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Optimization of concentrating solar thermal power plant based on parabolic trough collector

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ABSTRACT

Concentrating solar power (CSP) plant with parabolic trough collector (PTC) using synthetic or organic oil based heat transfer fluid is the most established and commercially attractive technology. In this paper, extensive energy and economic analysis of PTC based CSP plants, without storage, are reported. Effects of turbine inlet pressure, turbine inlet temperature, design radiation, plant size, and various modifications of Rankine cycle on overall efficiency as well as levelized cost of energy are studied. Furthermore, the variation in optimal turbine inlet pressure with turbine inlet temperature, design radiation, plant size, and various modifications of Rankine cycle are also analyzed. Energy and cost optimal turbine inlet pressures for 1 MWe plant (with basic Rankine cycle) are about 4.5–7.5 MPa and 3.5–7.5 MPa, respectively. The optimum pressure is observed to be a weak function of design solar radiation. The overall efficiency increases and levelized cost of energy decreases with increase in turbine inlet temperature, plant size and various modifications of the Rankine cycle.

1. Introduction

Concentrating solar power (CSP) is one of the viable options among renewable energy technologies (Krishna Priya and Bandyopadhyay, 2013). There are mainly four commercially available CSP technologies: parabolic trough collector (PTC), linear Fresnel reflector (LFR), solar power tower (SPT) and paraboloid dish. Among these technologies, PTC with synthetic or organic oil based heat transfer fluid (HTF), is the most established and commercially attractive technology (Purohit et al., 2013). In such a plant, the temperature limit is about 400 °C with a resulting steam temperature, at turbine inlet, of about 370 °C (Al-Soud and Hrayshat, 2009). However, if molten salt is used as a working fluid then the steam temperature up to 540 °C is achievable, which may lead to higher steam turbine efficiency (Zaversky et al., 2013). Direct steam generation (DSG) in the PTC field is also an economically viable option (Zarza et al., 2002).

The second most installed CSP technology after PTC is SPT (Zhang et al., 2013). SPT plant uses DSG (Müller-Steinhagen and Trieb, 2014) or molten salt as HTF (Caceres et al., 2013). Franchini et al. (2013) have presented the comparative analysis of CSP plants with PTC and SPT technologies. A detailed review on heliostat layout design (Collado and Guallar, 2013), central receiver design (Behar et al., 2013), and SPT technology based CSP plants (Ho and Iverson, 2014) have been reported in literature. LFR field with DSG has been proposed as a cheaper alternative because of flat mirrors and structural advantages (Nixon et al., 2013). However, it has a lower optical efficiency compared to PTC field (Zhu et al., 2014). Giostri et al. (2012a) and Morin et al. (2012) have presented the comparative analysis of CSP plants with PTC and LFR technologies. A paraboloid dish system is the least applied CSP technology for power generation (Sharma, 2011).

Heat storage is an important option to improve the stability and reliability for a CSP plant. Analysis of CSP plant using molten salt (Manenti and Ravaghi-Ardebili, 2013), molten salt and quartzite rock (Flueckiger et al., 2014), and phase change materials (Roget et al., 2013) based storage have been reported in literature. A detailed review on thermal energy storage technologies for CSP plants have been presented by Kuravi et al. (2013) as well as Tian and Zhao (2013). Dynamic simulation model with thermal energy storage has also been developed by Llorente García et al. (2011).

Selection of type and size of solar field, power cycle parameters, and sizing of power block are the most important aspects in designing a CSP plant. Several studies on optimization of different parameters for PTC based CSP plant are reported. Economic optimization of design radiation, the direct normal irradiance (DNI) at

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Nomenclature

A_p	aperture area of the collector (m^2)
C	Cost ($)
d	discount rate
E	annual electricity generation (kWh/y)
h	specific enthalpy (J/kg)
I	aperture effective direct normal irradiance (W/m^2)
m	mass flow rate (kg/s)
n	life time (y)
P	power (W)
Pr	pressure (MPa)
Q	heat flowrate (W)
T	temperature (°C)
U_l	heat loss coefficient based on aperture area ($W/(m^2 \cdot K)$)
x	dryness fraction

Greek symbols

Δ	difference
η	efficiency
θ	incidence angle (°)

Abbreviations

CSP	concentrating solar power
DNI	direct normal irradiance
DSG	direct steam generation
HTF	heat transfer fluid
LCOE	levelized cost of energy
LFR	linear Fresnel reflector
LPT	low pressure turbine
PTC	parabolic trough collector
SPT	solar power tower
TAC	total annualized cost

Subscripts

a	ambient
AR	annual replacement
CL	collector
D	design
HTF	heat transfer fluid
hx	heat exchanger
in	inlet
is	isentropic
m	mean
max	maximum
min	minimum
o	optical
O&M	operation and maintenance
opt	optimum
out	outlet
th	thermodynamic
u	useful

which plant produces the rated power output, has been presented by Montes et al. (2009). Effects of design radiation on capacity factor and dumped energy, for a PTC based CSP plant without hybridization and thermal storage, have been demonstrated by Sundaray and Kandpal (2013). Recently, Desai et al. (2014) reported a methodology to determine the optimum design radiation for CSP plant without hybridization and thermal storage.

García-Barberena et al. (2012) have evaluated different operational strategies using SimulCET computer program. Reddy and Kumar (2012) have presented modeling of PTC field as well as feasibility study of stand-alone PTC based CSP plant with HTF and DSG for various places in India. Kumar and Reddy (2012) have carried out energy, exergy, environmental, and economic analyses of stand-alone DSG based CSP plant of different sizes. Giostri et al. (2012b) have compared the PTC based CSP plants using conventional HTF, molten salt, DSG, DSG-HTF, and DSG-molten salt as working fluid and reported annual overall efficiency of 15.3%, 16.2%, 17.9%, 16%, and 17.8%, respectively. Probabilistic modeling of PTC based CSP plant has also been reported by Zaversky et al. (2012).

Conventional steam Rankine cycle is the most widely used power generating cycle in CSP plants. Many researcher have evaluated the performance of steam Rankine cycle in PTC based CSP plants (e.g., Manzolini et al., 2011; Desai et al., 2013). Fernández-García et al. (2010) have presented a survey of CSP plants with steam Rankine cycle for power generation. Kibaara et al. (2012) have analyzed the dry and wet cooled steam Rankine cycle based CSP plants and concluded that in case of a dry cooled plant, compared to a wet cooled plant, the capital cost and the levelized cost of energy (LCOE) are increased by 5% and 15%, respectively. Reddy et al. (2012) have reported increase in energetic and exergetic efficiencies by 1.49% and 1.51% with increase in turbine inlet pressure from 90 bar to 105 bar, respectively. It may be noted that, the dryness fraction of steam at the outlet of low pressure turbine (LPT) decreases with increase in turbine inlet pressure. Subsequently, the isentropic efficiency of the LPT also decreases. However, the isentropic efficiency of turbine has been kept constant during the analysis (Reddy et al., 2012). Al-Sulaiman (2013) has presented energy analysis of a typical 50 MWe PTC based CSP plant using a steam Rankine cycle as well as with steam Rankine cycle as a topping cycle and an organic Rankine cycle as a bottoming cycle. The effects of different design parameters on the size of solar field have been studied.

In this paper, extensive energy and economic analysis of a PTC based CSP plant, without storage, is carried out. Effects of turbine inlet pressure, turbine inlet temperature, design radiation, plant size, and various modifications of Rankine cycle on overall efficiency as well as LCOE are studied. Variations in turbine isentropic efficiency with turbine inlet pressure, temperature and mass flow rate as well as dryness fraction at the outlet of turbine are modeled appropriately in this paper. There is no such analysis reported in the literature. The analysis is useful for sizing of solar field, sizing of power block and deciding power cycle parameters.

2. Effect of turbine inlet pressure on overall efficiency and levelized cost of energy

Simplified schematic of a PTC based CSP plant is shown in Fig. 1. PTC field heats HTF to a high temperature using concentrated solar radiation (from state 1 to state 2) and then high temperature HTF is fed into a heat exchanger to produce steam (from state 4 to state 5). The cold HTF coming out of heat exchanger (state 3) is re-circulated back into the PTC field using HTF pump. The high temperature and high pressure steam is used to generate power through a conventional steam turbine (from state 5 to state 6). Finally, steam from the turbine exhaust is condensed in a condenser (from state 6 to state 7). The collector field useful heat gain (Q_u) and collector efficiency (η_{CL}) are given by,

$$Q_u = m_{HTF} \cdot (h_2 - h_1) = \eta_{CL} \cdot I \cdot A_p \quad (1)$$