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Closed-form modeling of direct steam generation in a parabolic trough solar receiver

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ABSTRACT

Solar thermal power is a promising and ever-growing source of carbon-free electricity. To date, analysis and design tools for solar thermal power generation with parabolic troughs are mathematically complex. We have developed a model of a solar parabolic trough, which advances the simulation of direct steam generators by describing their performance as a function of both time and axial position in closed form. We validate the model by comparing its predictions with data from the Direct Solar Steam (DISS) project, obtaining good agreement both temporally and spatially. The model predicts the profiles of fluid temperature, enthalpy, and quality as well as the lengths of each of the three different phase regions in the absorber. The formulation also yields the temperature profiles of the glass envelope and absorber wall. We further present the response to variable insolation. We propose this model as an engineering tool useful for preliminary modeling, sensitivity analyses, and benchmark solutions for more detailed studies of solar parabolic trough direct steam generators.

1. Introduction

Due to global climate change, it is critical to develop renewable energy that will meet future energy demand in an environmentally benign manner. Solar thermal power is a promising energy source in electricity generation. Traditional solar electricity generators use a heat exchanger for steam generation with a heat transfer fluid (HTF) such as oil or molten salt. The heat transfer fluid is heated in solar collectors such as parabolic troughs or central power towers. Direct steam generators (DSGs) produce the steam directly in the solar collector, eliminating the loop for the heat transfer medium. This configuration bears the following advantages compared with systems incorporating heat transfer media: lower investment and operating cost, reduced environment risk of HTF/oil leak, and reduced thermal losses in the heat exchanger [1].

The Direct Solar Steam (DISS) project based on DSGs was launched by a consortium of European research centers in 1996 [2]. This pilot-size facility (with 3000 m^2 of reflecting mirror surface and a total receiver length of 550 m) operated from 1997 to 2000 to investigate the technology and feasibility of direct solar steam generation. Located at Plataforma Solar de Almería, Spain; the DISS project consisted of three units, the solar field assembly, the steam production unit and the electricity generation block. The project demonstrated the feasibility of direct steam generation in horizontal parabolic trough collectors.

Mathematical modeling is important to extrapolate field experiences such as the DISS project [3] to commercial scale in a cost-effective manner. Modeling is likewise important to gain insight into the operating principles of energy processes. Many models of DSG in parabolic troughs that require numerical solution have been published. For example, Eck, Hirsch, et al. investigated the DSG process and built a dynamic model of a parabolic trough collector using the simulation tools Modelica, MATLAB and ANSYS [4–6]. Silva et al. simulated the one-dimensional thermal dynamic model to describe the fluid temperature along the longitudinal direction for the parabolic trough collector plant [7]. Roldan et al. investigated the temperature of absorber tubes in DSGs with the Finite Volume Method package FLUENT [8]. Yan built a dynamic model for the superheated steam generating process of DSGs [9]. Martinez et al. derived a two-dimensional model with the finite difference numerical method to investigate the temperature profile in the absorber of a direct steam generator [10]. The foregoing numerical solutions are accurate, comprehensive, and have contributed much to the analysis and design of DSGs. However, numerical solutions are unwieldy for rapid engineering calculations. An unsteady-state, closed-form model with spatial dependence would be useful for

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Nomenclature

a_1	constant in T_1 expression
a_3	constant in T_3 expression
A_e	cross-sectional area of the envelope
A_t	inside cross-sectional area of the absorber
b_1	constant in T_1 expression
b_3	constant in T_3 expression
c_a	heat capacity of the absorber
c_e	heat capacity of the envelope
$c_{p,k}$	heat capacity of the fluid in region k
$\overline{c_{p,k}}$	mean heat capacity of fluid in region k
CR_g	geometric concentration ratio of collector
D_{ai}	inner diameter of the absorber
D_{ao}	outer diameter of the absorber
D_{ei}	inner diameter of the envelope
D_{eo}	outer diameter of the envelope
f	stratification parameter
F	adjust factor
Fr	Froude number
g	acceleration of gravity
h_{2ph}	two-phase heat transfer coefficient
$\overline{h_{2ph}}$	averaged film heat transfer coefficient of region 2
h_{air}	convective coefficient from envelope to air
h_{ar}	radiation heat transfer coefficient between absorber and envelope
h_{er}	radiation heat transfer coefficient between envelope and sky
h_k	convective heat transfer coefficient between inside absorber circumferences in region k
$h_{\max}$	constant in $\overline{h_{2ph}}$ expression
$h_{\min}$	constant in $\overline{h_{2ph}}$ expression
H_0	enthalpy of feedwater
H_k	enthalpy in region k
H_{sl}	enthalpy of saturated water
H_{sv}	enthalpy of saturated steam
I	irradiance upon the envelope
$k_{f,k}$	thermal conductivity of fluid in region k
K_{IAM}	the incident modifier
L_1	position of boundary between liq. & two-phase flow
L_2	position of boundary between two-phase & vapor flow
L_m	mirrored length of collector
L_{tot}	total length of absorber
m_2	constant in H_2 expression
n_2	constant in H_2 expression
Nu_k	Nusselt number in region k
P_{ai}	inner circumferences of the absorber
P_{ao}	outer circumferences of the absorber
P_{ei}	inner circumferences of the envelope
P_{eo}	outer circumferences of the envelope
P_{in}	inlet pressure of absorber
P_{out}	outlet pressure of absorber
Pr_k	Prandtl number in region k
Q	net energy input
R	recirculation rate
Re_k	Reynolds number in region k
s_o	direct normal irradiance
t	time
T_0	feedwater inlet temperature
T_k, $T_{f,k}$	temperature of fluid in region k
T_{air}	ambient air temperature
$T_{e,k}$	temperature of the envelope in region k
$\overline{T_e}$	averaged envelope temperature
$T_{s,k}$	absorber surface temperature in region k
$\overline{T_{s,2}}$	average surface temperature in two-phase region
T_{sat}	steam saturation temperature
T_{sky}	effective sky temperature
u_k	velocity of the fluid in region k
u_0	mean velocity of the fluid
w_0	homogeneous mass flow rate of the fluid
w_{out}	mass flow rate after steam separator
w_{rec}	mass flow rate of recirculation stream
w_c	collector width
x	axial coordinate in absorber
X_k	steam quality in region k

Greek symbols

α_a	absorptance of the absorber
α_e	absorptance of the envelope
$\delta_{e,k}$	constant in $T_{e,k}$ of region k
$\delta_{s,k}$	constant in $T_{s,k}$ of region k
ΔH_{vap}	enthalpy of vaporation
ε_a	emissivity of the absorber
ε_e	emissivity of the envelope
$\Gamma_{s,2}$	constant in $\overline{T_{s,2}}$
γ	intercept factor of collector
$\gamma_{e,k}$	constant in $T_{e,k}$ of region k
$\gamma_{s,k}$	constant in $T_{s,k}$ of region k
η_o	optical efficiency of collector and envelope
μ_k	fluid viscosity in region k
θ_i	incident angle
ρ_a	density of the absorber
ρ_{col}	mirror reflectivity
ρ_e	density of the envelope
ρ_k	fluid density in region k
σ	Stefan–Boltzmann constant
τ_e	transmittance of the envelope
$\Omega_{s,2}$	constant in $\overline{T_{s,2}}$

initial or approximate analyses. While many models of DSG in parabolic troughs with numerical solutions have been published, existing closed-form models of DSG are either only related with absorber length in the steady state [11,12] or are unsteady state models without spatial dependence [5].

In this paper, we provide an unsteady, one-dimensional, and closed-form solution for direct steam generation in a horizontal parabolic trough. We then validate the model by comparing the presented result with data from the DISS Project [3,13]. Thus, the model that follows advances the simulation of direct steam generators by describing DSG performance as a function of both time and axial position in closed form. The simplified model is useful as an engineering tool for preliminary analyses, sensitivity studies, and benchmark solutions for more detailed studies.

2. Closed-form dynamic model

2.1. Model description

Fig. 1 shows the schematic of three segments of the absorber tube and the cross section of the absorber, including the evacuated glass envelope. We model the fluid in the absorber as a one-

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