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Innovations on direct steam generation in linear Fresnel collectors

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Abstract

Direct Steam Generation (DSG) in Linear Fresnel (LF) solar collectors is being consolidated as a feasible technology for Concentrating Solar Power (CSP) plants. The competitiveness of this technology relies on the following main features: water as heat transfer fluid (HTF) in Solar Field (SF), obtaining high superheated steam temperatures and pressures at turbine inlet (500ºC and 90 bar), no heat tracing required to avoid HTF freezing, no HTF degradation, no environmental impacts, any heat exchanger between SF and Balance Of Plant (BOP), and low cost installation and maintenance. Regarding to LF solar collectors, were recently developed as an alternative to Parabolic Trough Collector (PTC) technology. The main advantages of LF are: the reduced collector manufacturing cost and maintenance, linear mirrors shapes versus parabolic mirror, fixed receiver pipes (no ball joints reducing leaking for high pressures), lower susceptibility to wind damages, and light supporting structures allowing reduced driving devices. Companies as Novatec, Areva, Solar Euromed, etc., are investing in LF DSG technology and constructing different pilot plants to demonstrate the benefits and feasibility of this solution for defined locations and conditions (Puerto Errado 1 and 2 in Murcia Spain, Lidellin Newcastle Australia, Kogran Creek in South West Queensland Australia, Kimberlina in Bakersfield California USA, Llo Solar in Pyrénées France,Dhursar in India,etc).

There are several critical decisions that must be taken in order to obtain a compromise and optimization between plant performance, cost, and durability. Some of these decisions go through the SF design: proper thermodynamic operational parameters, receiver material selection for high pressures, phase separators and recirculation pumps number and location, pipes distribution to reduce the amount of tubes (reducing possible leaks points and transient time, etc.), etc. Attending to these aspects, the correct design parameters selection and its correct assessment are the main target for designing DSG LF power plants. For this purpose in the recent few years some commercial software tools were developed to simulatesolar thermal power plants, the most focused on LF DSG design are Thermoflex and System Advisor Model (SAM).

Once the simulation tool is selected,it is made the study of the proposed SFconfiguration that constitutes the main innovation of this work, and also a comparison with one of the most typical state-of-the-art configuration. The transient analysis must be simulated with high detail level, mainly in the BOP during start up, shut down, stand by, and partial loads are crucial, to obtain the annual plant performance.

An innovative SF configurationwas proposed and analyzed to improve plant performance. Finally it was demonstrated thermal inertia and BOP regulation mode are critical points in low sun irradiation day plant behavior, impacting in annual performance depending on power plant location.

Keywords: Linear Fresnel, Direct Steam Generation, Solar Field Configuration, Direct Reheating LF DSG.

1. Introduction

LF DSG power plants are maturing as an alternative to traditional PTC HTF (oil, molten salt, etc). Big international companies are investing on LF DSG as a competitive power generation technology. Integrated Solar Combined Cycle (ISCC) is a way of cutting down fossil fuel consumption and reducing environment impact. But also stand-alone LF DSG power plants are feasible, backed by Thermal Energy Storage system (TES) or Auxiliary Boilers, to warranty dispatchable generation, and securing energy supply, overcoming sun irradiation transitory.

Nomenclature

LF	Linear Fresnel	SAM	System Advisor Model
DSG	Direct Steam Generation	LCOE	Levelized Cost of Energy
SF	Solar Field	HTF	Heat Transfer Fluid
OT	Once-Through	BOP	Balance of Plant
CSP	Concentrating Solar Power	TES	Thermal Storage System
USC	Ultra Supercritical Steam	ISCC	Integrated Solar Combined-Cycle
SC	Supercritical Steam	RC	Recirculation loop
PTC	Parabolic Trough Collector	TSE	Thai Solar Energy Co., Ltd.
ISCC	Integrated Combined-Cycle		

Future LF DSG plants design should be focused on reducing Levelized Cost of Energy (LCOE). The following obstacles are being under investigation and development: new LF collector configurations with higher optical performance, new materials for higher temperatures and pressures [1], Once-Through (OT) configuration [2, 3] and control system, TES system for LF DSG power plants, receiver tubes selective coating compatible with higher temperatures, supercritical turbomachinery scalability, etc.

In this paper, Themoflex [4] was compared versus SAM [5] for designing LF DSG plans; main advantages and disadvantages were identified. Table 1 summarised both software tools main capabilities. Main energy flows differences were detected and impact on power output and efficiency computed. This analysis is oriented to detect the main simulation gaps to improve the results, and makes an adequate evaluation of the proposed SF configurations. A more detailed comparison are summarised in Tables 4, 5, 6, 7, 8, 9 and 10.

We assumed as optimal live steam parameters at turbine inlet (500°C and 90 bar) as stated in by Novatec [6]. As demonstrated higher steam temperatures above 500°C reduce LCOE, but not compensate receivers heat losses.

Regarding to pressure increasing, LF DSG offers a great advantage in comparison with traditional PTC plants, thanks to the lack of movable joints (fixed plumbing reduces potential leaks). However, in this study we achieved a pressure increasing analysis, maintaining fixed turbine inlet temperature and SF effective aperture area. We concluded higher pressures above 90 bar increase power cycle efficiency but reduce electrical power output, in the other hand lower pressures increase power output but decrease cycle efficiency.

Reference SF configuration based on parallel recirculation (RC) loops, see Fig. 1 and 2, widely validated in DISS project was assessed with SAM and Thermoflex. An innovative patented SF configuration [7] was analysed, see Fig. 6 and 7. This new solution is based on liquid phase recirculation from steam drums to next LF DSG loops group, providing a more stable scenario in SF operation, and reducing temperature fluctuations at turbine inlet. See results in Table 13 and 14. OT configuration [2, 3], with water injections to reduce "dry-out" effects, was also modelled, result are summarised in the Conclusion.

SF design main targets were to optimise pressure drops, thermal losses, and pipes length in LF DSG receivers and SF headers. Another dealt issue was reducing the number of SF auxiliary equipments (reticulation pumps, steam drums, control system, etc.) and simplify SF control system.

Thermal inertia in receivers and headers also helps to operational parameters stabilisation during Sun radiation transitory, but during plant start-up thermal inertia is considered an energy consumption to be computed in plant annual performance, as considered in SAM software.

Finally, we confirm Direct Reheating steam with LF DSG modules; see Fig. 5, would be very beneficial in LF power plants due the following facts: increasing unitary net power (kW/m2) around 4%, and hence reducing LCOE. Also under low sun radiation periods, maintaining steam qualityabove 0.9 at latest low pressure turbine stage before condenser, and avoiding “fan phenomenon”, negative power, in low pressure turbine last stage. See in Table 11 and 12 simulation results.

2. LF DSG design software selection

SAM (System Advisory Model) [5], developed by U.S. Department of Energy's primary national laboratory (National Renewable Energy Laboratory NREL), was selected to obtain a very reliable and quickly SF basic design. SAM integrates an innovative BOP Off-line characterization, by means of regression plant performance maps, BOP operational modes simulation (Start-up, Standby, Thermal Inertia, etc), SF control (stow and deployment angles, etc) and plant annual performance calculation.

Thermoflex [4] was considered as an alternative flexible simulation graphical environment to design new LF DSG SF configurations. Thermoflex provides a solution to model energy balances in power plants by mean of solving non-linear equations systems by Newton-Raphson numerical method. Thermoflex flexibility for SF configuration modeling is the main reason to select this tool for ouranalyses.

Table 1.Comparison of capabilities for LF DSG power plant design.

	Thermoflex	SAM
Graphical simulation environment showing energy streams properties	Yes	No
SF configuration modeling flexibility	Yes	No
Meteorological data directly loaded from weather files (TMY2, TMY3, EPW)	No	Yes
SF thermal inertia consumed during start up, shut down and radiationtransitory	No	Yes
SF pressure drop accurate models (saturated steam Friedel correlation, compressible superheated steam, etc)	Yes	No
SF control parameters (flow limit, stow and deploy limit, freezing limit, stow wind, etc)	No	Yes
Receiver heat losses accurate model (Kandlikar, Dittus-Boelter HTC correlations)	Yes	No
Receiver tubes thickness calculation and stress limit.	Yes	No
BOP Off-Line annual performance innovative regression model capability	Yes	No
BOP operational modes (start up, shut down, stand by, etc)	No	Yes
SF and BOP parasitic energy looses detail (tracking power, etc)	No	Yes
Supercritical water SF and BOP simulation	Yes	No
BOP reheating LF DSG modules	Yes	No
Condenser part load levels	No	Yes
Financial, incentives, depreciation models	No	Yes

3. LF DSG SF alternatives configurations

The following LF DSG power plants are under construction or recently commissioned: Puerto Errado 1 and 2 in Murcia Spain, Lidell in Newcastle Australia, Kogran Creek in South West Queensland Australia, Kimberlina in

Bakersfield California USA, Llo Solar in Pyrénées France, Dhursar in India, etc). Also Thai Solar Energy Co., Ltd. (TSE) also constructed the first commercial PTC DSG power plant in the world. These SF configurationswere considered as key reference.

Common input data for SF configurations comparison are summarised in Table 2a, 2b, 2c, 2d and 3.

3.1. Reference SF Configuration

This configuration, illustrated in Fig. 1 and Fig. 2, is based on DSG RCparallel loops, widely validated during DISS project.Design point and plant annual performance were calculated with Thermoflex and SAM, results were compared in Tables4, 5, 6, 7, 8, 9 and 10.

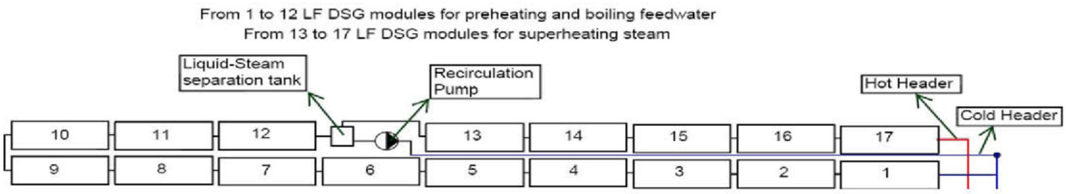

Fig.1. Reference SF unitary RC loop, similar to DISS projectunitary loop configuration.

Table 2a. LF DSG power plant location.

City	Dagget
Country	USA
Time zone	GMT-8
Elevation	558 m
Latitude	34.86 deg
Longitude	-116.8
Meteorological data	TMY3
Direct Normal (annual)	2723.5 kWh/m2

Table 2b. BOP main parameters.

Gross Power	50 MWe
Net Power	47.5 MWe
Gross Power to Net Power efficiency	0.94
Turbine Pressure Inlet (design-point)	90 bar
Minimum Pressure at Turbine inlet	45 bar
Turbine Temperature Inlet (design-point)	500 °C
High pressure Turbine inlet mass flow	53.46 kg/s

Table 2c. LFDSG and SF parameters.

Solar collector type	SuperNova [8]
Length (per Unit)	44.8 m
Width (per Unit)	16.5 m
Effective width (per Unit)	11.48 m
Effective aperture area (per Unit)	513.6 m2
Focal length	7.4 m
Nominal optical efficiency (boiling)	0.67
Nominal optical efficiency (superheating)	0.65
Cleanness factor	0.96
SF Solar Multiple	1
SF effective aperture area (Thermoflex)	227251 m2
SF effective aperture area (SAM)	227011 m2
Boiling modules SF effective aperture	161373 m2
Superheating modules SF effective aperture	65878 m2

Table 2d. LF DSG and SF parameters.

SF number of loops	26
Preheating and boiling modules per loop	12
Superheating modules per loop	5
Distance between two loops	4 m
SF inlet temperature (design point)	235 °C
SF outlet temperature (design point)	500 °C
SF outlet quality (design point)	0.8
Pressure drop across each loop	12 bar
SF thermal Power	132.4 MWth
Thermal inertia per unit area of solar field	2.7 kJ/K m2
LF boiler outlet steam quality	0.8
Hot headers length	1000 m
Cold headers length	1000 m

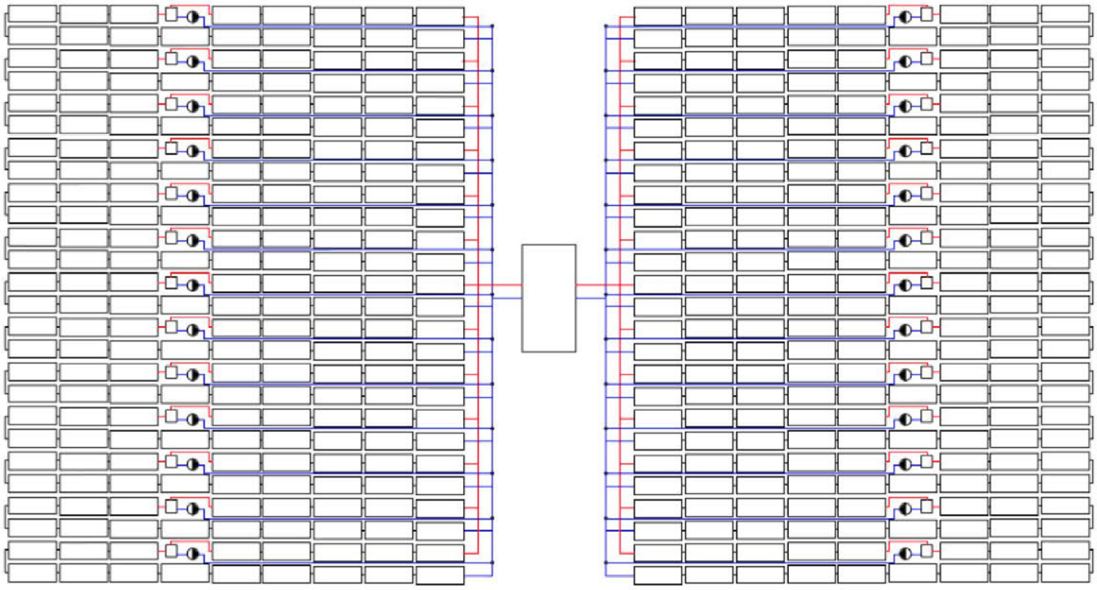

Fig. 2. Reference SF configuration based on parallel RC loops [8].

Table 3. Design Point 21st June meteorological data.

Time	11.5 hr
DNI	986 W/m2
Relative humidity	18 %
Dry bulb temperature	31.95 ºC
Wet bulb temperature	16 ºC
Site Altitude	588 m

Table 4. SF output comparison (Design Point 21st June).

	Thermoflex	SAM
Elevation	77.88 deg	77.91 deg
Zenith angle	12.12 deg	12.092 deg
Azimuth angle	159.1 deg	159.12 deg
Long.incidentangle	11.31 deg	11.31 deg
Transv. incidentangle	4.372 deg	4.372 deg

Table 5. SF output comparison (Design Point 21st June).

	Thermoflex	SAM
SF Incident energy	224.07MWth	223.83MWth
SF Received energy	133.92MWth	137.18 MWth
SF Thermal losses	6.6MWth	6.71MWth
SF Thermal power	127.32MWth	129.78MWth

Table 6. Boiling modules optical parameters (Design Point 21st June).

	Thermoflex	SAM
Optical Efficiency	67 %	67 %
Cleanliness factor	96 %	96 %
End Losses Factor	99.45 %	n/a
IAM	94.45 %	96%
Real optical efficiency (%)	60.42 %	61.74 %

Table 7.BOP output comparison (Design Point 21st June).

BOP	Thermoflex	SAM
Gross Power	50284kWe	51564kWe
Gross Efficiency	39.5 %	39.72 %
Net Power	47387kWe	48395.1 kWe
Net Efficiency	37.23 %	37.3%
Fan Power	1599.7 kWe	2708.25 kWe
Condenser Pump	61.76 kWe	131.93 kWe
Feedwater Pump	718.1 kWe	
SF parasitic	15.11 kWe	45.4 kWe
Fixed parasitic	502.84 kWe	283.25 kWe

Table 8. Superheating modules optical parameters (Design Point 21st June).

BOP	Thermoflex	SAM
Optical Efficiency	65 %	65 %
Cleanliness factor	96 %	96 %
End Losses Factor	98.71 %	n/a
IAM	94.45 %	96%
Real optical efficiency (%)	58.18 %	59.9%

Table 9. Main steams propertiesfor Reference SF configuration (Design Point 21st June).

BOP	Mass Flow (kg/s)	Pressure (bar)	Temperature (°C)	Entalphy (kJ/kg)	SteamQuality
1	53.51	101.5	239	1033.7	Subcooled Liq.
2	66.89	101.5	254	1104.8	Subcooled Liq.
3	13.37	101.5	308	1389.6	Subcooled Liq.
4	66.89	95.58	307.7	2464.5	0.8
5	13.37	95.58	307.7	1388.6	Saturated Liq.
6	53.51	95.58	307.7	2733.4	Saturated Steam
7	53.51	90.33	510.1	3412	Superh. Steam
8	53.46	87.7	508.9	3412	Superh. Steam
9	5.047	37.03	387.3	3190	Superh. Steam
10	2.622	14.39	271.8	2976.8	Superh. Steam
11	2.594	6.357	185.6	2816.4	Superh. Steam
12	2.423	3.13	135	2698.8	0.987
13	2.272	1.206	104.9	2563	0.946
14	1.903	0.3828	74.8	2417.4	0.907
15	36.6	0.0813	41.82	2265.2	0.87
16	43.25	9.75	42.82	180.1	Subcooled Liq.
17	43.25	9.356	69.06	289.8	Subcooled Liq.
18	43.25	8.976	98.93	415.2	Subcooled Liq.
19	43.25	7.378	128.9	541.2	Subcooled Liq.
20	53.51	104.7	161.6	688.1	Subcooled Liq.
21	53.51	103.6	189.9	811.3	Subcooled Liq.
22	53.51	101.5	239	1033.7	Subcooled Liq.

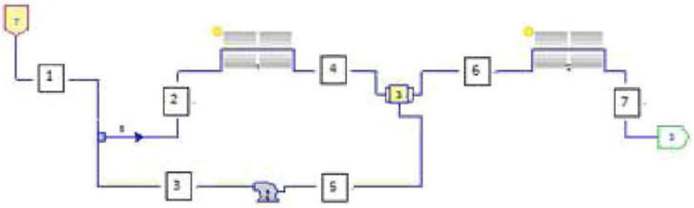

Fig. 3. SF Thermoflex model.

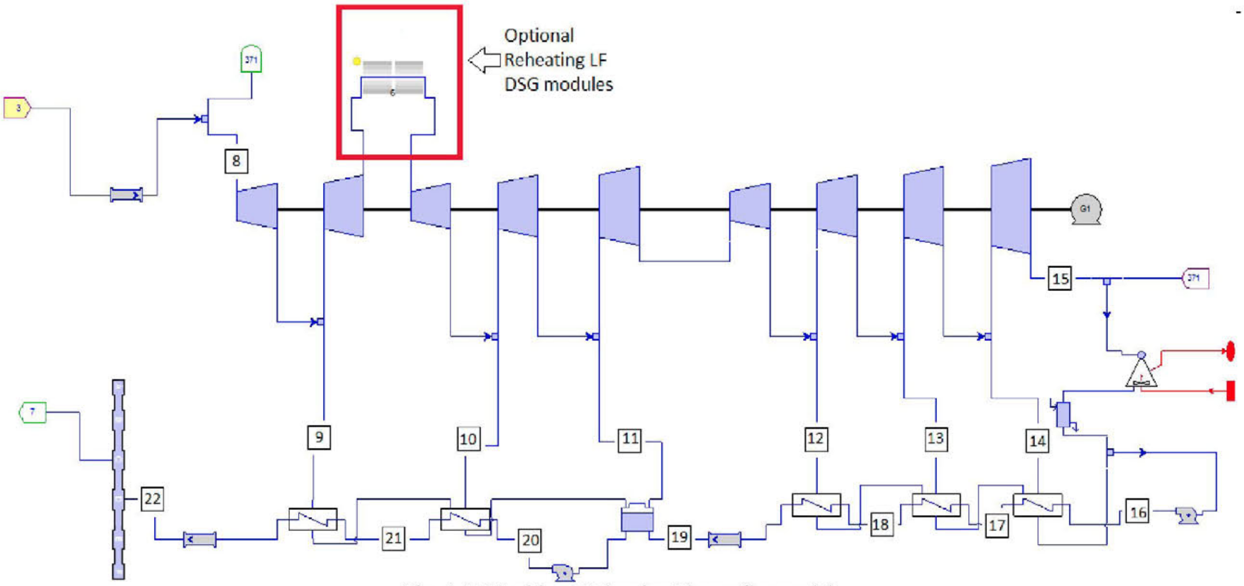

Fig. 4. BOP without Reheating Thermoflex model.

SAM calculates thermal inertia to heat up receiver and headers pipes during LF DSG plant start up and shut down. In Dagget, California, USA, cloudy days not impact two much in total annual performance power generated.

Table 10. Reference SF configuration, annual (monthly) plant performance.

	Thermoflex Gross Power (MWh)	SAM Gross Power (MWh)	Thermoflex Gross Power (MWh) *	Thermoflex Net Power (MWh)	SAM Net Power (MWh)	Thermoflex Net Power (MWh) *
January	2438	2336	2294	2330	2205	2189
February	3649	3577	3498	3482	3389	3334
March	6053	5871	5881	5769	5546	5600
April	8132	8009	7982	7721	7495	7573
May	10396	10282	10263	9838	9531	9705
June	11650	11539	11529	10930	10613	10807
July	11001	10772	10848	10273	9903	10119
August	10973	10848	10858	10282	9985	10166
September	8420	8324	8272	7933	7651	7786
October	5651	5404	5481	5363	4969	5197
November	3324	3024	3193	3173	2850	3045
December	2290	2275	2164	2187	2124	2063
TOTAL	**83977**	**82260**	**82263**	**79281**	**76262**	**77584**

* Note: Low pressure turbine last stage bypassed in low Sun radiation periods to avoid "fanphenomenon".

3.2. Reference SF configuration with Direct ReheatingLF DSG modules

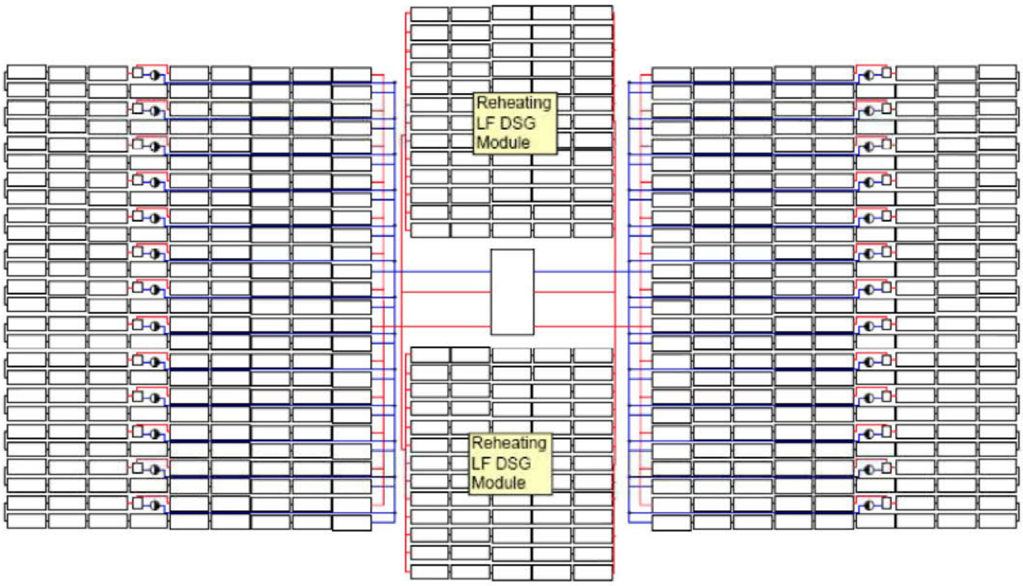

Fig. 5. First SF configuration base on parallel RC loops designed in DISS project. 50 MWe plant with 2 groups of 13 RC loops.Each loop with 12 boiling units and 5 superheating units (Novatec supernova [8]). The power block is located in the middle of the SF. Reheating loops are provided.

Table 11.Reference SF configuration output with Direct Reheating with LF DSG modules (Design Point 21st June).

Reheating Temperature (ºC)	Gross Power (MWe)	Gross Efficiency (%)	Net Power (MWe)	Net Efficiency (%)	Reheating aperture area (m2)	Total SF aperture area (m2)	Specific Net power (MWe/m2)
373	50460	38.3	47465	36.03	8139	235457	0.20158
400	52799	39.02	49755	36.77	14469	241787	0.20578
450	56963	40.17	53830	37.96	26282	253600	0.21226
500	59553	40.63	56349	38.44	34639	261957	0.2151
517	60508	40.82	57279	38.64	37524	264842	0.21627

Table 12. Reference SF configuration, annual (monthly) plant performance.Comparison between Reference SF config. with/without Reheating.

	Thermoflex Without Reheating Gross Power (MWh)	Thermoflex With Reheating Gross Power (MWh)	Thermoflex Without Reheating Net Power (MWh)	Thermoflex With Reheating Net Power(MWh)
January	2294	2770	2189	2651
February	3498	4143	3334	3960
March	5881	7081	5600	6767
April	7982	9563	7573	9108
May	10263	12393	9705	11764
June	11529	13826	10807	13019
July	10848	13099	10119	12279
August	10858	13027	10166	12250
September	8272	9924	7786	9379
October	5481	6555	5197	6237
November	3193	3767	3045	3603
December	2164	2602	2063	2487
TOTAL	**82263**	**98750**	**77584**	**93504**

3.3.An innovative LF SF configuration

This innovative solution [7] is based on liquid phase recirculation from steam drums to the next loops group, instead of recirculation liquid phase to the loop entrance; see Fig. 6 and Fig. 7. Auxiliary equipments are grouped (recirculation pumps, steam drums) to be shared between 4 loops. Also superheating and direct reheating loops are located around BOP, to reduce compressible steam pressure drops.

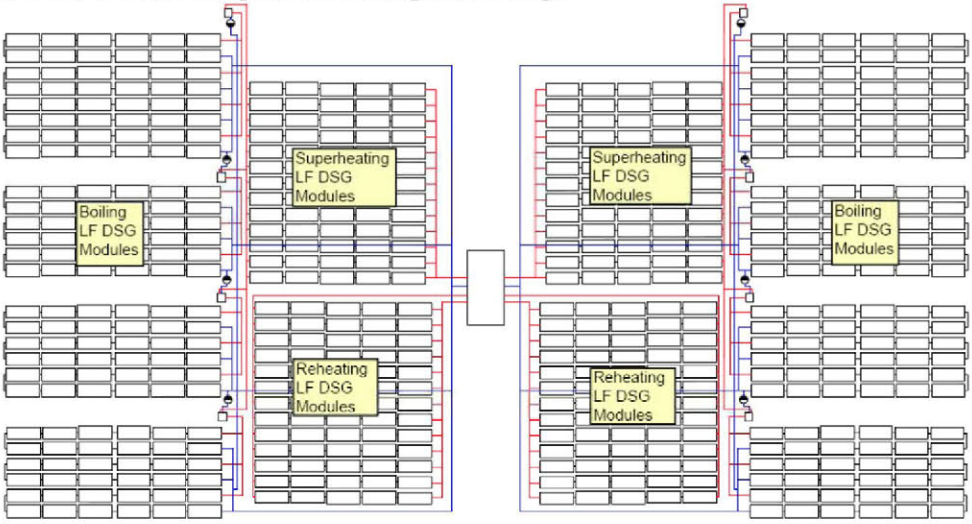

Fig. 6. The innovative SF configuration is a patented UPM solution [7] to reticulate liquid phase from one group of loops to the adjacent ones in order to optimise feed-water mass flow, and obtain an equilibrated behaviour between different loops groups, absorbing transitory in large SF.

Proposed innovative SF configuration [7], main advantages are listed below:
- SF output temperature fluctuations are minimizing during disequilibrium in solar radiance in LF collectors.
- During start up and shut down, or other SF transitory states due to low radiation, SF operates as a block, reducing temperature gradients, and heating up SF gradually.
- Feed water flow requirements from BOP are optimized.
- Recirculation control system widely experienced in DISS project is maintained. Only minor changes are required, as new control valve installation.
- New proposed SF configuration could be compatible and interchange at runtime with reference configuration, by means of opening and closing valves, depending on the SF operation mode selected.
- For huge SF (above 50 MWe or with TES system) configurations, the recirculation liquid phase to the entrance of the adjacent “zone” could be an operational practice to warranty SF homogeneous thermodynamic conditions.

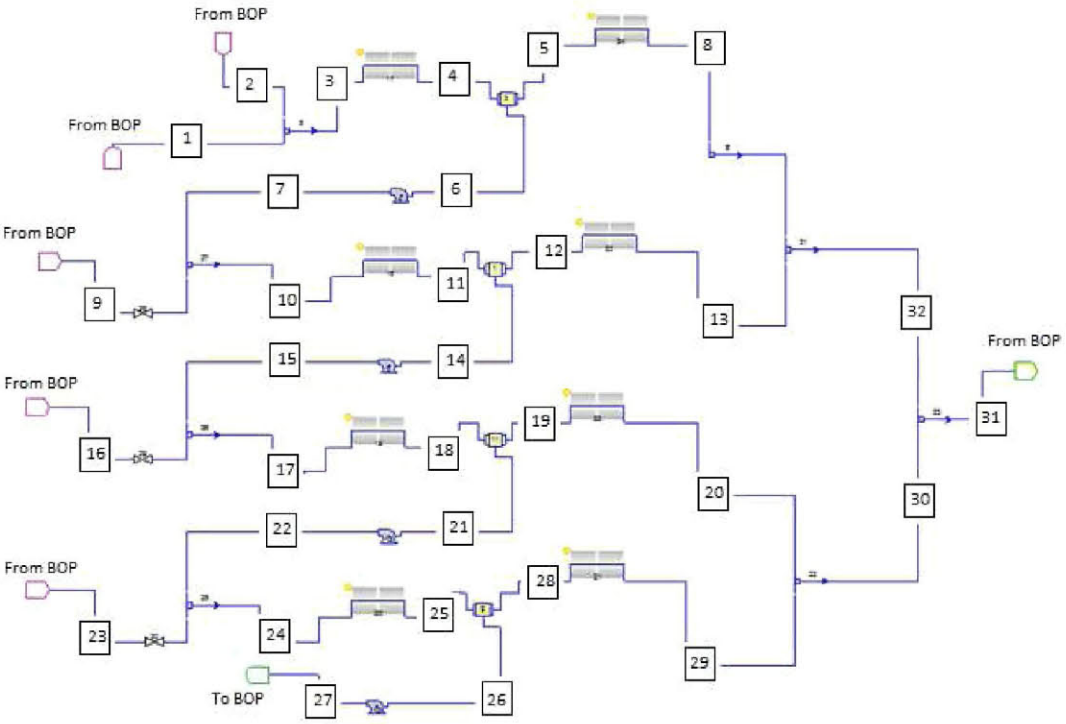

Fig. 7.The innovative SF configuration is a patented UPM solution to reticulate liquid phase from one group of loops to the adjacent ones in order to optimise feed-water mass flow and obtain an equilibrated behaviour between different loops groups, absorbing transitory in large SF.

4. Conclusions

Software design tool selection is a key stone in LF DSG power plants designing process. In this paper two main applications, Thermoflex [4] & SAM [5], were assessed. Themoflex provides a flexible simulation environment, adaptable streams configurations between equipments and components. SAM integrates a quickly and reliable annual plant performance tool. Also integrates SF and BOP control parameters. SF thermal inertia is computed as start up energy, impacting in annual plant performance, mainly at location with low Sun radiation levels. Synergy between both software tools development is required.

The power output increment in LF DSG power plants requires an analysis about the optimum SF configuration to reduce LCOE. Huge SF requires an equilibrium and stabilization in thermodynamic parameters in all integrating RC loops. During start up, shut down, irregularities in solar radiation in different loops, and other SF disequilibrium, could impact as thermal gradients and stresses in receivers pipes and headers. New configuration [7], see Fig. 6 and 7, main advantage is to maintain SF operation parameters stability. This configuration requires minor changes from the legacy DISS project. Also could be interchanged during runtime with reference configuration be means on opening and closing valves. In Table 13 and 14 it can be seen the resume of the main features of the patented SF configuration simulation.

Finally, OT configuration [2] is being developed in DUKE project [3] for PTC collectors. OT configuration presents another chance for LF DSG to reduce LCOE, and to be compatible and interchanged during operation with RC and innovative configurations studied in this paper. New emerging materials developed for fossil power plants [1] presumes an impact in OT configuration development, simplifying control system and increasing thermal stress allowance. OT configuration was also modeled in Thermoflex and SAM. Annual performance was 80779 MWh and 79799 MWh Gross Power, 76158 MWh and 73592 MWh Net Power respectively.These valuesgo up to 98639 MWh Gross Power, and 93460 MWh Net Power, with Reheating LF DSG modules.

Table 13.Main steams properties for innovative SF configuration (Design Point 21st June).

BOP	Mass Flow (kg/s)	Pressure (bar)	Temperature (°C)	Entalphy (kJ/kg)	Steam Quality
1	3.34	101	239	1033.7	Subcooled
2	13.36	101	308	1389.4	Subcooled
3	16.7	101	254	1104.8	Subcooled
4	16.7	95.53	307.7	2464.4	0.8
5	13.36	95.53	307.7	2733.5	1
6	3.34	95.53	307.7	1388.4	0
7	3.34	101	308	1389.4	Subcooled
8	13.36	90.58	514	3422	Superheat
9	13.36	101	239	1033.7	Subcooled
10	16.7	101	254	1104.8	Subcooled
11	16.7	95.53	307.7	2464.4	0.8
12	13.36	95.53	307.7	2733.5	1
13	13.36	90.58	514	3422	Superheated
14	3.34	95.53	307.7	1388.4	0
15	3.34	10	308	1389.4	Subcooled
16	13.36	101	239	1033.7	Subcooled
17	16.7	101	254	1104.8	Subcooled
18	16.7	95.53	307.7	2464.4	0.8
19	13.36	95.53	307.7	2733.5	1
20	13.36	90.58	514	3422	Superheated
21	3.34	95.53	307.7	1388.3	0
22	3.34	101	308	1389.4	Subcooled
23	13.36	101	239	1033.7	Subcooled
24	16.7	101	254	1104.8	Subcooled
25	16.7	95.53	307.7	2464.4	0.8
26	3.34	95.53	307.7	1388.4	0
27	3.34	101	308	1389.4	Subcooled
28	13.36	95.53	307.7	2733.5	1
29	13.36	90.58	514	3422	Superheated
30	26.72	90.58	514	3422	Superheated
31	53.44	90.58	514	3422	Superheated
32	26.72	90.58	514	3422	Superheated

Table 14. The innovative SF configuration, annual (monthly) plant performance.

	Thermoflex Without Reheating Gross Power (MWh)	Thermoflex Without Reheat Gross Power (*) (MWh)	Thermoflex With Reheat Gross Power (MWh)	Thermoflex Without Reheat Net Power (MWh)	Thermoflex Without Reheat Net Power (*) (MWh)	Thermoflex With Reheat Net Power (MWh)
January	2222	2251	2726	2120	2148	2611
February	3369	3420	4127	3211	3261	3949
March	5764	5864	6996	5489	5584	6687
April	7833	7894	9433	7431	7490	8986
May	10070	10110	12421	9522	9559	11792
June	11314	11389	13810	10603	10671	13007
July	10674	10740	12999	9951	10013	12187
August	10652	10710	13010	9975	10026	12246
September	8096	8201	9862	7617	7715	9323
October	5359	5404	6529	5080	5123	6215
November	3088	3133	3836	2943	2988	3670
December	2074	2102	2606	1977	2005	2495
TOTAL	**80520**	**81221**	**98357**	**75921**	**76586**	**93170**

5. Acknowledgements

The authors gratefully acknowledge Polytechnic University of Madrid (UPM) and Thermo energetic investigation group (GIT) for World International Patent ”Solar Power Plant for Direct Steam Generation” [7].

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