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Modeling the dynamics of the multiphase fluid in the parabolic-trough solar steam generating systems

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ABSTRACT

Direct steam generation in parabolic-trough solar collectors has been under evaluation in recent years for its technical feasibility, process control and cost. Knowledge of the dynamic behavior of such system is particularly important as changes in inlet water conditions or in the solar radiation affect the amount of steam generated in the solar field. The process must therefore be controlled to ensure constant quality of produced steam. This work introduces a computational fluid dynamic simulation approach to predict the behavior of a solar steam generating system, which is located at the Plataforma Solar de Almería, Spain. The STAR-CCM+ code has been used to implement an efficient multiphase model capable of simulating the dynamics of the multiphase fluid in parabolic-trough solar collectors. Numerical and experimental data are compared in a wide range of working conditions.

1. Introduction

Solar steam generating systems using parabolic trough collectors (PTCs) have been in use since the 1970s and have experienced an important commercial deployment in the last decade, with the construction of several power plants around the world [1]. Thomas [2] summarizes the different design concepts existing for solar steam generating systems using PTCs, i.e. unfired boiler concept, flash boiler concept and direct steam generation (DSG) concept. Most of the commercial power plants are designed following the unfired boiler concept, which is a solar field configuration utilizing a heat transport loop that delivers hot synthetic oil from the solar collectors to the steam generator and recirculates the oil to the collectors via a circulating pump. More recently the feasibility of the direct steam generation process in PTCs has been proven in the DISS project [3,4] (see Fig. 1), under real solar condition at pressure up to 10 MPa and steam temperature up to 400 °C, with more than 10000 h of operation. The detailed engineering of any parabolic-trough solar field for DSG requires accurate understanding of the inherent thermo-hydraulic phenomena, and of their influence on the stability of the process and on the thermo-mechanical behavior of the absorber tubes.

In the DISS project, thermal–hydraulic behavior and system performance have been investigated for the so-called "once-through" configuration mode (see Fig. 2). In this solar field configuration feed water is preheated, evaporated, and converted into superheated steam as it circulates from the inlet to the outlet of the collectors' loops of a solar field [5].

Since the source of solar radiation cannot be manipulated, the heating process output must be controlled by regulating the system flow. The energy input is affected by several types of disturbances. These can be smooth, such as those produced by variations in the solar radiation on a clear day, or they can be fast and large, such as those due to clouds or changes in the inlet water conditions (temperature or pressure). Therefore, the main objective of the control system implemented in the test facility is to maintain steam at constant temperature and pressure, at the outlet of the solar field [6]. For this reason any variation in the inlet water conditions or in the solar radiation should lead to a change in the amount of steam produced by the system, but not in the steam quality.

Taitel et al. [7] proposed a simplified transient formulation for calculating dynamic behavior of two-phase flow in pipelines, which assumes a quasi-steady gas flow and a local equilibrium momentum balance. Steady state solutions for the case of flow in two parallel pipes were calculated by Natan et al. [8] by using flow pattern analysis, as well as a drift flux method. Minzer et al. [9] applied a simple model to account for the transient behavior following the approach of Taitel et al. [7]. In their work the heated pipe is subdivided into three parts, a subcooled liquid section close to the inlet, an evaporation section and a superheated section close to the exit. Average pressure drops and temperature changes are calculated for each section. Taitel and Barnea [10] presented a transient

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Nomenclature

$f(\varphi)$	normalized heat-flux distribution (dimensionless)
$\vec{f}$	external body forces (N)
g	gravitational acceleration (m/s^2)
h_j	enthalpy of the species j (J/kg)
h_{lat}	enthalpy of vaporization (J/kg)
k_{eff}	effective thermal conductivity (W/m K)
$\dot{m}_{ec}$	rate of interfacial mass exchange between the vapor and the liquid (kg/s m^2)
$\dot{m}_{ew}$	vapor mass generation on the heating surface (kg/s m^2)
n_p	Prandtl number exponent
p	pressure (MPa)
q_{bw}	surface boiling heat flux (W/m^2)
t	time (s)
$\vec{v}$	velocity vector (m/s)
C_{ew}	rate heat flux fraction used to create vapor bubbles (dimensionless)
C_l	flux concentration ratio (dimensionless)
C_p	specific heat capacity (J/kg K)
C_{qw}	constant dependent on the liquid/surface combination (dimensionless)
$C_{HTC\times Area}$	local heat transfer coefficient between the vapor and the surrounding liquid, multiplied by the interfacial area density (W/m^2 K)
E	energy transfer (J/kg)
Q	heat flux per unit area (W/m^2)
Q_{loss}	heat loss per unit area (W/m^2)
Pr	Prandtl number (dimensionless)
Re	Reynolds number (dimensionless)
Ref	mirrors reflectance (dimensionless)
S_{ct}	turbulent Schmidt number (dimensionless)
S_h	volumetric heat source (W/m^3)
S_m	mass source (kg)
T	temperature (°C)

Greek

θ	angle of incidence (degrees)
μ	liquid viscosity (kg/m s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
τ	transmittance of the absorber glass cover (dimensionless)
$\bar{\bar{\tau}}$	stress tensor (N/m^2)
$\bar{\bar{\tau}}_{eff}$	viscous stress tensor (N/m^2)

Subscripts

in	inlet
l	liquid
sat	saturation
v	vapor
w	wall

Acronyms

CFD	computational fluid dynamics
DISS	DIrect Solar Steam
DSG	direct steam generation
LHM	Local Homogeneous Model
MIT	Massachusetts Institute of Technology
MTD	maximum temperature difference
NSE	Nuclear Science and Engineering
NURBS	Non-uniform Rational B-Spline
PSA	Plataforma Solar de Almería
PTC	parabolic-trough solar collector
SQ	steam quality

model for flow rate distribution in evaporating parallel lines based on the drift flux formulation and solved it numerically.

Bonilla et al. [11] developed a dynamic object-oriented model to study the DISS test facility behavior using the Modelica package. The formulation adopted was optimized for short computing times and low CPU load.

Another dynamic modeling of a DSG parabolic-trough solar system is given by Hirsch et al. [12,13], and includes some consideration of plant start-up and shutdown. In this work the modeling was confined to studying the recirculation operation mode, which had been selected as the reference solution for the pre-commercial plant [14]. A satisfactory control system about the feed-forward strategy was also advised [15].

Fig. 1. View of one parabolic-trough solar collector of the DISS test facility.

Complete understanding of the dynamic behavior of the direct steam generation process is essential for proper operation of this type of solar plant. Given the relevance of the issue, and the limitations evidenced by the previously adopted modeling approaches, three-dimensional CFD modeling of the DSG process in parabolic-troughs is considered particularly advantageous, and is investigated in this work. Accurate CFD modeling could offer clear benefits in the detailed design of DSG solar collector fields. CFD can offer accurate modeling of thermo-hydraulic phenomena in the pipes of parabolic-trough collectors using water and steam as heat transfer medium and, in addition, it allows identifying critical process conditions that may lead to anticipated failures.

This paper is organized as follows: Section 2 details the characteristics of the experimental set up. Section 3 provides the description of the CFD modeling approach adopted to simulate the dynamic behavior of the DISS test facility. Section 4 summarizes the simulation results and includes a comparison with experimental data. Discussion of the results and conclusions are presented in Section 5.

2. Description of the experimental test-facility and input data

The experimental test facility (see Fig. 1) is formed by a single North–South oriented solar collectors' loop, composed of 11 units of parabolic-trough collectors connected in series, with a total length of 500 m (see Fig. 2). The experimental DISS test facility is located at the Plataforma Solar de Almería, Spain [3]. The PTCs in this solar field are type LS-3 (see characteristics in Table 1) and have a length of 50 m each with the exception of collectors #9 and #10, which are special test collectors with a length of 25 m.