'Keeffe et al. (2018b) obtain an analytic expression for the temperature of the nanofluid as it flows through the NDAPSC which they used to calculate collector efficiency. A comprehensive review of the literature surrounding the application of heat-mirrors to NDAPSCs can be found in O'Keeffe et al. (2018b). A heat-mirror is a selectively transmissive/reflective material that is highly transparent at short wavelengths, but highly reflective at long wavelengths, and was introduced for use in solar-thermal energy conversion applications in the 1970s by Fan and Bachner (1976). Previous research had suggested that heat-mirror coatings could improve the efficiency of an NDAPSC (Taylor et al., 2011; Khullar et al., 2014; Li et al., 2016), however, O'Keeffe et al. (2018b) 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.

Although several researchers have studied the performance of NDAPSCs, there are still significant gaps in the literature. Most notably, the solar intensity at a fixed position on Earth is constantly changing (Kimball, 1935), however, existing NDAPSC models assume that incoming solar intensity is constant. Kolb (2011) notes how a solar collector must, by its nature, operate under dynamic conditions. The pipes in a solar collector expand as they are heated, and this expansion process produces mechanical strains. A solar collector needs to withstand these temperature fluctuations over its life cycle and perform efficiently under realistic operating conditions; therefore, one must be able to predict the relationship between fluctuating solar intensity and solar collector temperature.

This paper proposes an approximate analytic expression for the temperature and efficiency of a time-dependent nanofluid-based direct-absorption parabolic trough solar collector under a turbulent flow regime. In Section 2.2 the system's conservation of energy is modelled. Time-dependence is introduced into this model via the source term, and in Section 2.3 two potential source terms which operate on two different time-scales are described. The first of these terms represents the effect of dynamic cloud cover, and the second represents the effect of the Earth's rotation about its axis. We rescale and non-dimensionalise the model in Section 2.4 to yield five dimensionless controlling groups. These were also obtained by the authors in previous research (O'Keeffe et al., 2018b). Realistic parameter values applied to these groups demonstrates that two of the dimensionless parameters have a comparatively small impact on the model. In Section 2.6 we describe an analytic method for solving the governing system of equations. This method leads to an expression for the temperature of the nanofluid as it flows through the collector. We use this analytic expression for the temperature to evaluate the collector's efficiency in Section 2.7 before discussing the collector's performance further in Section 3.

2. Model

2.1. Problem configuration

The NDAPSC is modelled as a cylinder, wherein the variables, x^*, r^*, and ϕ define a three-dimensional system such that x^* is the axial coordinate, r^* is the radial coordinate, and ϕ is the azimuthal angle (note that * denotes a dimensional variable). Fig. 1(b) shows the system geometry in more detail. The nanofluid enters the receiver at the inlet ($x^* = 0$) at an inlet temperature of T_I^*, before being pumped through the receiver. As the nanofluid flows towards the outlet ($x^* = L$), it heats up before exiting the system with temperature T_O^*.

2.2. Conservation of energy

The equation describing the conservation of heat energy is similar to the system described in O'Keeffe et al. (2018b), however, that paper only concerns the steady-state case. Here, conservation of energy in the system is given by

$$\rho_{nf}\, c_{p,nf}\, [T^*_{t^*} + \mathbf{u}\cdot\nabla T^*] = k_{nf}\,\nabla^2 T^* + q, \tag{1}$$

where $\mathbf{u} = (u^*, w^*, v^*)$ is the fluid velocity, $T^*(x^*, r^*, \phi, t^*)$ is the fluid temperature, $q(r^*, \phi, t^*)$ is the time-dependent source term, and the physical properties, ρ_{nf}, $c_{p,nf}$, and k_{nf} represent, the nanofluid's density, specific heat capacity, and thermal conductivity respectively. The inlet temperature condition is $T^*|_{x^*=0} = T_I^*$, whilst the initial condition is $T^*|_{t^*=0} = T_0^*$. At the surface of the receiver there is no slip, and thus $\mathbf{u}|_{r^*=R} = 0$. The radiative boundary condition at the surface of the