CHEMICAL ENGINEERING TRANSACTIONS

VOL. 45, 2015

A publication of
AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Jun Yow Yong, Xia Liu

ISBN 978-88-95608-36-5; **ISSN** 2283-9216

DOI:10.3303/CET1545267

Comparison of Parabolic Trough and Linear Fresnel Collectors based Concentrating Solar Power Plants using Organic Rankine cycle

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Concentrating solar power (CSP) plants with parabolic trough collector (PTC) using thermal oil as heat transfer fluid (HTF) and conventional steam Rankine cycle (SRC) as power generating cycle is the most commercially developed technology. Direct steam generating linear Fresnel reflector (LFR) systems are developed as a cheaper alternative to PTC systems. The major drawbacks of LFR systems are low optical efficiency and production of saturated steam. These result in higher solar field area requirement compared to PTC based plants of same capacity. Organic Rankine cycle (ORC) based power block, with dry working fluids, offers higher cycle efficiency as well as improved part-load turbine efficiency compared to SRC in modular scale plants with heat sources up to 400 °C. ORC is more suitable to LFR based CSP plants. In this paper, thermo-economic analysis of PTC and LFR based CSP plants with ORC has been presented. An approximate selection methodology, for LFR and PTC based CSP plants, is proposed and the selection diagram generated using the proposed methodology can be used for LFR and PTC based CSP plants with any working fluid of Rankine cycle. The applicability of the selection diagram is demonstrated using case studies of n-Pentane, Octamethyltrisiloxane (OMTS) and water working fluids based plants. Selection diagram captures the variations of power generating cycle efficiency, and costs of collector fields.

1. Introduction

Concentrating solar power (CSP) plants with parabolic trough collector (PTC) using thermal oil as heat transfer fluid (HTF) are the most proven technology for solar thermal power generation (Pavlović et al., 2012). Direct steam generating linear Fresnel reflector (LFR) systems, in which water directly evaporates, are developed as a cheaper option to PTC systems (Xie et al., 2012). The major drawbacks of LFR systems are low optical efficiency (Zhu et al., 2014) and it usually produces saturated steam (Desai and Bandyopadhyay, 2015a), resulting in higher solar field area requirement compared to PTC based plants of same capacity. Conventional steam Rankine cycle (SRC) is used as a power generating cycle in most of the commercially developed CSP plants. The power block of SRC based small-medium scale (less than 2 MWe) plants have much lower efficiency and high cost compared to large size plants (Desai and Bandyopadhyay, 2015a).

In recent years, the worldwide interest for highly efficient and modular CSP plants increased significantly. In such applications, organic Rankine cycles (ORCs), which use an organic fluid as working medium, are very promising due to a number of advantages over the conventional steam Rankine cycle. ORC based power block, with dry working fluid, offers higher design point as well as part-load efficiency compared to SRC in small-medium scale plants with heat sources up to 400 °C (Hung et al., 1997). Unlike SRC turbines, the ORC turbines with dry working fluids can operate at almost same efficiency with superheated and saturated conditions of the fluid at turbine inlet. The other advantages of ORC are low operating and maintenance costs, fully automatic operation, improved part-load characteristics, long service life, etc (Algieri and Morrone, 2012). Significant number of plants based on ORC, which mainly uses biomass, waste heat or geothermal as a heat source, have been installed worldwide (Quoilin et al., 2013). However, only one commercial plant (in MW range) uses concentrated solar energy as a heat source for an ORC (Quoilin et al., 2013).

Please cite this article as: Desai N.B., Bandyopadhyay S., 2015, Comparison of parabolic trough and linear fresnel collectors based concentrating solar power plants using organic rankine cycle, Chemical Engineering Transactions, 45, 1597-1602 DOI:10.3303/CET1545267

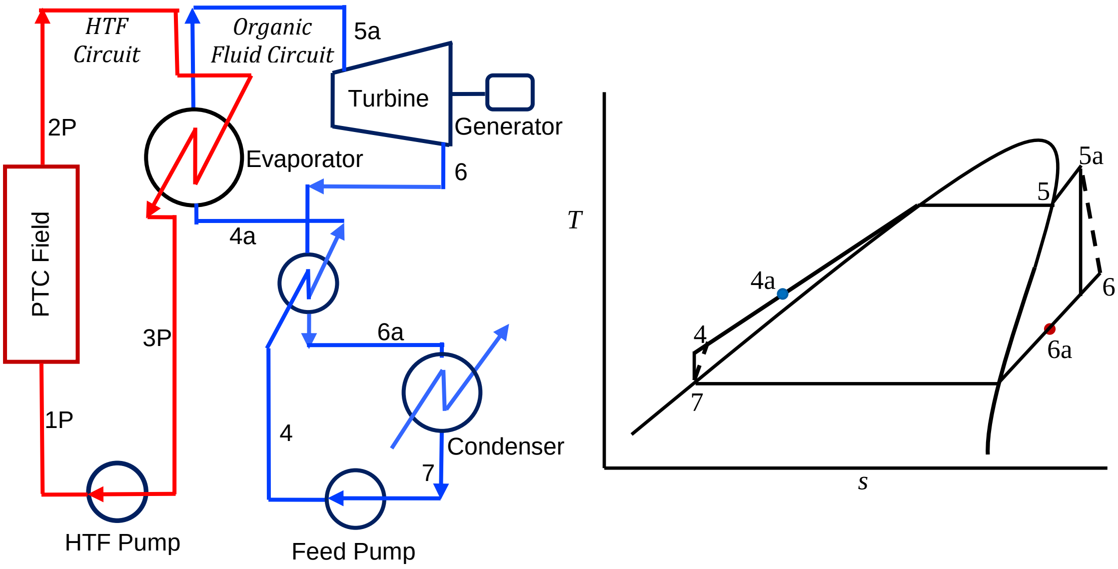
Several studies on efficiency improvement of basic ORC have been reported. In case of dry organic working fluids, the condition of expanded stream at the outlet of turbine is always superheated and the temperature of the fluid is always higher than that at the evaporator inlet. Therefore, the heat from fluid at the turbine outlet is transferred to evaporator feed. This is known as regeneration, resulting in improvement in thermal efficiency (Saleh et al., 2007). Basic ORC can also be modified by incorporating both regeneration and turbine bleeding to improve thermal efficiency (Desai and Bandyopadhyay, 2009).

Mavrou et al. (2014) presented the analysis of low temperature solar (using flat plate collectors) ORC using different working fluids. Thermodynamic analysis of CSP plants using ORC as a power generating cycle and PTC with thermal oil in solar field (He et al., 2012) and LFR with thermal oil in solar field (Cocco and Serra, 2015) have been reported in the literature. Cau and Cocco (2014) compared the thermodynamic performances of thermal oil based PTC and LFR plants using ORC and reported that PTC based plant gives about 35 - 38 % higher electricity output compared to LFR based plant. It may be noted that the cost of LFR field is lower than PTC field. Therefore, thermo-economic analysis of PTC and LFR based CSP plants using ORC is necessary. Based on the condition for equality of the levelized costs, an approximate selection methodology, for LFR and PTC based CSP plants, is proposed in this paper. The selection diagram generated using the proposed methodology can be used for LFR and PTC based CSP plants with any working fluids of Rankine cycle.

2. Approximate thermo-economic analysis of PTC and LFR based CSP plants with ORC

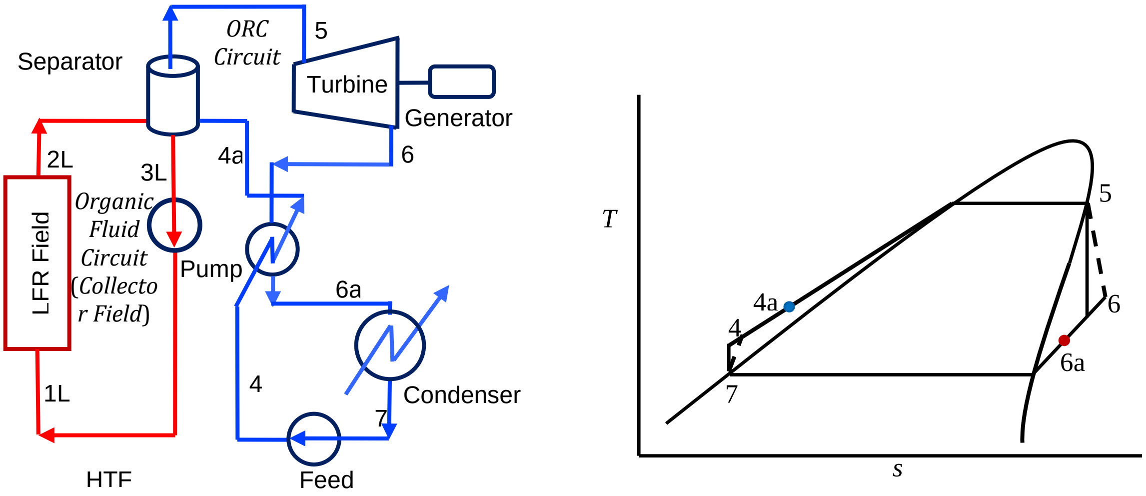
Simplified schematic and Temperature-Entropy (*T*-*s*) diagram of PTC based CSP plant, using regenerative ORC, are shown in Figure 1. The concentrated solar radiation is used to heat thermal oil to a high temperature. This heat is used in a power generation cycle to produce electricity. It may be noted that the condition of organic fluid at the inlet of organic turbine may be saturated vapor or super heated vapor for dry organic fluids.

Simplified schematic and Temperature-Entropy (*T*-*s*) diagram of LFR based CSP plant, using regenerative ORC, are shown in Figure 2. It may be noted that the low cost LFR system (LFR field + separator) usually produces saturated vapor of the working fluid. Aperture area of the solar field is determined from the following relation (Desai and Bandyopadhyay, 2015b):



(a) (b)

Figure 1: PTC based CSP plant using regenerative ORC (a) Simplified schematic, and (b) T-s diagram



(a) (b)

Figure 2: LFR based CSP plant using regenerative ORC (a) Simplified schematic, and (b) T-s diagram

$$A_{p,\mathrm{CL}} = \frac{P_D \cdot \Delta h}{\Delta_{\mathrm{CL}} \cdot \Delta h_{is} \cdot \eta_{is,D}} = \frac{P_D}{\Delta_{\mathrm{CL}} \cdot \eta_{cycle}} \qquad (1)$$

$$\Delta_{\mathrm{CL}} = \left(\eta_o \cdot I_D - U_l \cdot \Delta T\right)_{\mathrm{CL}} \text{ and } \eta_{\mathrm{cycle}} = \left(\frac{\Delta h_{is}}{\Delta h}\right) \cdot \eta_{is,D} \qquad (2)$$

where η_o is the optical efficiency of collector field, U_l is the heat loss co-efficient based on aperture area of collector field (W/(m^2·K)), ΔT is the difference between T_m and T_a, T_m is the mean temperature of collector field (°C), T_a is the ambient temperature (°C), P_D is the design power output (W), Δh_{is} is the isentropic enthalpy change in turbine (J/kg), Δh is specific heat input to power generating cycle (J/kg), $\Delta h = h_{5a}–h_4$ (for PTC based plant with basic ORC) or $h_{5a}–h_{4a}$ (for PTC based plant with regenerative ORC) or $h_5–h_{4a}$ (for LFR based plant with regenerative ORC), $\eta_{is,D}$ is the design point isentropic efficiency of turbine, η_{cycle} is the thermal efficiency of a power generating cycle efficiency (neglecting pump work), I_D is the aperture effective design DNI (product of DNI and IAM) at which plant produces rated power output, DNI is direct normal irradiance (W/m^2), and IAM is incidence angle modifier, which express the reduction of the optical efficiency due to the incidence angle in PTC fields and due to the incidence and the transversal angles in LFR fields. Thermodynamically and cost optimum design radiation (I_D) for a CSP plant is calculated from the methodology given by Desai et al. (2014).The condition when levelized costs of energy for LFR based and PTC based CSP plants are equal, is given by:

$$\mathrm{LCOE}_{\mathrm{LFR}} = \mathrm{LCOE}_{\mathrm{PTC}} \qquad (3)$$

$$\frac{C_{\mathrm{CL,LFR}} \times A_{p,\mathrm{LFR}} \times \mathrm{CRF} + \beta_{0,\mathrm{LFR}} \times \mathrm{CRF} + \beta_{1,\mathrm{LFR}}}{E_{\mathrm{LFR}}} = \frac{C_{\mathrm{CL,PTC}} \times A_{p,\mathrm{PTC}} \times \mathrm{CRF} + \beta_{0,\mathrm{PTC}} \times \mathrm{CRF} + \beta_{1,\mathrm{PTC}}}{E_{\mathrm{PTC}}} \qquad (4)$$

where $C_{\mathrm{CL,LFR}}$ is the specific LFR field investment cost (\$/m^2), $C_{\mathrm{CL,PTC}}$ is the specific PTC field investment cost (\$/m^2), β_0 is the sum of power block cost, civil works cost, miscellaneous cost, land and site development cost, etc. (\$), β_1 is the annual operation and maintenance cost (\$/y), *E* is the annual electricity output (kWh/y), CRF is the capital recovery factor (annualization factor), *n* is lifetime (year), and *d* is the discount rate,. It may be noted that the solar field is the most expensive component of CSP plants and it has a significant impact on the overall cost and levelized cost of energy (LCOE) of a solar thermal power plant. Moreover, the value of β_0, β_1 and *E* are marginally higher for the PTC based CSP plants compared to the LFR based plants. Therefore, Eq(4) can be simplified using the following assumption (Desai and Bandyopadhyay, 2015b):

$$\frac{\beta_{0,\mathrm{LFR}} \cdot \mathrm{CRF} + \beta_{1,\mathrm{LFR}}}{E_{\mathrm{LFR}}} \approx \frac{\beta_{0,\mathrm{PTC}} \cdot \mathrm{CRF} + \beta_{1,\mathrm{PTC}}}{E_{\mathrm{PTC}}} \qquad (5)$$

Based on the above assumption, Eq(4) may be simplified.

$$\frac{C_{\mathrm{LFR}}}{C_{\mathrm{PTC}}}=\frac{A_{p,\mathrm{PTC}}}{A_{p,\mathrm{LFR}}}\cdot\frac{E_{\mathrm{LFR}}}{E_{\mathrm{PTC}}} \tag{6}$$

where $C_{\mathrm{LFR}}/C_{\mathrm{PTC}}$ is the relative solar field costs.
Furthermore, using Eq(1), Eq(6) may be expressed as,

$$\frac{C_{\mathrm{LFR}}}{C_{\mathrm{PTC}}}=\frac{\Delta_{\mathrm{LFR}}}{\Delta_{\mathrm{PTC}}}\cdot\frac{\eta_{\mathrm{cycle,LFR}}}{\eta_{\mathrm{cycle,PTC}}}\cdot\frac{E_{\mathrm{LFR}}}{E_{\mathrm{PTC}}} \tag{7}$$

It may be noted that the optical efficiency and loss co-efficient of the solar field depend on the type of reflecting material and receiver, respectively. Moreover, the cost of the solar field depends on reflecting material and receiver. Therefore, the cost of solar field with respect to unit energy gain ($/W) can be represented as:

$$\frac{\left(C/\Delta\right)_{\mathrm{LFR}}}{\left(C/\Delta\right)_{\mathrm{PTC}}}=\frac{\eta_{\mathrm{cycle,LFR}}}{\eta_{\mathrm{cycle,PTC}}}\cdot\frac{E_{\mathrm{LFR}}}{E_{\mathrm{PTC}}} \tag{8}$$

Eq(8) gives the condition of equality of the levelized costs for PTC and LFR based CSP plants.

3. Selection Diagram

Selection diagram captures the variations of power generating cycle efficiency, and costs of solar fields per unit of energy gain ($/W), which influences the choice of PTC and LFR based CSP plants. Figure 3 shows the selection diagram for PTC and LFR based CSP plants using the data given in Table 1 and results are tabulated in Table 2. It may be noted that the low cost LFR systems require higher solar field area, about 38 % for n-Pentane and 29 % for Octamethyltrisiloxane (OMTS) working fluids for ORC, compared to PTC based plants of same capacity.

The condition of equality of the levelized costs for a PTC and LFR based CSP plants are shown in Figure 3. Right side of the line indicates that the optimal configuration of a CSP plant based on PTC as a solar field. Optimal configuration of a CSP plant with LFR as a solar field lies on the left side of separating line. Figure 3 also shows that there is no significant change in the optimal regions with working fluids of the Rankine cycle. However, the decision of selection between PTC and LFR fields is influenced by the working fluids. The calculated values of cost optimum design radiation (I_D) for PTC and LFR based plants with SRC are 580 W/m^2 and 530 W/m^2, respectively. However, these values for PTC and LFR based plants with ORC are 610 W/m^2 and 550 W/m^2, respectively (Location: Jodhpur). It may be noted that the cost optimum design radiation changes with location.

The applicability of the selection diagram is demonstrated using case studies of n-Pentane, OMTS, and water working fluids based plants. Based on the assumed data, SRC based plant should have PTC as a solar field. This is mainly because of very low saturated turbine efficiency, which is used in LFR based plant. The design point of n-Pentane and OMTS based plant is very close to the separation line between two regions and the LCOE of these plants with PTC and LFR is expected to be very close to each other (slightly lower for LFR based plants). Therefore, the plant can be designed by any of the field. It may be noted that the ORC turbines with dry working fluids can operate at almost same efficiency with superheated and saturated conditions of the fluid at turbine inlet. Figures 4 demonstrate that there are no significant variations in optimum regions of selection diagram with change in location for LFR and PTC based CSP plant.

4. Conclusions

PTC with thermal oil as HTF and SRC as power generating cycle is the most promising technology for large scale CSP plants (more than 10 MWe). ORC based power block, with dry working fluids, have higher efficiency with superheated as well as saturated turbines for modular scale plants with medium temperature heat sources. Therefore, ORC is more suitable for LFR based CSP plants compared to SRC. Low cost LFR systems require higher solar field area, about 38 % for n-Pentane and 29 % for OMTS working fluids for ORC, compared to PTC based plants of same capacity. However, the LCOE of LFR based plant with n-Pentane and OMTS is lower than the PTC based CSP plant. Approximated selection diagram generated using the condition of equality of LCOE can be used for selection between PTC and LFR based CSP plants with any working fluid of Rankine cycle. Selection diagram captures the variations of power generating cycle efficiency, and costs of collector fields. The decision of selection between PTC and LFR is influenced by the working fluids of Rankine cycle.

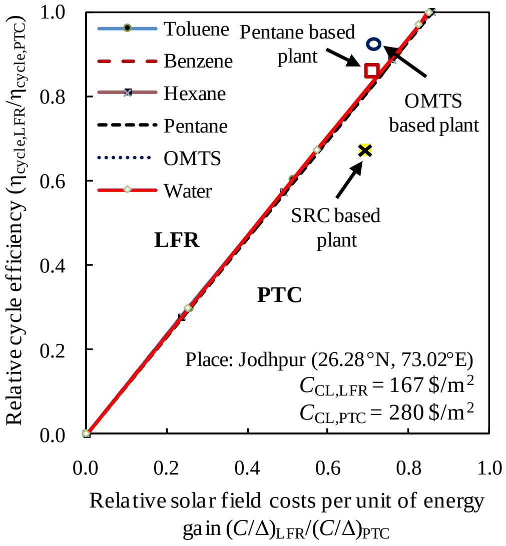
Table 1: Data used for the analysis of CSP plants based on PTC and LFR

Input Parameter	CSP plant using PTC	CSP plant using LFR
Solar field efficiency model parameters	$\eta_o = 0.7$; $U_l = 0.1$ W/(m^2·K)	$\eta_o = 0.65$; $U_l = 0.1$ W/(m^2·K)
Collector tracking mode	Focal axis N-S horizontal and E-W tracking	Focal axis N-S horizontal and E-W tracking
Location	Jodhpur (26.28°N, 73.02°E)	Jodhpur (26.28°N, 73.02°E)
IAM effect	Euro Trough design (Schenk et al. 2014)	Novatech design (Schenk et al. 2014)
Solar field and HTF system cost, C_{CL} (\$/m^2)	280	167
Heat transfer fluid	Therminol VP-1	Water/Organic Fluid
Degree of superheat at turbine inlet (ΔT_{sup})	40 °C (for ORC); 100 °C (for SRC)	0 °C
Collector outlet temperature (T_{2P})	$T_{eva}+\Delta T_{sup}+40$ °C	T_{eva}
Ambient temperature (T_a)	30 °C (design value)	30 °C (design value)
Plant capacity (P_D)	1 MWe	1 MWe
Isentropic efficiency of the turbine at design ($\eta_{is,D}$)	0.65 (for SRC); 0.77 (for ORC)	0.45 (for SRC); 0.77 (for ORC)
Turn down ratio of turbine (P_{min}/P_{max})	0.2 (for SRC); 0.1 (for ORC)	0.2 (for SRC); 0.1 (for ORC)
Willans' line equation: Turbine power output (P) = $a + b \cdot m$	$a = -y \cdot P_D$; $b = (1+y) \cdot \Delta h_{is} \cdot \eta_{is,D}$ (Desai et al., 2014) $y = 0.2$ (for SRC); 0.1 (for ORC)	$a = -y \cdot P_D$; $b = (1+y) \cdot \Delta h_{is} \cdot \eta_{is,D}$ (Desai et al., 2014) $y = 0.2$ (for SRC); 0.1 (for ORC)
Auxiliary consumption	10 % of gross power output	10 % of gross power output
Temperature driving force (ΔT_{min})	10 °C (for heat exchanger and regenerator); 5 °C (for condenser)	10 °C (for regenerator); 5 °C (for condenser)
Isentropic efficiency of pump	0.6	0.6

Table 2: Properties of working fluids used in the analysis and results

Working Fluid	P_{crit} (MPa)	T_{crit} (°C)	P_{eva} (MPa)	T_{eva} (°C)	P_{cond} (MPa)	T_{cond} (°C)	$A_{p,PTC}$ (m^2)	$\eta_{cy,PTC}$ (%)	$A_{p,LFR}$ (m^2)	$\eta_{cy,LFR}$ (%)
Toluene	4.126	318.6	3.154	297	0.0099	45	7,738	32.2	10,227	29.2
OMTS	1.415	290.9	0.882	260	0.005*	66.6	9,466	26.3	12,215	24.3
Benzene	4.894	288.9	3.583	264	0.0298	45	8,448	29.3	11,290	26.2
Hexane	3.034	234.7	2.308	216	0.0451	45	9,431	26.1	12,689	23.1
Pentane	3.37	196.6	2.45	176	0.1361	45	11,092	22	15,283	19
Water	22.06	373.9	4.0	250	0.0096	45	11,595	22.7	20,006	15.3

* Lowest pressure accepted for the condenser *(*Drescher and Bruggemann, 2007*)*.



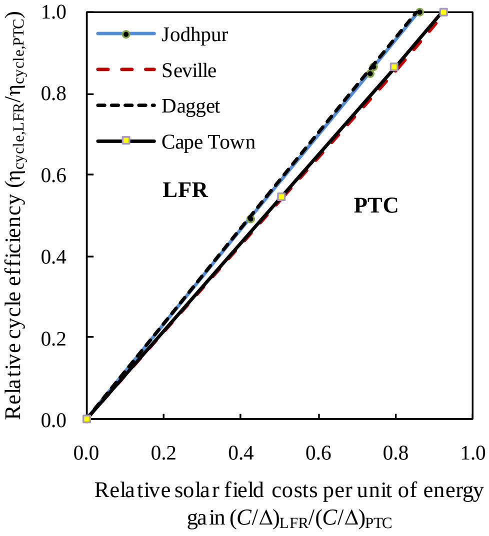


Figure 3: Selection diagram for LFR and PTC based of CSP plants

Figure 4: Variations in selection diagram with location

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