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Analysis of solar thermal plants through parabolic

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Abstract
This paper compares the application of conventional solar thermal plants based on parabolic trough technology and Fresnel technology. Parabolic trough can be considered the state of the art for solar thermal power plants thanks to the almost 30 years experience gained in SEGS and, recently, Nevada Solar One plants in US and Andasol plants in Spain.

Keywords: conventional solar thermal, parabolic, Fresnel technology

1. Introduction

Fresnel technology have an optical efficiency of 67% which is lower than 75% of parabolic trough. Calculated net electric efficiency is about 19.25%, while parabolic trough technology achieves 23.6%. In off-design conditions, the gap between Fresnel and parabolic trough increases because the former is significantly affected by high radiation incident angles. The calculated sun-to-electric annual average efficiency for Fresnel plant is 10.2%, consequence of the average optical efficiency of 38.8%, while parabolic trough achieve an overall efficiency of 16%, with an optical one of 52.7%. An additional case with Fresnel collector and synthetic oil outlines differences among investigated cases.

Finally, because part of performance difference between PT and Fresnel is simple due to different definitions, additional indexes are introduced in order to make a consistent comparison.

Analysis

In order to evaluate the impact of each component of the solar plant on the solar-to-electric efficiency, overall performances are calculated as the product of five different efficiencies (the same methodology was already introduced in previous works [1, 2]). All efficiency indexes are used at nominal conditions as well as for annual simulations. At nominal conditions all terms in Eq. (1) are evaluated on the basis of power (Watt), while in the second case on energies (Joule) estimated over 8760 hours (an hourly time frame is assumed).

$$\eta_{overall} = \eta_{optical} \cdot \eta_{thermal} \cdot \eta_{piping} \cdot \eta_{net\_PB} \cdot \eta_{aux\_SF} = \frac{E_{el,annual}}{E_{SUN}} \qquad (1)$$

where:

$\eta_{optical}$ is the optical efficiency that compares the radiation on the absorber tube to the incident solar radiation; $\eta_{thermal}$ is the thermal efficiency and takes into account the collector thermal losses; η_{piping} evaluates the impact of piping thermal losses (also night time losses) on the HTF transferred thermal power; η_{net_PB} expresses the efficiency conversion of the thermal input into electricity; η_{aux_SF} expresses the impact of solar field circulating pumps and tracking consumptions on the net power block output.

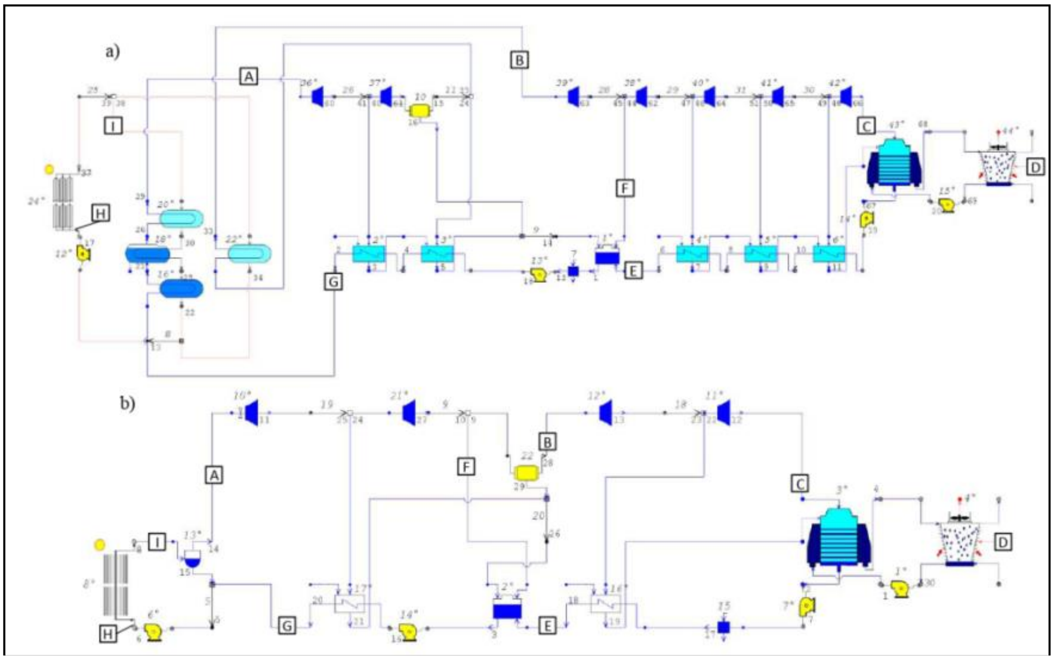

Fig 1: Indirect cycle plants layout (a) and Fresnel plant layout (b). These figures are Screenshots from Thermoflex® 20

Table 1: Stream properties for the three different studied layouts

	IND - PAR				IND - FRE				DSG			
Stream	fluid type	M [kg/s]	p [bar]	T [°C]	fluid type	M [kg/s]	p [bar]	T [°C]	fluid type	M [kg/s]	p [bar]	T [°C]
A	Water(v)	61.3	99.94	371.0	Water(v)	59.7	99.9	371.0	Water(v)	77.2	55.0	270.0
B	Water(v)	49.4	18.3	371.0	Water(v)	48.4	18.3	371.0	Water(v)	53.5	2.7	130.0
C	Water(v)	39.6	.06	41.5	Water(v)	39.0	.08	41.5	Water(v)	49.6	.08	41.5
D	Air	1184.6	1.0	35.0	Air	1155.4	1.01	35.0	Air	1435.6	1.0	35.0
E	Water(l)	46.6	9.2	126.8	Water(l)	45.4	9.2	126.5	Water(l)	54.6	3.9	90.0
F	Water(v)	3.5	8.0	274.3	Water(v)	3. 3	8.0	273.6	Water(v)	4.93	2.7	130.0
G	Water(l)	61.3	100.5	234.8	Water(l)	59.7	100.4	234.6	Water(l)	77.2	55.0	179.5
H	HTF	615.7	27.7	297.3	HTF	601.0	20.4	296. 5	Water(l)	96.5	66.0	195.7
I	HTF	531.4	13.0	391.0	HTF	518.6	13.0	391.0	Water(v)*	96.5	55.0	x_v=0.6

PT and LFR have different definitions of the optical efficiency: in PT case, the incident area is evaluated adopting the aperture area, while the reflective area is considered in LFR. In order to make a consistent comparison, two additional indexes are introduced: $\eta_{optical\_modified}$ and $\eta_{overall\_modified}$, where also for PT, the calculation of incident energy is carried out considering the reflective area.

Results for design conditions are summarized in Table 1 and Table 2.

Table 2: Performances at on-design conditions for investigated technologies.

	IND-PAR	IND-FRE	DSG
Gross power [MW]	54.87	53.45	52.52
Steam cycle aux cons. [MW]	1.72	1.68	1.40
Cooling tower aux cons. [MW]	0.65	0.63	0.85
Number of operating flow paths	72	75	43
Pump head [bar]	23.34	10.86	11.01
Solar field aux cons. [MW]	2.51	1.14	0.19
Total SCA aperture area [m^2]	235,899	268,596	289,101
Total required land area [m^2]	683,902	594,465	593,205
$\eta_{optical}$[1] [%]	71.24	63.65	63.64
$\eta_{optical\_modified}$ [%]	64.35	63.65	63.64
$\eta_{thermal}$ [%]	95.22	91.99	95.43
η_{piping} [%]	99.17	98.44	99.78
η_{net_PB} [%]	36.74	36.71	31.88
η_{aux_SF} [%]	95.23	97.78	99.62
$\eta_{overall}$ [%]	23.53	20.69	19.25
$\eta_{overall\_modified}$ [%]	21.25	20.69	19.25

Overall efficiency for IND-PAR is equal to 23.6% and is close to existing plant performances [2]. This result is mainly determined by the low efficiency of the power block, consequence of the maximum temperature limit in the solar field. IND-FRE achieves a lower overall efficiency of 3 percentage points because of optical and thermal efficiency penalties. In particular, optical efficiency is 63.5% vs. 71.2% of parabolic trough because of mirror inclination that reduces the effective reflecting area even with zero incidence angle. If optical efficiencies are compared using modified definition (as previously discussed), this difference almost disappears. In terms of steam mass flow in the power block, IND-FRE shows the lower value (59.87 vs. 61.14 kg/s) because of the lower solar field auxiliaries consumptions. IND-PT and IND-FRE have the same HTF temperature working range (from 297 to 391°C), but LFR has no vacuum annulus (i.e. reflecting current technology), thus leading to higher heat losses.

Linear Fresnel Concentrator has a more complicated incidence angle definition: two projections on different planes are necessary, on longitudinal and transversal plane respectively. For this reason, incidence angle can be split into two components as shown in Figure 2: (i) $\theta_{\parallel}$ defined as the angle between vertical axis and sunray vector projection on longitudinal plane, (ii) $\theta_{\perp}$ defined as the angle between vertical axis and sunray vector projection on transversal plane.

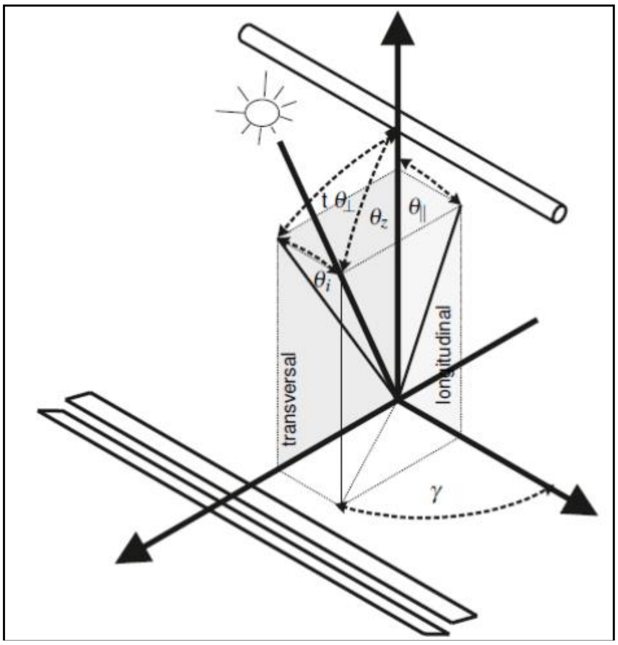

Fig 2: Angles definition of a Linear Fresnel Reflector with horizontal N-S orientation tracking axis [3]

In addition, another characteristic angle named θ_i can be defined as the angle between sunray vector and its projection on transversal plane. This angle corresponds to the above described incidence angle of parabolic trough technology. Relations between angles are summarized in Eq.(2) to Eq.(4):

$$\theta_{\perp} = \arctan(|\sin(\gamma)| \tan(\theta_z)) \tag{2}$$
$$\theta_{\parallel} = \arctan(\cos(\gamma)\tan(\theta_z)) \tag{3}$$
$$\theta_i = \arctan(\cos(\gamma)\sin(\theta_z)) \tag{4}$$

Where γ is the azimuth angle and θ_Z is the zenith angle. Referring to parabolic trough technology, correction of optical efficiency for the incidence angle is usually expressed by the cosine effect and the Incidence Angle Modifier (IAM), which includes optical properties variations (e.g. selective coating absorptivity and glass envelope transmissivity) as a function of the incidence angle.

Among different definitions present in literature, the global parameter $K(\theta)$ definition is here assumed, which considers both cosine effect, IAM, tail end losses, absorber support shading and intercept factor variation. $K(\theta)$ corresponding to Euro Trough (ET-100) is adopted [4], and its formulation is:

$$K(\theta)_{ET} = \cos(\theta) - 5.251\cdot 10^{-4}\,\theta - 2.8596\cdot 10^{-5}\,\theta^2 \tag{5}$$

Parabolic mirror row shading efficiency, representing the ratio of the effective mirror aperture area, i.e. the illuminated area of mirror, to the total aperture area, is taken into account using Eq.(6):

$$\eta_{shadowing} = \frac{W_{eff}}{W} = \min\left[\max\left(0; \frac{L_{spacing}}{W}\cdot\frac{\cos(\theta_z)}{\cos(\theta)}\right);1\right] \tag{6}$$

Where $L_{spacing}$ is the spacing length between rows, W is the real aperture area and W_{eff} is the effective aperture area. Concerning Linear Fresnel Concentrator, correction of optical efficiency is more complex, due to different characteristic angles as aforementioned.

The overall efficiency of IND-PAR case is about 16% (1% point lower focusing on modified efficiency), which is in the range of commercial plants based on the same technology [4-5], supporting reliability of calculations methodology.

Both Fresnel cases, IND-FRE and DSG, achieve a net electric efficiency in the range of 10%, which is about 25% lower than reference PT technology. The resulting efficiency reduction compared to the design conditions is equal to 50% for LFR and 24% for PT, mostly due to optical efficiency decay.

Conclusions

Fresnel technology, can be considered as a promising way to reduce electricity cost. In order to make a detailed comparison, both an indirect and direct cycle were considered for Fresnel technology. Plant design conditions are defined assuming a net power output of 50 MW. Calculations are carried out with a commercial code named Thermoflex®, able to describe power plants either at rated and off-design conditions.

Results at nominal conditions evidenced a slightly superiority of parabolic trough over Fresnel with indirect cycle, mainly because of the higher optical efficiency with the conventional definition. Adopting a modified index which is more consistent, this difference almost disappear. Fresnel with DSG showed a significantly lower efficiency of about 6% points, because of the saturated steam cycle adopted.

Parabolic trough predominance is even larger comparing net electricity production over one year: calculated overall efficiency is 16% (15%, if referred to reflective area) compared to 10% of Fresnel plants.

Fresnel suffers of a significant optical efficiency decay which is about 40% on an average basis. In particular, optical efficiency decreases for high incidence angles even if no shadowing issues between modules are present like in Parabolic Trough plants. This decay is significant also because of the concentration ratio assumed for LFR which is twice than PT.

However, Fresnel is seen as a promising technology because of investment cost savings (e.g. lighter structure is required, fewer civil works, easier glass cleaning), thus only a detailed economic analysis will determine if cost reduction related to the considered Fresnel technology compensates the lower performances. Moreover different Fresnel collectors technologies, with other receiver shapes, could lead to optical and thermal performance improvement.

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