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Thermo-economic optimization of molten salt steam generators

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ABSTRACT

This paper presents a methodology to guide the design of heat exchangers for a steam generator in a solar power tower plant. The low terminal temperature difference, the high fluid temperatures and the high heat duty, compared to other typical shell and tube heat exchanger applications, made the design of the steam generator for molten-salt solar power towers a challenge from the thermomechanical point of view. Both the heat transfer and the thermal stress problems are considered to size the preheater, evaporator, superheater and reheater according to the TEMA standards and ASME Pressure Vessel code. An integral cost analysis on the steam generator design effects on the power plant performance reveals an extremely low value for the optimum evaporator pinch point temperature difference. Furthermore, an optimization using genetic algorithms is performed for each heat exchanger, which leads to economical and feasible designs.

A 110 MWe solar power tower plant is studied. Two configurations of the steam generator are proposed: with one or two trains of heat exchangers. The results show that the optimum pinch point temperature differences are very close to 2.6 °C and 3 °C for the steam generator with one and two trains, respectively. The proposed design of the steam generator consists of a U-shell type for superheater and reheater, a TEMA E shell forced circulation evaporator and a TEMA-F shell preheater. Also, the approach point temperature difference analysis is performed to avoid subcooled flow boiling in the preheater. An economic study to compare forced and natural circulation evaporator designs is carried out.

1. Introduction

Commercial concentrating solar plants normally include an indirect steam generator (SG) system in which the energy is transferred by means of a heat transfer fluid (HTF) to produce steam. Typically, a SG includes four heat exchangers: superheater, reheater, evaporator and preheater. Additionally, the SG includes the steam drum, feed-water pumps, hot salt pumps and supporting systems. A conventional shell and tube heat exchangers are normally selected for the SG. The intermittent operation conditions, the high working temperatures and the large mass flow rates associated present significant issues for heat exchanger designers.

Different studies for the design of molten-salt SGs of solar power tower plants (SPTPs) are available in the literature. The design requirements consider the material selection, geometric parameters and overall performance [1]. Other design guidelines also include the economical evaluation of the SG [2]. In both cases, these design recommendations analyze the SG design for a 100 MWe commercial SPTP. In spite of Foster Wheeler recommendations [1], a different approach is accomplished for the SG design of the experimental facility Solar Two [3] and Molten Salt Electric Experiment (MSEE) [4], showing that the SG design is a wide open research field.

The SG design depends also on the manufacturer. In this sense, several SG solutions proposed by different manufacturers were analyzed for a 100 MWe commercial solar power plant in [2]. For instance, ABB Lummus [2] design includes a kettle evaporator and U-tube/straight shell heat exchangers. The salt is placed on the shell side in the superheater and preheater, whereas in the reheater the salt is placed on the tube-side. The superheater design is divided into two shells in series in order to decrease the thermal stress in the tubesheet. The SG design proposed by ABB Lummus presents the lowest cost compared to other manufactures. Struthers Wells [2] uses the same concept as ABB Lummus employing a kettle evaporator and U-tube/straight shell heat exchangers. The principal feature of this design is that the high-pressure water is placed on the shell side in all heat exchangers. This leads to high thicknesses, and thus, high thermal inertia. On the other hand, Foster Wheeler [1,2] proposes a straight tube/straight shell design with the molten salt placed on the shell side. In this design, the inlet and outlet streams pass through different tubesheets,

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Nomenclature

Abbreviations

B&W	Babcock and Wilcox
CT	cold tank
CSP	concentrating solar plants
ESDU	engineering science data unit
EV	evaporator
FW	feed water
GA	genetic algorithm
HEN	heat exchanger network
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
MSEE	molten salt electric experiment
OSV	onset of significant voids
PH	preheater
REC	receiver
RH	reheater
SAM	system advisor model
SG	steam generator
SH	superheater
SPTP	solar power tower plant
TAC	total annualized cost (€/year)
TES	thermal energy storage

Symbols

A	heat transfer area (m^2)
B_c	baffle cut (–)
C	cost (€)
Cp	specific heat capacity (J/kg °C)
D	diameter (m)
H_y	annual plant operation time (h/year)
K	resistance coefficient (–)
L	length (m)
L_{bc}	baffle spacing (m)
L_{tp}	tube pitch (mm)
N_b	number of baffles (–)
N_{hot}	number of hot starts
N_{warm}	number of warm starts
N_{tp}	number of tube passes (–)
N_{tt}	number of tubes (–)
N_s	number of shells (–)
P	pressure (Pa)
Q	heat (W)
R	fouling resistance (°C m^2/W)
$R_{\min}$	U-tube minimal radius (mm)
S	stream flow area (m^2)
T	temperature (°C)
U	global heat transfer coefficient (W/m^2 °C)
W	weight (kg)
h	convective coefficient (W/m^2 °C) or
i	specific enthalpy (J/kg)
l_{ts}	tubesheet thickness (mm)
$\dot{m}$	mass flow rate (kg/s)
pc	penalty coefficient (–)
q_w	local heat flux (W/m^2)
t_s	shell thickness (m)
v	velocity (m/s)
$\mathbf{x}$	vector of optimization variables (–)
$\mathbf{y}$	vector of feasible constraints (–)

Greek Symbols

ΔS_{h-c}	hot and cold leg overhand difference (mm)
η	efficiency (–)
θ_{tp}	tube layout (°)
ρ	density (kg/m^3)
ϕ_v	viscosity correction factor (–)

Subscripts

dc	downcomer
r	riser
s	shell
sat	saturated
sub	subcooled
t	tube
ti	inside of tube
w	window zone
x	cross-flow zone

avoiding the potential temperature gradients in the no-tube passes zone. The differential thermal expansion is accommodated by floating tubesheets. Furthermore, a natural circulation design is selected for the evaporator. The design proposed by Babcock and Wilcox (B&W) [2] consists of U-tube/U-shell heat exchangers with the molten salt placed on the shell side. Similarly to the straight tube/straight shell design, the U-shell design also avoids temperature gradients produced by inlet and outlet streams. In addition, the U-shaped tubes can expand or contract in response to the thermal expansion between tubes and shell without the need of floating tubesheets. The main disadvantage is that the U-shell design presents relative high costs. A forced circulation evaporator is selected instead of natural circulation evaporator.

In spite of these useful recommendations shown in [2], several design parameters such as velocities, pressure drops or tube diameters of the heat exchangers are missing. Nevertheless, these recommendations were used for the SG design of the experimental facility Solar Two [3]. Some problems appeared in Solar Two. On the one hand, problems related to the stress corrosion materials appeared in such facility. For this reason, higher corrosion resistance materials for SG have been recommend by different authors [5,6]. On the other hand, further problems related to the salt freeze inside of the tubes of the kettle evaporator occurred in Solar Two [7], pointing out the difficulties found in the industry to design and operate SG systems.

Most recent studies have been made for higher SPTPs capacities where a prelaminar SG design can be found. Kolb [8] carried out a study to increase the efficiency of these plants. The SG sizing for 160 MWe subcritical and supercritical steam-cycles was calculated including the associated heat transfer areas and pressure drops. Kelly [9] proposed different strategies to reduce the levelized cost of electricity using supercritical heat transport fluids for central receiver power plants. The sizing and cost analysis of subcritical and supercritical SGs for 400 MWe plants were also studied.

Recently, genetic algorithms (GA) have been used extensively as an optimization method in the heat exchanger design. For instance, Caputo et al. [10] and Sadeghzadeh et al. [11] performed a cost design optimization of shell and tube heat exchanger using GA. Their results show significant cost reductions over heat exchangers designed using traditional methods. Hajabdollahi et al. [12] used both GA and particle swarm method to optimize the cost of a shell and tube heat exchanger condenser. They claim that GA provides