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Analytical model for the design of volumetric solar flow receivers

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ABSTRACT

The development of efficient solar thermal receivers has received significant interest for solar to electrical power conversion and heating applications. Volumetric flow receivers, where the incoming solar radiation is absorbed in the volume of a heat transfer fluid (HTF), promise reduced heat loss at the surface compared to surface absorbers. In order to efficiently store the thermal energy in the volume, nanoparticles can be suspended in the HTF to absorb the incoming radiation. In such systems, compact models are needed to design and optimize the performance. This paper presents an analytical model that investigates the effect of heat loss, particle loading, solar concentration and channel height on receiver efficiency. The analytical model was formulated by modeling the absorption of solar radiation by the suspended nanoparticles as a volumetric heat release inside the flowing HTF. The energy equation was solved with the surface heat losses modeled using a combined radiative and convective heat loss coefficient. The analytical solution provides a convenient tool for predicting the effect of different parameters, in terms of dimensionless numbers (Pe, Nu_E, $\overline{G}$, and θ_{amb}), on two-dimensional temperature profiles and system performance. By combining the receiver efficiency with a power generation efficiency, idealized by the *Carnot* efficiency, an optimum receiver length where the total efficiency is maximized is determined. However, in practice, the maximum efficiency depends on the maximum allowable temperature of the working HTF. As a case study, predictions were made for Therminol® VP-1 with suspended graphite nanoparticles in a 1 cm deep channel with a solar concentration of 10. The model predicts an optimum total system efficiency of 0.35 for a dimensionless receiver length of 0.86. Finally, the analytical model was used to estimate the optimum efficiency and the corresponding optimum receiver length for different design configurations with varying Nu_E and $\overline{G}$. The results from this paper will help guide experimental design of volumetric flow receivers for solar thermal based power systems.

1. Introduction

Most solar thermal technologies today, ranging from hot water heating to concentrated solar power, use absorbing surfaces to convert solar energy from its radiative form into thermal energy. Although surface-based receivers efficiently convert radiative energy into thermal energy, the thermal resistance between the absorber and the heat transfer fluid (HTF) leads to a temperature difference between the absorber and the fluid which lowers the overall conversion efficiency of solar energy. Alternatively, nanofluids, nanoparticles suspended in the HTF can be used to directly absorb concentrated solar radiation and transfer the heat to the surrounding fluid.

Volumetric absorption using small particles, originally proposed by Abdelrahman et al. [1] and Hunt [2], minimizes the temperature difference between the absorber and the carrier fluid due to the large surface to volume ratio of the particles [2,3] and promises to be a more efficient heat transfer mechanism. To model the coupled radiative and convective heat transfer inside the particle-based receivers, researchers have developed numerical models capable of predicting the response of these systems. Initial models of fluid-based volumetric receivers focused on non-scattering semi-transparent fluids flowing over opaque surfaces [4,5]. Kumar and Tien [6] developed a model incorporating the spectral and directional radiative properties of the particles and the boundary conditions which provided a framework for future modeling studies. Miller expanded these past studies to include the oxidation of carbon particles in a three-dimensional model [3,7]. More recently, Tyagi et al. simplified past models to specifically model a nanofluid collector [8]; while, Otanicar et al. [9] built on their model to include multiple and dependent scattering, and size-dependent optical properties in nanofluid systems. Despite the increased functionality added to these numerical models, the optimal design of volumetric solar flow receivers remains unclear.

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Nomenclature

A	coefficient in homogeneous solution [–]
c	speed of light [m/s]
C	solar concentration factor [–]
c_p	heat capacity [J/kg K]
f_v	particle volume fraction [–]
G	green's functions [–]
G_s	incident solar radiation [W/m^2]
$\overline{G}$	dimensionless incident solar flux [–]
h	Planck's constant = 6.626(10^{-34}) [J s]
H	receiver height [m]
h_E	combined surface heat loss coefficient [W/m^2 K]
J	spectral flux [W/m^2 m]
k	absorptive index [–]
k_B	Boltzmann's constant = 1.3807(10^{-23}) [J/K]
k_c	thermal conductivity [W/m K]
K_1	effective fluid and particle absorptive index [–]
L	length of receiver [m]
m	relative complex refractive index [–]
n	refractive index [–]
P	radiative flux [W/m^2]
$\dot{q}'''$	volumetric heat release [W/m^3]
T	temperature [K]
U	plug-flow velocity [m/s]
x, y	coordinates [m]

Greek symbols

α	eigenvalue [m$^{-0.5}$]
η	efficiency [–]
θ	dimensionless temperature difference [–]
κ	absorption coefficient [m^{-1}]
λ	wavelength [m]
ρ	density [kg/m^3]

Superscripts

$\bar{}$	dimensionless quantity
$*$	optimum
+	along positive y-dir.
–	along negative y-dir.

Subscripts

abs	absorbed
amb	ambient
att	attenuation
avg	average or bulk
f	fluid medium
in	receiver inlet
λ	spectral
p	particle
rec	receiver
s	solar

The objective of this study is to present an analytical method to describe flowing nanoparticle-based volumetric solar receivers in low to mid-temperature regimes which can be used to determine the optimum length and outlet temperature of these systems. Previous numerical modeling efforts have only considered particular combinations of nanoparticles and carrier fluid in a specific geometry [3,6,8,9]. However, even for relatively simple geometries of volumetric receivers, numerous parameters can be varied and the results of the coupled radiative and heat transfer equation become difficult to predict. We present an analytical model which combines radiative and convective losses into a single heat loss coefficient to efficiently investigate a large parametric space such as varying particle loading and solar concentration, and to optimize the total system efficiency. This combined heat loss approximation is reasonable for temperatures below 750 K which includes most current solar thermal applications since they are limited by material degradation and increasingly significant radiative losses at higher temperatures.

2. Model formulation

We investigate a flowing solar receiver where the normally incident concentrated solar radiation (CG_S) is absorbed volumetrically within the channel due to the presence of suspended nanoparticles, as shown in Fig. 1. The nanofluid is heated volumetrically as it flows with a uniform velocity, U, through a parallel plate channel of height, H. We assume a plug flow profile which has been commonly used in the modeling of low temperature solar flow nanofluid receivers [8]. The heat losses from the receiver are modeled using a heat loss coefficient (h_E) acting at the top surface. Thermal re-emission from within the fluid is neglected since it constitutes less than 5% of the total radiative heat loss for temperatures below 750 K. The thermophysical properties of the nanofluids are assumed to be equal to those of the pure heat transfer fluid owing to the low nanoparticle volume fractions considered in this study (f_v < 0.006). Reflection from the top surface and losses associated with optical concentration of solar radiation are not considered, but can be incorporated through an optical efficiency for a specific system design.

2.1. Energy equation

The energy equation for the receiver, accounting for the volumetric heat release, can be written as:

$$\rho U c_p \frac{\partial T}{\partial x} = k_c \frac{\partial^2 T}{\partial y^2} + \dot{q}'''(y) \tag{1}$$

where, ρ is the density, U is the velocity (assuming plug flow), c_p is the specific heat, and k_c is the thermal conductivity of the fluid.

The energy equation can be nondimesionalized using the following parameters:

$$\bar{y} = \frac{y}{H}; \quad \bar{x} = \frac{x}{PeH}; \quad Pe = Re\ Pr = \frac{\rho U c_p H}{k_c} \tag{2a}$$

$$\theta = \frac{k_c(T - T_{in})}{CG_s H} \tag{2b}$$

$$\bar{\dot{q}}'''(\bar{y}) = \frac{\dot{q}'''^{(y)} H}{CG_s} \tag{2c}$$

The dimensionless spatial coordinates are given in Eq. (2a), where H is the channel height and Pe is the Peclet number. Pe serves as a scaling parameter for this axial coordinate; as the Pe number increases, the length of channel needed to achieve a certain temperature in the receiver increases. In this study, the flow is assumed to be laminar but with a large enough Pe such that conduction along the direction of the flow (x-dir.) is negligible compared to advection (*i.e.*, $10 < Pe < Re_{crit}\, Pr$). θ is the dimensionless temperature (Eq. (2b)) where k_c is the thermal conductivity, G_s is the incident solar flux (1000 W/m^2) and C is the level of solar concentration. Lastly, Eq. (2c) represents the dimensionless heat release profile resulting