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Dynamic simulation of integrated rock-bed thermocline storage for concentrated solar power

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Abstract

In contrast to wind and photovoltaic, concentrated solar power plants can be equipped with thermal energy storage in order to decouple intermittent energy supply and grid feed-in. The focus of this study is the technical evaluation of a cost-efficient storage concept for solar tower power plants. Consisting of a quartzite-rock bed that is charged with a hot air flow and discharged by cold air counter-flow, the storage essentially operates like a regenerator. For such systems, the discharge temperature typically declines with time. Furthermore, the use of a randomly packed bed results in considerable pressure loss. In order to describe the relevant flow and heat transfer mechanisms in rock beds used for thermal storage, a mathematical model written in the modelling language Modelica is developed and validated. Good agreement with experimental data from literature is obtained. With the aid of the validated model, a rock-bed thermal storage for application in a semi-industrial scale solar power plant (1.5 $\mathrm{MW_{el}}$) is designed and optimised with respect to electrical efficiency of the plant during the charge and discharge cycle. The storage capacity is equivalent to four hours of full-load operation. Results show that compressor work should be considered directly in the selection of packed-bed geometry in order to minimise the efficiency penalty of storage integration in the solar plant.

Keywords: Rock-bed thermal storage; Dynamic simulation; Pressure loss; Concentrated solar power

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1. Introduction

Increased penetration of the electricity market by renewable energy has recently drawn public attention to two major issues: Firstly, wind turbines and photovoltaic modules naturally provide a volatile feed-in requiring a conventional power plant reserve in order to balance current supply and demand within the grid. Secondly, competitiveness of renewable power plants is affected by the typically low annual utilisation with respect to nominal capacity. Concentrated solar power (CSP) plants are capable of decoupling solar radiation and electrical power output by using thermal storage devices. System-level simulation shows that the integration of a 6-h thermocline storage system in a CSP plant will almost double the annual capacity factor (Flueckiger et al., 2014). Hence, the development of efficient storage technologies and their optimisation for specific applications is essential for improved cost-efficiency of CSP plants and for the integration of large renewable shares in the energy system. Availability of accurate simulation tools is expected to be a key factor in this effort.

Generally, thermal energy storage (TES) is classified according to sensible, latent and chemical storage concepts (Gil et al., 2010). Kuravi et al. (2013) published an extensive review of the various TES technologies applicable

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Nomenclature

A	area (m^2)
Bi	Biot number (–)
c	specific heat capacity (kJ/(kg K))
c_p	isobaric heat capacity (kJ/(kg K))
d_p	particle diameter (mm)
D	packed bed diameter (m)
h	specific enthalpy (kJ/kg)
H	packed bed height (m)
k	convective–conductive heat transfer coefficient (W/(m^2 K))
$\dot{m}$	mass flow rate (kg/s)
n_poly	polytropic exponent (–)
N	number of grid points (–)
Nu	Nusselt number (–)
p	static pressure (Pa)
P	power (kW)
Pe	Péclet number (–)
Pr	Prandtl number (–)
Q	design capacity (MWh)
$\dot{Q}$	heat flow (W)
Re$_\mathrm{p}$	particle Reynolds number (–)
T	temperature (°C)
t	time (s)
u	axial fluid velocity (m/s)
V	volume (m^3)
w	specific work (kJ/kg)
W	work (kJ)
x	axial position (m)
α	convective heat transfer coefficient (W/(m^2 K))
ε	void fraction (–)
η	dynamic viscosity (kg/(ms))
η_el	electrical efficiency (%)
η_Rankine	gross efficiency of the water/steam cycle (%)
η_th	thermal efficiency (%)
η_is	isentropic efficiency (–)
λ	heat conductivity (W/(mK))
ρ	density (kg/m^3)
χ	moisture content (%)
Ψ	numerical error tolerance (–)

Subscripts

amb	ambient
aux	auxiliary
cross	cross-section
eff	effective
el	electrical
f	fluid
i	index
in	inlet
l	linear
out	outlet
res	residual
s	solid
th	thermal
w	wall
0	based on empty-tube velocity
α	convection

Abbreviations

const	constant
CSP	concentrated solar power
DASSL	Solver for partial-differential equations based on predictor-corrector methods
HTF	heat transfer fluid
SG	steam generator
TES	thermal energy storage

to CSP plants. Chemical storage requires endothermic chemical reactions that need to be fully reversible for recovering the potential energy stored in molecular bindings. Latent storage uses the enthalpy difference required for material phase change, rendering the choice of suitable materials according to temperature crucial. Albeit the concept with the lowest energy density, sensible heat storage is a technically mature approach used in widespread applications. For CSP plants using molten salt as heat transfer fluid (HTF), Electric Power Research Institute (2010) concluded that a 24% average reduction of TES investment costs could be reached by replacing a conventional two-tank molten-salt storage with a sensible rock-bed storage. A packed bed of rocks has also been repeatedly proposed as thermal storage for air-based central-receiver solar plants (Heller and Gauché, 2013). Among the major advantages of air as HTF are the elimination of process temperature restrictions for conventional HTFs such as mineral oil (304 °C, cf. Radosevich and Wyman, 1983) and molten salt (565 °C, cf. Moore et al., 2010), abundance and cost-effectiveness of the working fluid and simplicity of storage operation. No additional heat exchanger is required and chemical inertia of the system permits to choose economical construction materials. As a downside, the specific heat capacity is lower compared to conventional HTFs so that larger air mass flows are required, which translates into increased demand of auxiliary energy. Due to the small heat transfer coefficient compared to oil and molten salt, the efficiency of the air-based thermal storage is lower (Cascetta et al., 2014).

A great number of studies on packed beds for thermal storage application are available in the literature, but most of them are concerned with laboratory-type spherical particles. Some researchers also investigated structured packed beds of bricks and concrete blocks (Sagara and Nakahara, 1991; Singh et al., 2006; Kuravi et al., 2013) as well as the combination of packed beds with phase change materials (Zanganeh et al., 2014; Nithyanandam