Applied Thermal Engineering xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Thermo-economic comparisons between solar steam Rankine and organic Rankine cycles

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HIGHLIGHTS

- Comparison between parabolic trough and linear Fresnel collectors based plants.
- Methodology to select working fluid and appropriate solar collector field.
- Selection diagrams for optimal configuration of solar thermal power plant.
- Selection of configuration and design parameters without multiple simulations.
- Effects of different parameters on selection of optimal configuration.

ARTICLE INFO

Article history:
Received 14 December 2015
Revised 7 April 2016
Accepted 12 April 2016
Available online xxxx

Keywords:
Concentrated solar power
Linear Fresnel reflector
Organic Rankine cycle
Parabolic trough collector
Selection diagram

ABSTRACT

Among all concentrated solar power technologies, plants with parabolic trough collector and steam Rankine cycle are the most matured and established technology. Organic Rankine cycle is a promising option for modular scale power plants with low temperature heat sources. The decision of selection between steam Rankine and organic Rankine cycles is influenced by solar collector field characteristics and cost, steam Rankine cycle efficiency, and power block cost. In this paper, based on the condition of equality of the levelized cost of energy, a methodology for selecting working fluid through a novel graphical representation, called working fluid selection diagram, is proposed. The proposed methodology also includes selection between parabolic trough and linear Fresnel collector based plant, for a given working fluid of the Rankine cycle. Most of the methods, proposed in literature, require multiple simulations for selecting various design parameters and optimum configuration of the plant. The proposed working fluid and solar collector field selection diagrams can be used for quick suggestion about optimal configuration of a concentrated solar power plant, without any detailed simulations. Based on the thermodynamic and economic parameters, R113 and isohexane achieves levelized cost of energy close to the parabolic trough collector based plant with steam Rankine cycle. Effects of different parameters on selection of optimal configuration of a concentrating solar power plant are also studied. The analytical procedures developed for selecting solar collector field and working fluid of the power generating cycle are important during conceptual design of a concentrated solar power plant. These methodologies can be applied at the initial design stage to compare the alternative configurations and to reduce the search space related to various design parameters.

1. Introduction

Today, concentrated solar power (CSP) plants are proven technology. Concentrated solar power plants with line-focusing concentrating solar collectors, like parabolic trough collector [1] and linear Fresnel collector [2], are simple in design and achieve temperature up to 400 °C. The overall operational capacity of the CSP plants is about 4.7 GW [3]. Parabolic trough collector (PTC) based CSP plant, using synthetic or organic oil as a heat transfer fluid, is the most mature technology with about 87% of the worldwide operational CSP plants capacity [3]. Concentrated solar power plants with direct steam generating parabolic trough collector field still have to be demonstrated at larger scales. Direct saturated steam generating linear Fresnel reflector (LFR) systems have been developed as a cost effective alternative to thermal oil based parabolic trough collector systems. All the commercial plants based on linear Fresnel reflector field (operational capacity about 170 MW)

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http://dx.doi.org/10.1016/j.applthermaleng.2016.04.055
1359-4311/

Nomenclature

a	Willans' line equation parameter (W)
A_p	aperture area of solar collector field (m^2)
b	Willans' line equation parameter (J/kg)
C	cost ($)
CRF	capital recovery factor (y^{-1})
d	discount rate
DNI	direct normal irradiance (W/m^2)
E	net annual energy generation (kW h/y)
f_{ar}	fraction of annual solar field component replacement cost
h	specific enthalpy (J/kg)
I	aperture effective solar radiation (W/m^2)
K_θ	incidence angle modifier effect
LCOE	levelized cost of energy ($/kW h)
m	mass flow rate (kg/s)
n	life time (y)
P	power (W)
Pr	pressure (MPa)
SP	size parameter (m)
T	temperature (°C)
U_l	heat loss coefficient based on aperture area ($W/(m^2\,K)$)
V	volumetric flow rate (m^3/s)
y	fraction of internal losses of turbine

Greek symbols

Δ	difference
β_0	complete power block cost ($)
β_1	sum of land & site development cost, civil works cost, and miscellaneous cost ($)
β_2	annual operating and maintenance cost ($/y)
η	efficiency

Subscripts

a	ambient
c	cut-off
CL	collector
cond	condenser
crit	critical
D	design
eva	evaporator
is	isentropic
m	mean
max	maximum
min	minimum
o	optical
out	outlet
RC	Rankine cycle
SF	solar field
sup	superheat
T	Turbine

Abbreviations

CSP	concentrated solar power
HMDS	hexamethyldisiloxane
LFR	linear Fresnel reflector
OMTS	octamethyltrisiloxane
ORC	organic Rankine cycle
PTC	parabolic trough collector
SRC	steam Rankine cycle

used direct steam generation [3]. Therefore, parabolic trough collector system with thermal oil and direct steam generating linear Fresnel reflector system are considered in the present work. It may be noted that the direct steam generation based plant, with storage, has higher efficiency but the capital cost as well as levelized cost of energy are also higher, compared to the thermal oil based plant with storage. Point-focusing concentrating solar collectors, like solar power tower and paraboloid dish, can be used in high temperature applications due to high concentration ratio [4]. Concentrated solar power plants that mainly works on steam Rankine cycle (SRC) are not economical in small-medium scale applications [5]. Organic Rankine cycle (ORC) uses an organic fluid as a working medium, instead of water, within a Rankine cycle [6]. Organic Rankine cycle is a promising alternative to the steam Rankine cycle in low-medium temperature applications with small-scale [7]. Organic Rankine cycle based power block manufacturers have installed significant number of plants mainly for biomass, waste heat, or geothermal energy sources [8]. There is only one organic Rankine cycle based commercial plant (in MWe range) which uses concentrated solar energy as a heat source [3]. Parabolic trough collector based organic Rankine cycle systems for combined heat and power plant [9] and solar–geothermal hybrid plant [10] have also been proposed as a promising option.

The main advantages of organic Rankine cycle over steam Rankine cycle are high turbine efficiency, low mechanical stress, long plant life, low operation and maintenance cost, simple start up procedures, completely automatic and unmanned operation, etc. The choice of working fluid for an organic Rankine cycle depends on the temperature of heat source, which can range from about 70 °C to 400 °C. The most important thing is to know whether the organic working fluid is really better than water for a given application. In case of the low temperature heat sources, an organic Rankine cycle has distinct advantages over steam Rankine cycle. On the other hand, the advantages of an organic Rankine cycle have to be proved over steam Rankine cycle for medium–high temperature applications.

Extensive investigations on low temperature ORCs (<150 °C) powered by geothermal energy sources [11], waste heat recovery [12], ocean thermal energy conversion [13], etc. have been presented in literature. Detailed analyses of the low temperature solar organic Rankine cycle using flat plate collector [14], evacuated tube collector [15], and compound parabolic concentrator [16] have also been reported. Organic Rankine cycle can be employed for solar combined heat and power systems [17], exhaust heat recovery from a compressed natural gas engine [18] and a liquid natural gas engine [19], exhaust flue gas heat recovery [20], exhaust heat recovery from an internal combustion engine [21], and internal combustion engine cooling water waste heat [22], etc. Use of organic fluid mixtures for organic Rankine cycle applications, for example, solar thermal [23], geothermal [24], exhaust heat recovery from diesel engine [25], etc. have been proposed as a promising option. It may be noted that there exists the optimal mixture ratio for different mixtures, and it changes with the evaporation temperature [26].

Working fluids for medium–high temperature ORCs, like biomass combustion, industrial heat recovery, combined cycle, gas turbine exhaust, concentrated solar power plant, etc., should be necessarily different than low temperature organic Rankine cycle applications. The most widely used working fluids in commercial organic Rankine cycle based plants are R134a, R245fa, Solkatherm, Pentane, Octamethyltrisiloxane (OMTS), Toluene, etc. [27]. However, for the medium–high temperature applications of