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Steady-state and dynamic validation of a parabolic trough collector model using the ThermoCycle Modelica library

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ABSTRACT

Small-capacity (< 200 kW_{el}) concentrated solar power plants has been recognized as a promising technology for micro power applications. In particular, parabolic trough collectors have been identified as the most promising focusing technology. In this context, physics-based dynamic model of parabolic trough constitutes a significant tool for the further development of the technology, allowing to evaluate and optimize response times during transients, or to implement and test innovative control strategies. In this contribution, the dynamic model of a parabolic trough line based on the ThermoCycle Modelica library is validated against steady-state and transient experimental results from the parabolic trough test loop available at the Plataforma Solar de Almería, Spain. The simulation results are in good agreement with the measurements, both in steady-state and in transient conditions. The validated model is readily usable to investigate demanding dynamics-based problems for low capacity solar power systems.

1. Introduction

Recent studies have envisaged the potential of small-capacity (< 200 kW_{el}) concentrated solar power (CSP) plants in case the future distributed energy scenario is considered (Casati et al., 2012; Prabhu, 2006). The first documented CSP systems date back to the end of the 10th century (Butti and Perlin, 1980). Several CSP systems were developed and tested during the years, and the first commercial plants were built in the 80s in California, USA (IEA-ETSAP and IRENA, 2013). The main collector technologies are point-focus single parabolic dishes, solar towers, and line-focusing parabolic troughs, vacuum tube or non-concentrating flat plate collectors (Winter et al., 1991). Non or low-concentrating configurations are particularly attractive for small-scale power units, as the lower investment costs may lead to economic viability. In particular, parabolic trough collectors (PTCs) are suited to supply low or medium temperature thermal energy to generate electricity in combination with low-temperature organic Rankine cycle (ORC) engines (Verneau, 1978; Angelino et al., 1984).

PTCs are by far the most mature solar concentrating technology, as commercially demonstrated (Fernández-García et al., 2010). A PTC is a line-focusing parabola-shaped mirror which concentrates direct solar radiation on the absorber tube, located in the parabola's focal line. A heat transfer fluid (HTF) is pumped through the absorber tube acquiring thermal energy from the concentrated solar radiation. Parabolic trough solar thermal power plants commonly use thermal oil as HTF. These systems have been significantly improved since the first commercial implementation (Canada et al., 2005), and, in recent years, water has been tested as HTF in the collectors. The technology, called Direct Steam Generation (DSG), generates superheated steam directly from the collectors and presents important challenges due to phase changes in the HTF (Bonilla et al., 2015).

Due to the non-constant nature characterizing the direct solar irradiation, specific control strategies ensuring safe and optimal operation of the CSP systems in any conditions are required. In order to design effective control strategies, the dynamics of the CSP plant must be investigated. To this end, it is fundamental to study the transient related to the solar field. In the literature, dynamic models of PTCs are mainly one-dimensional in flow direction and date back to the late 70s. The Finite Volume (FV) method is the preferred approach for the discretization of the absorber tube, while Moving Boundary (MB) models have been developed for the modelling of DSG plants.

Ray (1981) presented in 1980 a non-linear dynamic model of a parabolic trough unit for DSG. The FV discretization approach was adopted and the transient responses of the model under different step

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Nomenclature

Acronyms

CSP	concentrated solar power
PTC	parabolic through collectors
ORC	organic Rankine cycle
HTF	heat transfer fluid
DSG	direct steam generation
FV	finite volume
MB	moving boundary
PSA	Plataforma solar de Almería
HCE	heat collection element
CV	control volume
TT	temperature transmittance
DNI	direct normal irradiation
ETC	EuroTrough collector
SF	solar field
EI	exogenous inputs
IAM	incidence angle modifier
PCE	percentage computational effort

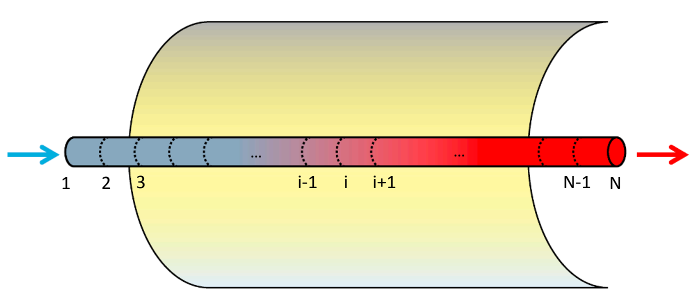
Subscripts

su	supply
ex	exhaust
conv	convection
amb	ambient
sol	solar
rad	radiation
ext	external
int	internal
meas	measured
el	electrical
wf	working fluid

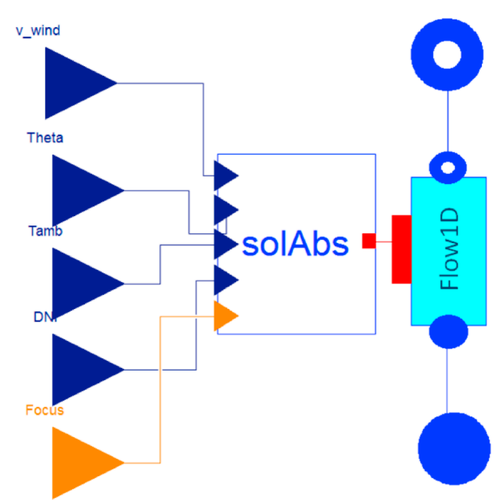
Symbols

p	pressure (bar)
T	temperature (°C)
V_s	volume (m^3)
$\dot{q}$	heat flux ($kW\,m^{-2}$)
M	mass (kg)
h	specific enthalpy ($kJ\,kg^{-1}$)
ρ	density ($kg\,m^{-3}$)
$\dot{m}$	mass flow ($kg\,s^{-1}$)
C_p	specific heat capacity ($kJ\,(kg\,K)^{-1}$)
A	area (m^2)
D	diameter (m)
N	number of nodes (–)
$\bar{\varepsilon}$	relative error (%)
E	energy (kJ)

disturbances were presented as typical results. Hirsch et al. (2005) and Eck and Hirsch (2007) developed one of the first Modelica PTC models. A FV based solar collector model of a DSG plant was introduced together with a preliminary validation based on the first experimental results of the DISS facility at the Plataforma Solar de Almería (PSA), Spain. More recently, a tri-dimensional non-linear dynamic thermo-hydraulic model of a PTC was developed in Modelica and coupled to a solar industrial process heat plant modelled in TRNSYS (Silva et al., 2013). A DSG PTC model was validated against results from the DISS facility, in Lobón (2014), showing a good agreement. Several dynamic models of CSP plants were developed in Modelica based on the ThermoSysPro library (Hefni, 2014). A full scale dynamic model of a parabolic trough power plant with a thermal storage system was presented in Al-Maliki et al. (2016a); simulation results were compared to experimental data from the real power plant. This work was extended in Al-Maliki et al. (2016b) including the power block and all the automation processes, simulated results were compared to measured data from an existing solar power plant. A simulation model for DSG in PTCs was developed in TRNSYS (Biencinto et al., 2016), results were validated with real data at the DISS facility. A thermal hydraulic RELAP5 DSG PTC model was validated against the DISS facility in Serrano-Aguilera et al. (2017), a new experimental correlation for heat losses



(a)



(b)

Fig. 1. Parabolic trough collector model in ThermoCycle. (a): One-dimensional finite-volume modelling of the PTC. (b): Object diagram of the solar collector model from the GUI of Dymola.