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Transient thermo-mechanical analysis of steam generators for solar tower plants

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HIGHLIGHTS

- Thermal-stress modeling of the steam-generator dynamic behavior for a solar tower plant.
- The highest stresses occur in the superheater tubesheet junction.
- High stresses were found under part-load conditions instead of nominal conditions.
- Start-up takes between 50 min and 110 min, depending on the steam-generator initial-condition.
- Between 600 tons and 716 tons of hot salt are needed for the start-up procedure.

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ABSTRACT

In solar power tower plants, fast start-ups and/or load changes are mandatory to increase the power plant dispatchability. The high temperatures of the working fluids and the partial-load operation will reduce the lifetime of the thick-walled components at the steam generator. Therefore, a proper heat exchanger design should consider the stress evolution during the transient operation of the plant.

This work addresses, for the first time, a methodology to determine the dynamic behavior of all heat exchangers of a steam generator train. The methodology proposed here is a powerful tool for the design of solar power plants. The stress analysis model identifies the most important components of the steam generation train during transient operation. The methodology consists of the combination of analytical models to obtain the coupled response of the steam generation train from the following dynamic variables: temperature, pressure and stress.

An example of this methodology is presented for two start-up initial conditions: the assumption of non-isothermal and isothermal temperature profiles of the heat exchangers. A steam generator train based on conventional shell and tube heat exchangers is analyzed. The analysis shows that the non-isothermal condition takes approximately 50 min to reach nominal conditions, whereas the isothermal condition takes approximately 110 min, requiring 600 tons and 716 tons of hot salt to perform the start-up procedure, respectively.

1. Introduction

In recent years, significant effort has been made to reduce the operation and investment costs of concentrating solar power (CSP) plants. One of the main differential features with respect to other renewable technologies, such as photovoltaics or wind, is the flexibility provided by CSP when integrated with a thermal energy storage (TES) system. This increases the economic competitiveness of these power plants. On the one hand, the increase of the capacity factor diminishes the cost per unit of energy produced. On the other hand, the instantaneous solar source is decoupled from the electricity generation and therefore can be delivered on demand. Then, CSP with a TES system enhances the possibility of participating in grid balancing services [1]. In this manner, these plants may be considered as dispatchable, and therefore, improvements in the flexibility by means of fast start-ups and/or load changes may lead to additional revenue [2]. Moreover, fast start-ups are especially interesting for CSP plants due to the increase of the annual electricity production [3,4]. However, the start-up and/or load change ramps are limited by the thermal stresses in thick-walled parts of the steam generator (SG) and/or steam turbine. These thermal changes may produce fatigue and/or creep damage in the SG [5]. For this reason, considerable effort should be made to develop dynamic

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Nomenclature

Abbreviations

CCPs	combined-cycle plants
CSP	concentrating solar plants
EV	evaporator
FEA	finite element analysis
FW	feed water
HP	high pressure
HPT	high-pressure turbine
HRSG	heat recovery steam generator
HTF	heat transfer fluid
HT	hot tank
Hx	heat exchanger
LP	low pressure
LPT	low-pressure turbine
PH	preheater
R	receiver
RH	reheater
SG	steam generator
SH	superheater
SPTP	solar power tower plant
TES	thermal energy storage
UTS	ultimate tensile strength

Symbols

A	heat transfer area (m^2)
A_c	cross-section area (m^2)
C	specific heat capacity (kJ/kg K)
C_m	dimensionless thermal capacitance of a metal wall (-)
D	diameter (m), characteristic time constant (-)
E	modulus of elasticity (MPa)
F	force (N)
I	moment of inertia (m^4)
K	stiffness (N/m)
K'	inverse of stiffness (m/N)
L	length (m), characteristic length constant (-), level (m)
L_{tp}	tube pitch (mm)
L_{ts}	tubesheet thickness (m)
M	mass (kg), moment (N m)
P	pressure (Pa)
R	radius (m)
R_{otl}	radius of a circle circumscribed to the outermost tube of a bundle (m)
T	temperature (°C)
T	dimensionless temperature (-)
V	volume (m^3), vertical force (N)
W_t	turbine power (MWe)
a	thermal diffusivity (m/s^2)
h	convective coefficient (W/m^2 °C)
i	specific enthalpy (J/kg)
l_{ts}	tubesheet thickness (mm)
$\dot{m}$	mass flow rate (kg/s).
t	time (s)
t_j	thickness of component j (m)
t	dimensionless time (-).
r	radial coordinate (-)
u	specific internal energy (kJ/kg)
y	vertical displacement (m)
z	axial coordinate (-)

Greek symbols

α_t	thermal stress concentration factor (-)
α_m	pressure stress concentration factor (-)
β_t	linear thermal expansion coefficient (1/K)
θ	rotation angle (°)
ν	Poisson's ratio (-)
ρ	density (kg/m^3)
σ	stress (MPa)
ψ	U-tube stress concentration factor (-)

Subscripts

0	nominal conditions
ave	average
atemp	attemperator
b	bending
cyl	cylinder
d	drum
dc	downcomer
h	head
i	inlet, inner
m	metal
i	inlet
o	outlet, outer
r	riser
rec	recirculated
s	shell
sa	salt
sat	saturated
st	steam
su	surface
t	tube
tp	tube pitch
ts	tubesheet
w	water

models that consider the lifetime of the heat exchangers. These models allow the study of different strategies for operating the plant on the safety-side while saving energy during the start-up and shutdown processes.

One of the main features of solar power tower plants (SPTPs) is their higher operating temperatures compared to parabolic trough and linear Fresnel plants [2]. This leads to an increase in the thermal efficiency of the power block, which also reduces the specific costs. Examples of the feasibility of CSP technology are Gemasolar [6], Crescent Dunes [6] and Suncan Dunhuang [6], the three large-scale SPTPs currently in operation. However, other technologies, such as fire-boilers or combined-cycle plants (CCPs), work at similar temperatures to CSP plants. One of the main differences between conventional and CSP plants appears in the SG. The heat exchangers of the SG are based on conventional shell and tube designs. These heat exchangers are sized by means of analytical methods proposed by TEMA standards [7] and/or ASME code Section VIII-Div1 [8] considering the operation at nominal conditions [9]. Then, because the SG will be operated with daily start-ups, load changes and shutdowns, a transient stress analysis is required. Moreover, no specific guidelines are proposed in the TEMA standards and/or ASME code for complex zones, such as the tubesheet, when: transients thermal loadings occur [10], temperature gradients on the junction appear [11] or the tubesheet has a non-standard design [12]. Therefore, these issues must be accomplished by finite element analysis or by complex analytical methods to obtain accurate results.

Start-up and shutdown operations become critical to the creation of