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Optimization of design radiation for concentrating solar thermal power plants without storage

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Abstract

Prior to the detailed design of a concentrating solar power (CSP) plant, it is necessary to develop a conceptual design of the plant. Conceptual design activities help in screening of various design objectives prior to the detailed design of the overall power plant. Conceptual design of a CSP plant includes type and size of solar field, power generating cycle and the working fluid, sizing of the power block, etc. One of the most important parameters for conceptual design of a CSP plant is to determine the design radiation of the plant. Design radiation for a CSP plant is the direct normal irradiance (DNI) at which the plant produces the rated power output. Due to daily and seasonal variation of radiation, determining appropriate design radiation is extremely important; low design radiation results in excessive unutilized energy and high design radiation results in low capacity factor of the plant. In this paper, a methodology is proposed to determine the thermodynamically and the cost optimum design radiation for CSP plants without hybridization and storage. The proposed methodology accounts for the characteristics of the collector field as well as turbine characteristics. There is no such analytical methodology reported in the literature. Applicability of the proposed methodology is demonstrated through illustrative case studies incorporating parabolic trough collectors (PTC) as well as linear Fresnel reflectors (LFR). Design radiations for ten different places in India are also reported. However, the proposed methodology is not restricted to India only.

Keywords: Concentrating solar power; Linear Fresnel reflector; Parabolic trough collector; Design radiation

1. Introduction

Technical feasibility of producing high-temperature steam using concentrated solar power (CSP) and to produce power through conventional Rankine cycle has already been successfully demonstrated. Today, there are solar thermal power plants based on CSP technology with electrical power generation capacity of few kW to 50 MW and more in various sun rich regions around the world (Fernández-García et al., 2010). There are mainly four commercially available CSP technologies. Two of them, parabolic trough collector (PTC) and linear Fresnel reflector (LFR), concentrate direct radiation onto a line, whereas the other two, paraboloid dish and solar power tower (SPT) technologies, concentrate direct radiation onto a point. Comparative analysis between PTC and LFR based CSP plants have been presented by Morin et al. (2012) and Giostri et al. (2012a). Franchini et al. (2013) have presented the comparative analysis between PTC and SPT based CSP plants. Detailed studies on economic aspects of CSP plants have been reported by Krishnamurthy et al. (2012) and Kost et al. (2013). Among the CSP technologies, plants with PTC, using synthetic or organic oil as heat transfer fluid

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Nomenclature

a	Willans' line equation parameter (W)
A_p	aperture area of the collector (m^2)
b	Willans' line equation parameter (J/kg)
C_P	specific heat (J/kg)
E	aperture specific energy output (Wh/m^2)
h	enthalpy (J/kg)
I	aperture effective direct normal irradiance (W/m^2)
L	loss (W/m^2)
m	mass flow rate (kg/s)
P	power (W)
Q	heat (W)
T	temperature (°C)
U_L	heat loss coefficient based on aperture area (W/m^2 K)
x	dryness fraction
y	fraction of internal losses of turbine

Greek symbols

Δ	difference
η	efficiency
θ	incidence angle (°)
τ	constant

Abbreviations

CSP	concentrating solar power
DNI	direct normal irradiance
DSG	direct steam generation
HTF	heat transfer fluid
LFR	linear Fresnel reflector
PTC	parabolic trough collector
SAM	system advisor model
SPT	solar power tower

Subscripts

a	ambient
C	threshold
CL	collector
D	design
hx	heat exchanger
is	isentropic
m	mean
max	maximum
min	minimum
o	optical
w	water

(HTF), are found to be more attractive commercially (Purohit et al., 2013). In such plants, the maximum temperature is limited to about 400 °C with a resulting steam temperature at the turbine inlet about 350–370 °C.

Use of molten salt as a HTF can raise the steam temperature up to 540 °C, allowing steam turbines to operate at greater efficiency (Montes et al., 2010; Giostri et al., 2012b; Yang and Garimella, 2013; Zaversky et al., 2013). It may be noted that the direct steam generation (DSG) in PTC field is also an economically viable option (Odeh et al., 1998; Zarza et al., 2002; Eck and Steinmann, 2005; Eck and Hirsch, 2007; Hirsch et al., 2014). Several investigators have proposed DSG in LFR field as cheaper alternative due to the use of flat mirrors and simpler structures, though with a lower optical efficiency (Mills and Morrison, 2006; Xie et al., 2012; Sahoo et al., 2012, 2013; Zhu, 2013). LFR based CSP plants have been tested and installed on a utility scale around the world (Facão and Oliveira, 2011; Abbas et al., 2012; Zhu et al., 2014). Under the initiative of Indian Institute of Technology Bombay (IIT Bombay), a one megawatt CSP plant was proposed in the year 2009 and currently being commissioned in India that integrates a LFR field for DSG and PTC field for HTF (Desai et al., 2013). HTF is used for both steam generation and superheating the combine steam (Desai et al., 2013). A similar configuration has been proposed by Manzolini et al. (2011) where the PTC field is divided into two sections: one generates saturated steam like in DSG process and the second heats up a conventional HTF which is used for superheating and reheating the steam.

SPT is the second most installed CSP plant technology after PTC, and gradually gaining acceptance (Avila-Marin et al., 2013; Zhang et al., 2013). Some commercial SPT plants now in operation use DSG (Müller-Steinhagen and Trieb, 2004) and other plants use molten salts as HTF as well as storage medium (Amadei et al., 2013; Cáceres et al., 2013). A detailed review on design of central receiver and SPT based CSP plants have been reported by Behar et al. (2013) as well as Ho and Iverson (2014), respectively. Non-traditional heliostat field layouts (e.g., on hillsides) has also been reported in the literatures (Noone et al., 2011; Slocum et al., 2011). A paraboloid dish can be used for operating a Stirling engine located at its focus, DSG or linked with other dishes to heat a transfer fluid which is then used to drive a conventional turbine (Wu et al., 2010; Siva Reddy et al., 2013; Reddy and Veershetty, 2013). It is interesting to note that paraboloid dish systems give the highest efficiency among CSP technologies (Sharma, 2011).

Conventional Rankine cycle which uses water/steam as working fluid is most widely used in the CSP plants. With growing interest for highly efficient and modular CSP plants (Quoilin et al., 2011; Casati et al., 2013), organic Rankine cycles (i.e., a Rankine cycle that uses an organic fluid as the working medium) are very promising due to a