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Comparison of different heat transfer models for parabolic trough solar collectors

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HIGHLIGHTS

- We summarized different assumptions and details for 1-D math models of PTC.
- All the heat transfer processes were considered.
- It can choose an appropriate 1-D model under a certain condition due to this paper.
- A simple algorithm was adopted to make control equations linear and solve easily.
- 1-D model is precise and simple enough compared with 3-D model by comparison.

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ABSTRACT

Parabolic trough solar collector (PTC) is one of the solar thermal energy applications, which focuses sunlight to heat the heat transfer fluid (HTF) circulating through the receiver. Researchers have put forward several heat transfer models for PTCs, basing on laws of conservation. This paper summarized the one-dimensional (1-D) mathematical models under different assumptions and details for PTCs. All the heat transfer processes were considered: convection within the absorber, in the annulus and between the glass and ambient; conduction through glass cover, absorber and support brackets; radiation in the annulus and from the glass to the sky. Moreover, a simple algorithm was adopted to make the control equations linear and solve easily. The difference in accuracy for diverse 1-D models were presented and analyzed on the basis of the experimental data from Sandia National Laboratories. The 1-D models with various details were different in accuracy and complexity. It can choose an appropriate 1-D model under a certain condition, which can be used in investigating the thermal performance of a PTC. In addition, the most accurate 1-D model presented in this paper were precise enough compared with the three-dimensional (3-D) model from other paper. The average difference of outlet temperature between the most accurate simulation in this paper and test data was 0.65 °C, however it was 2.69 °C between the 3-D model and experiment results. The reason may be that there were more assumptions for 3-D models than 1-D models, therefore the error was bigger.

1. Introduction

A PTC focuses direct solar radiation onto the absorber located on its focal line. By circulating through the receiver, the HTF absorbs the concentrated solar thermal energy to raise its enthalpy (see Fig. 1). The application of PTCs can be divided into two major groups. One is Concentrated Solar Power (CSP) plants with the fluid temperature from 300 °C to 400 °C. The other supplies a temperature between 100 °C and 250 °C for domestic hot water, space heating and heat-driven refrigeration, etc. [1].

Many scholars have developed mathematical models for the PTC to study the heat transfer characteristics and improve its thermal performance. Dudley et al. [2] tested a SEGS LS-2 PTC with the black chrome and cermet coating under vacuum or air in the annulus, and bare receiver. Numerous papers quoted their experiment results to validate the theoretical models. Taken the thermal performances of different working oils into consideration, Ouagued et al. [3] proposed a 1-D model dividing the HCE into several segments for PTCs. Padilla et al. [4] established control equations for fluid, absorber and glass. Meanwhile, improvements in radiative heat transfer analysis were presented. Both 1-D and 2-D models were built in [5]: the 2-D model discretized the receiver into "N" segments along the length, the 1-D model did opposite. Almost all the physical

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Q	heat transfer capacity (W)
W	solar irradiation absorption (W)
c_p	specific heat (J kg^{-1} K^{-1})
t	temperature (K)
t_{b0}	temperature of the fin base (K)
h	enthalpy (J kg^{-1}), convection heat transfer coefficient (W m^{-2} K^{-1})
g	gravity acceleration (m s^{-2})
z	altitude (m)
RT	source term (W m^{-3})
v	speed (m s^{-1})
x	axial direction
V	volume (m^3)
l	axial length of the receiver (m)
l_b	focal length (m)
d	diameter (m)
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
f	friction factor
Ra	Rayleigh number
$b_{r\text{-}g}$	interaction coefficient
$P_{r\text{-}g}$	annulus gas pressure (mm Hg)
k	mean-free-path between collisions of a molecule (cm)
A	area (m^2)
F	view factor
U	perimeter (m)
K	incident angle modifier
I	solar irradiation heat (W)
R	coefficient matrix
T	temperature matrix
M	constant matrix

Greek symbols

ρ	density (kg m^{-3})
ρ_c	reflectivity of the mirror
ε	emissivity
τ	time (s)
τ_g	transmissivity of the glass
λ	thermal conductivity (W m^{-1} K^{-1})
Δ	incremental value
α	accommodation coefficient
$\alpha_{g\text{-}a}$	thermal diffusivity (m^2 s^{-1})
α_g	glass absorptivity for solar irradiation
α_r	absorber absorptivity for solar irradiation
γ	ratio of specific heats for the annulus gas
δ	molecular diameter of annulus gas (cm)
σ	Stefan Boltzmann constant (5.67 × 10^{-8} W m^{-2} K^{-4})
ν	kinematic viscosity (m^2 s^{-1})
β	volumetric thermal expansion coefficient (K^{-1})
η	efficiency
μ	dynamic viscosity (Pa s)

Subscripts

f	heat transfer fluid
r	absorber
g	glass cover
a	air
s	sky
b	support bracket
in	inner surface
ou	outer surface
$conv$	convection
$cond$	conduction
rad	radiation
p	plug into the absorber
i	node i
j	node j
std	standard temperature and pressure

Abbreviations

PTC	parabolic trough solar collector
1-D	one-dimensional
2-D	two-dimensional
3-D	three-dimensional
HCE	heat collection element
HTF	heat transfer fluid

parameters related to the model were discussed in it, as well as the model assumptions, limitations and proposals for improvement. Kalogirou et al. [6] considered conduction through the absorber pipe and glass cover at the same time in modeling. Odeh et al. [7] developed a model based on the absorber wall temperature, which can evaluate the collector performance with various kinds of working fluids. Kassem [8] simulated numerically the natural convection heat transfer between the absorber and glass envelope. A conclusion that the heat transfer can be optimized with a suitable eccentricity had been drawn. Li et al. [9] presented the hydrogen permeation model for PTCs. The least squares support vector machine (LSSVM) method was established to model and optimize the PTC system [10]. Gong et al. [11] combined an optimized 1-D model with a 3-D end model for PTCs, which showed a good accordance with the test data. Lu et al. [12] developed a non-uniform thermal model, both absorber and glass being divided into two regions for uneven solar radiation and temperature. He et al. analyzed the complicated coupled heat transfer process in PTC system by combination of Monte Carlo Ray Trace (MCRT) and Finite Volume Method (FVM) [13]. They proposed a more-detailed 3-D model [14]. Wu et al. [15] considered the non-uniform temperature distribution in their model, which was required to identify the causation of parabolic trough receiver's failure.

Various heat transfer mathematical models established by different scholars were not exactly the same although they were all based on energy balance. This paper summarized these 1-D mathematical models under different assumptions and details for PTCs. All the heat transfer processes have been discussed. In order to find the key to the accuracy of models, the simulated data were analyzed and validated with experimental data from Sandia National Laboratories [2]. A simple algorithm for solving the control equations was adopted. The 1-D models with diverse details were different in accuracy and complexity. A 1-D model may be more accurate, but more complicated. We can choose an appropriate 1-D model to investigate the thermal performance of PTCs under a certain condition. In addition, the most accurate 1-D model in this paper was compared with a 3-D model from other paper [13].

2. Heat transfer model

2.1. HCE introduction

HCE is a core component of a PTC, as shown in Fig. 2. It consists of an absorber pipe surrounded by a glass cover with bellows at each end. The annulus space between them is usually vacuum to reduce heat loss. The absorber is a metallic tube with a selective coating that has high absorptivity for solar radiation but low emissivity in long wave energy spectrum, and this can decrease thermal radiation loss. Thermal resistance of the selective coating is negligible for simplification [5]. The getter is used to absorb