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A quasi-dynamic simulation model for direct steam generation in parabolic troughs using TRNSYS

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HIGHLIGHTS

- Direct steam generation can improve the efficiency of parabolic-trough technology.
- A new simulation model for DSG in parabolic troughs is developed in TRNSYS.
- The new model addresses dynamic conditions with low computational resources.
- The tool can be used to perform annual production analyses for DSG solar plants.
- The results are validated with real data from a DSG test facility in Almería, Spain.

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ABSTRACT

This work describes and evaluates a new simulation model for direct steam generation in parabolic-trough solar collectors. In direct steam generation, water is heated and evaporated through a solar field to feed a steam Rankine cycle or an industrial process. However, the behaviour of the involved multiphase fluid poses some challenges to simulation models. The model explained in this work is based on a steady-state approach but deals with transient conditions such as start-up, shutdown and clouds in a reasonable computing time. A new simulation tool is implemented in the TRNSYS software environment by means of new components that are suitable to be integrated into a whole solar plant model in order to carry out long-term energy production analyses with low computational resources. The main advantages of the new quasi-dynamic approach include fast computation with satisfactory accuracy; consideration of thermal inertia when addressing transient conditions; and flexibility to use different types of collector or solar field configurations. The performance of the model is validated with real experimental data obtained from the DISS solar test loop in Plataforma Solar de Almería, Spain. This paper describes the modelling approach and summarizes the comparison of simulation results with measurements taken at the DISS facility.

1. Introduction

Solar thermal power plants based on parabolic-trough collectors are presently a successful technology for electricity generation, with more than 3000 MW_e installed and in operation around the world [1]. Most of them operate with synthetic oil as heat transfer medium in the receiver tubes, but recently other working fluids, such as water, are being investigated in order to improve the performance of parabolic-trough technology and avoid the environmental issues of synthetic oils [2]. In direct steam generation (DSG), water is heated and evaporated through the solar field to feed a steam Rankine cycle or an industrial process, such as cleaning, heating or distillation in the food and beverage sector [2], avoiding the need for heat exchangers and hence increasing the efficiency of the whole system [3]. In this way, DSG in parabolic-trough solar collectors is thought to be one of the most feasible options for the economic improvement of concentrating solar thermal technologies for either electricity generation or industrial process heat supply [4].

The feasibility of the DSG process in parabolic-trough collectors has been already proved in the DISS project [5] under real solar conditions, at pressures up to 10 MPa and temperatures up to 400 °C, with more than 10,000 h of operation. Nevertheless, the existence of single-phase (either water or steam) and two-phase

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Nomenclature

A	area of a surface, m^2
A_c	net collection area, m^2
A_{ml}	mean logarithmic area, m^2
Bo	Boiling number, –
Co	Convection number, –
c_p	specific heat capacity, J/(kg K)
D	diameter, m
E_b	direct normal solar irradiance, W/m^2
f	Darcy friction factor, –
F_{clean}	cleanliness factor, –
F_{sh}	shadowing factor, –
$\mathfrak{F}$	Chisholm proportionality factor, –
Fr_l	Froude number with all flow as liquid, –
g	standard gravity, m/s^2
G	mass flow rate per unit area, $kg/(m^2\ s)$
h	specific enthalpy, J/kg
$\mathscr{h}$	heat transfer coefficient, $W/(m^2\ K)$
Re	Reynolds number, –
Pr	Prandtl number, –
k	thermal conductivity, W/(m K)
$K(\theta)$	incidence angle modifier, –
L	length, m
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
p	pressure, Pa
$\dot{Q}$	thermal power, W
R	radius of pipe or elbow, m
$\mathfrak{R}$	Friedel proportionality factor, –
t	time, s
T	temperature, °C
v	fluid velocity, m/s
We_l	Weber number with all flow as liquid, –
$\dot{x}$	steam quality, –
z	height, m

Abbreviations

CFD	computational fluid dynamics
DISS	direct solar steam
DNI	direct normal solar irradiance (equivalent to E_b)
DSG	direct steam generation

Greek symbols

α	void fraction, –
Δ	difference or variation
$\eta_{opt,0^\circ}$	peak optical efficiency, –
θ	incidence angle, °
λ	latent heat of vaporization for water, J/kg
μ	dynamic viscosity, kg/(m s)
ξ	pressure loss coefficient for elbows, –
ρ	density, kg/m^3
σ	surface tension between liquid and steam, N/m

Subscripts

abs	absorber tube
acc	accessories
amb	ambient
2p	two-phase
g	vapour phase
in	inlet
l	liquid phase
out	outlet
rad	radiation

flow in the absorber pipes of solar collectors poses a challenge for the development of both simulation tools and control schemes suitable for this technology. Up to the present, several theoretical models have been applied to describe the behaviour of a DSG process. For instance, the works of Natan et al. [6], Minzer et al. [7] and Taitel and Barnea [8] propose simplified formulations based on quasi-steady-state approaches, flow pattern analyses or drift flux methods. Regarding pressure drop analysis, a numerical study [9] was carried out by comparing experimental data of pressure losses in the DISS loop with results of several empirical correlations. As a result, the modelling based on the correlations of Friedel [10] and Chisholm [11] shows the better performance and is suitable for designing DSG solar fields and implementing simulation tools.

A wide range of software tools has been used to implement simulation models for DSG in parabolic-troughs. For instance, Bonilla et al. [12] developed a dynamic object-oriented model for the DISS facility in the Modelica package that deals with chattering problem in two-phase flow. Hirsch et al. [13,14] presented another dynamic model coded in Modelica that simulates parabolic-trough loops with DSG in recirculation operation mode and includes some consideration of plant start-up and shutdown. Also, a one-dimensional model for DSG in complete solar collector rows under steady-state conditions [15] and a three-dimensional thermal model for DSG under superheated conditions [16] have been implemented in Matlab. Silva et al. describe an analysis of parabolic-trough plants for process heat applications [17], working with saturated steam, based on a co-simulation model [18] built by coupling several software environments.

Recently, software tools used in the nuclear industry have been applied to the simulation of DSG, such as RELAP in the work of Moya et al. [19] or ATHLET in the study of Hoffmann et al. [20], in order to apply the strict safety requirements of nuclear power plants. Besides, computational fluid dynamic (CFD) modelling has been used to overcome the limitations of classical approaches. For instance, CFD models have been implemented in ANSYS Fluent to analyse superheated steam in a single receiver tube [21] or to evaluate the heat transfer enhancement by inserting metal foams in all the receiver tubes [22]. Also, another model developed in the STAR-CCM+ software has shown a good performance for reproducing both static [23] and dynamic [24] behaviour of the whole DISS loop. However, due to their huge memory space requirements and high execution time, both CFD and nuclear industry tools are conceived to simulate short time periods and identify critical process conditions that may lead to anticipated failures.

The above-commented numerical models can reproduce the system response over a time period from a few hours to a day, but they are not intended to perform long-term simulations, such as monthly or yearly studies. Trying to provide an engineering tool for fast calculations of DSG, Xu and Wiesner developed a closed-form modelling [25] that can be useful for preliminary analyses. However, this model is considered to yield approximate results and does not address any pressure drop evaluation. On the other hand, the work of Elsafi [26] provides an accurate model for quick estimations of temperature and pressure drop in DSG loops by means of flow pattern analysis, but it is only focused on steady-state conditions. In summary, despite the great amount of models