SolarPACES 2023, 29th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Emerging and Disruptive Concepts

https://doi.org/10.52825/solarpaces.v2i.918

Published: 20 Nov. 2024

Design of Coil-Wound Once-Through Steam Generator System for Concentrating Solar Power Plants

D. Pardillos-Pobo[1], P. A. González-Gómez[1], M. Berbey-Burgos[1], and D. Santana[1]

[1] Energy Systems Engineering Group (ISE), Department of Thermal and Fluid Engineering, University Carlos III of Madrid, Spain

Abstract. The viability of solar tower plants is endangered owing to multiple failures, mainly in their steam generators. These failures produce unscheduled shutdowns with significant economic losses that increase the financing costs of this technology due to its technological risk. On the other hand, if the flexibility of the steam generator rises, solar power tower plants could participate in the energy adjustment market, improving their returns, encouraging the penetration of variable renewable energies, and providing security to the power grid. A novel steam generator system design based on a once-through steam generator composed of two coil-wound heat exchangers is proposed for a highly reliable, flexible, and quick response steam generator. Coil-wound heat exchangers reduce thermal stress and allow part load operation, while once-through steam generators permit fast load changes and reduce the number of components. Compared with traditional shell and tube designs, the results indicate that the proposed steam generator reduces heat exchange area by 22%, molten salt pressure drop by 79%, and tube-to-tubesheet joints by 73%.

Keywords: Coil-Wound Heat Exchanger, Once-Through Steam Generator, Concentrating Solar Power Plants

1. Introduction

Power grids are integrating a great number of variable renewable energy sources, like photovoltaics, with low generation costs but a low contribution to the reliability of the electric grid. Therefore, flexible non-renewable power plants like gas turbine combined cycles are expected to play an important role in the power generation system [1]. Nevertheless, Solar Tower Plants (STP) could work as flexible plants generating electricity early in the morning, late in the afternoon, and overnight [2], with the possibility to participate in grid services like grid balancing, spinning reserve, or ancillary services [3]. The main cause of forced outage periods in flexible plants such as combined cycles is failures in the heat recovery steam generators [4]. Hence, due to construction similarities, the steam generator system (SGS) of STP operated as a flexible power plant could be considered the most critical component. In fact, a recent study presented by the National Renewable Energy Laboratory [5] reveals that the main concern of the STP industry was SGS reliability.

The design of the SGS of existing STP is based on conventional shell and tube heat exchangers, which employ thick plates called tubesheets that are susceptible to high thermal stresses under rapid transient operations. In addition, conventional shell and tube heat exchangers are typically designed following TEMA standards and ASME Section VIII-Div1, which do not include cyclic assessment, fatigue, or fatigue-creep analyses [6]. On the other hand, current STP operations only experience a daily startup and shutdown; therefore, SGS issues for the next generation of flexible STP will significantly worsen if the SGS designs are not improved.

The present work aims to increase the SGS reliability of current and future flexible STP by providing a new design based on a coil-wound once-through steam generator (Figure 1) where the preheater (PH) and evaporator (EV) will be accommodated in one shell (PH&EV) and the superheater (SH) and reheater (RH) will be in another shell (SH&RH). This new SGS design is expected to increase the reliability level of STP, reducing forced outages and keeping operational costs at suitable levels. In addition, an SGS design optimised for flexible operation will allow STP to participate in grid balance services, increasing their profits and helping to reduce the generation of non-renewable flexible power plants in the future.

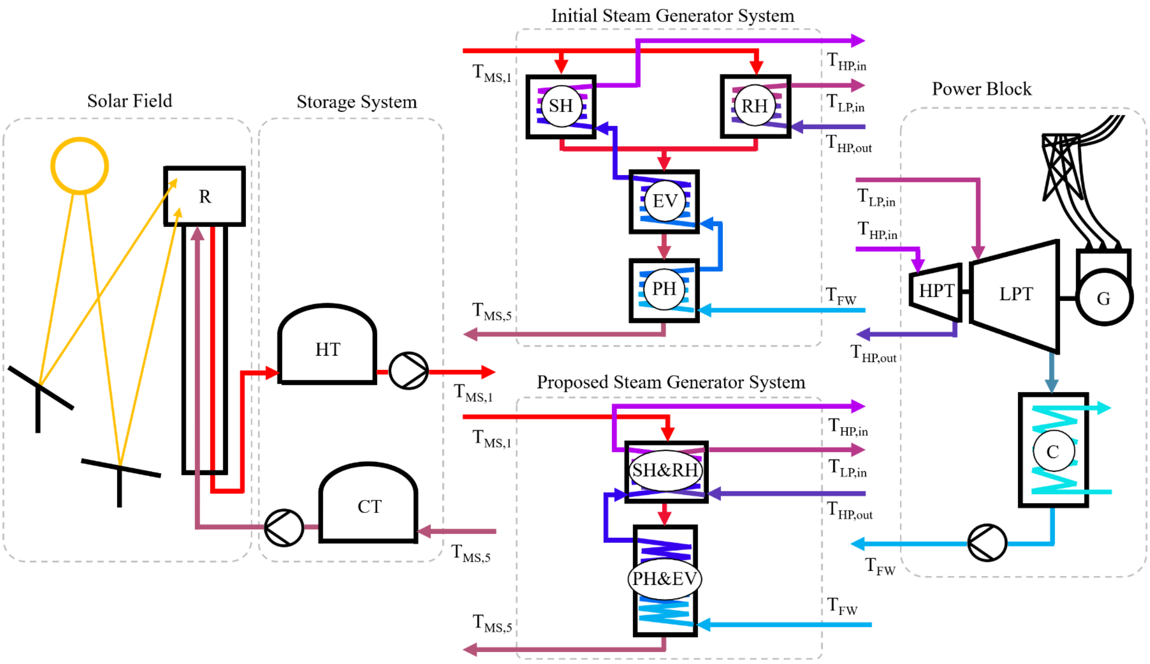

***Figure 1**. Initial and proposed steam generator system comparison in a solar tower plant*

Coil-wound heat exchangers (CWHE) can support extreme conditions, especially when fast and cyclical temperature and pressure changes are specified [7]. The use of CWHE for STP presents potential benefits such as the ability to absorb high differential thermal expansions between tubes and shell by means of a coiled tube bundle and the possibility of using a once-through steam generator layout, reducing the number of tube-to-tubesheet connections, which are susceptible to failure. In addition, the total number of SGS heat exchangers is reduced from 4 to 2 (Figure 1). Furthermore, CWHE has high performance under part load operations due to the possibility of separated parallel flow paths on the tube side. Consequently, the tubesheet diameter is reduced, which also decreases the thermal stress in tube-to-tubesheet connections under quick transients. Moreover, the heat transfer coefficient on the tube side is increased due to the curvature of the coiled tubes, which induces centrifugal forces and secondary flow perpendicular to the main fluid direction. However, CWHE has some difficulties in the design process and optimisation due to the high cost of manufacturing prototypes and doing experiments for such a large-scale heat exchanger. Therefore, an effective and reliable method to design and optimise CWHE is strongly required [8].

In the literature, there are different works about once-through steam generators employing CWHE [9, 10, 11]. The main conclusion of the literature review is that all works about once-through steam generators employing CWHE are applied to nuclear purposes. However, STP operating conditions are harder than nuclear systems because the high-pressure turbine inlet temperature grows from ~300 ºC to 550 ºC and the inlet pressure increases from ~60 bar to 126 bar. The more demanding working conditions will affect the CWHE mechanical design for STP applications, resulting in additional mechanisms of damage such as creep damage, creep-fatigue damage combination, and stress relaxation.

2. Coil-Wound Once-Through steam generator system

Figure 2 shows a conceptual scheme of the coil-wound once-through steam generator, where the preheater and evaporator are accommodated in one shell in series and the superheater and reheater are in another shell in parallel. Between the evaporator and the superheater is placed a separator to carry out the start-up processes more efficiently [12]. The separator vessel has a small size and a slight wall thickness compared with a traditional steam drum, enabling it to achieve temperature gradients of 10K/min, double that is permitted in the steam drum. This compact, once-through design increases STP flexibility because the steam generator enables for quick start-ups and load adjustment. This two coil-wound SGS design also allows for the reduction of a huge number of components between heat exchangers, like pipes or valves. Furthermore, each CWHE has different input tubes that allow part load operation without changing the operational conditions inside the tubes. Moreover, helical tubes function like springs, reducing thermal stress and therefore increasing reliability and capability for quick load changes.

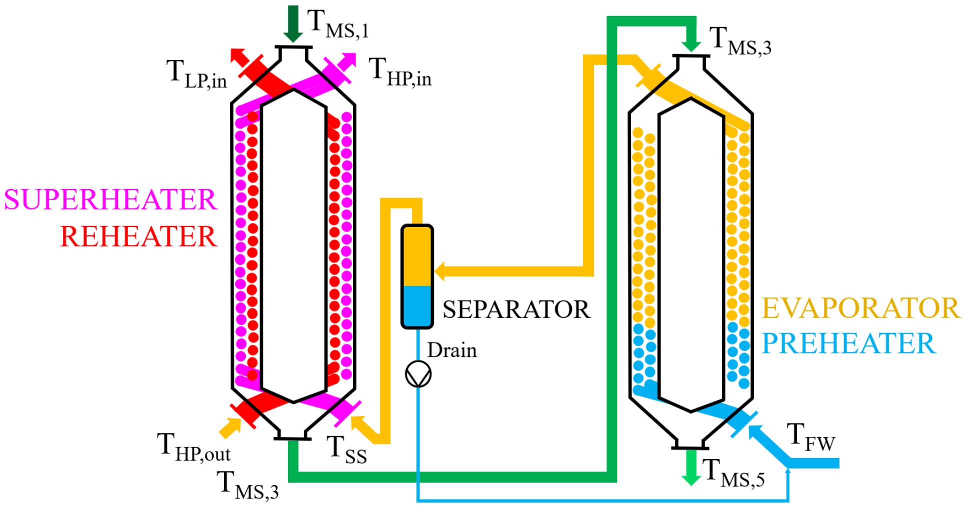

***Figure 2**. Coil-Wound Once-Through Steam Generator System*

The steam generator operation parameters (Table 1) come from P.A. González-Gómez et al. [13], where the Crescent Dunes solar power tower plant is analysed to optimise the steam generator. This solar power tower plant can generate 110 MWe with a 52% capacity factor, thanks to the 10 hours molten salt storage tanks. The solar field reflects the solar radiation into a tower receiver, which heats the molten salt from the cold tank ($T_{MS,5} = 286\ ºC$) and stores it in the hot tank ($T_{MS,1} = 565\ ºC$). The temperature of the molten salt in the evaporator inlet is about $T_{MS,3} = 447\ ºC$. The power block, which consists of a subcritical Rankine cycle with a regenerative system, has an efficiency of 44%.

Table 1. *Steam generator operation parameters*

SG point	Pressure (MPa)	Temperature (ºC)	Mass flow (kg/s)
High pressure in (HPT in)	12.6	550	86.92
High pressure out (HPT out)	3.4	371	78.70
Low pressure in (LPT in)	*	550	78.70
Feed-Water (FW)	*	245	86.92

*Subjected to pressure drop

3. Materials and method

3.1 Physical model

Figure 3 shows a conceptual CWHE to visualise the principal geometrical parameters. The geometrical design parameters are the following: outer tube diameter (d_o), radial tube pitch (PT_R), longitudinal tube pitch (PT_L), inner shell diameter (D_i), number of columns (N_C), and total number of tubes (N_T). The rest of the parameters, like inner tube diameter (d_i), outer shell diameter (D_o), space bar thickness (B), coil-wound angle (α), coil-wound pitch (S_C), and number of rows (N_R), can be determined geometrically. A deeper explanation of the geometry and the equations that relate the parameters to each other could be found in Xing Lu et al. work [14].

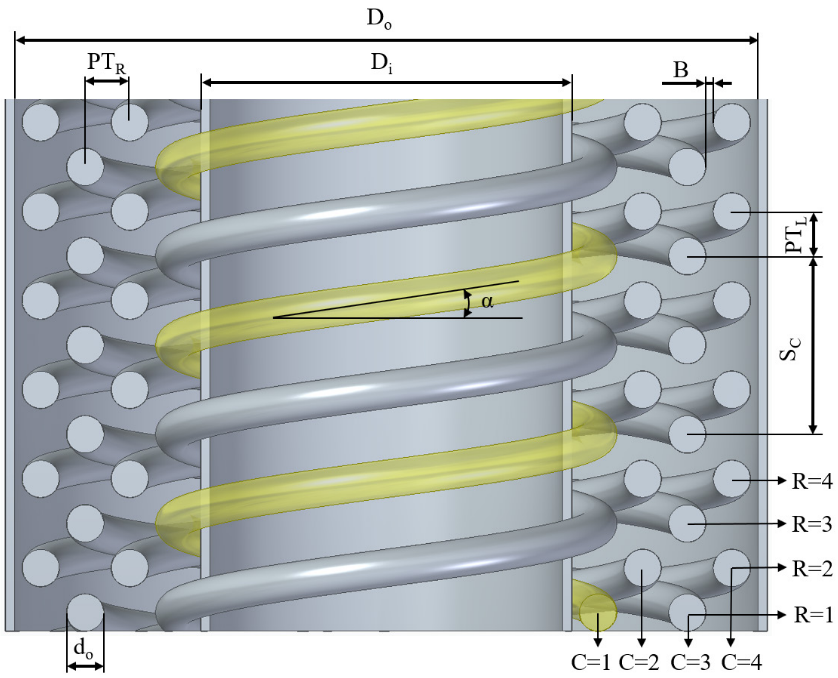

Figure 3. *Coil-Wound Heat Exchanger geometrical parameters*

3.2 Numerical model

The numerical model is based on the study of Yao et al. [15] about the thermal and geometrical parameters of a helical coil once-through steam generator system for nuclear reactors. Yao divides the once-through evaporation process into four zones: the subcooled water zone, the subcooled boiling zone, the saturated nucleate boiling zone, and the liquid deficiency zone. The shell side heat transfer calculation can be enhanced with the correlation of Tang et al. [16], which considers the winding angle of the coil-wound tubes.

3.3 Methodology

According to the numerical model, the thermal design of the Preheater&Evaporator should be carried out considering the different zones in the evaporation process. Hence, the heat transfer equation is solved through an explicit finite difference methodology in each increment of tube length (ΔL) until the vapour quality is 100%. The overall heat transfer coefficient (eq. (1)) and the heat transferred (eq. (2)) in each iteration (i) are determined considering prior iteration (i) properties. The same way, eqs. (3, 4) determine the next iteration (i+1) properties by means of previous iteration properties (i) and the heat transferred in the current iteration (i). The length of the medium coil is the sum of each increment of tube length (ΔL).

$$U(i) = \left[\frac{d_o}{d_i \cdot h_w(i)} + \frac{1}{h_s(i)} + R_s + \frac{d_o \cdot R_w}{d_i} + \frac{d_o \cdot R_t}{2} \cdot log\left(\frac{d_o}{d_i}\right)\right]^{-1} \tag{1}$$

$$\Delta Q(i) = U(i) \cdot \Delta L \cdot \pi \cdot d_o \cdot NT \cdot [T_w(i) - T_s(i)] \tag{2}$$

$$H_w(T_w(i+1), P_w(i+1)) = \Delta Q(i)/\dot{m}_w + H_w(T_w(i), P_w(i)) \tag{3}$$

$$T_s(i+1) = \Delta Q(i)/[\dot{m}_s \cdot cp_s(i)] + T_s(i) \tag{4}$$

On the other hand, the Superheater&Reheater can be solved through the medium logarithmic temperature difference (eq. (5)), due to the fact that the superheater and the reheater are single-phase heat exchangers. Point out that the superheater and reheater share the same shell; hence, the length of the medium coils should also be the same. Therefore, the relationship between the number of tubes in the superheater and the reheater is iterated until the length of both medium coils is the same. Hence, the overall heat transfer coefficient (eq. (6)) and the length of the medium coil tubes (eq. (7)) should be calculated in each iteration until convergence.

$$\Delta T_{lm,j} = \left[(T_{so} - T_{ji}) - (T_{si} - T_{jo})\right]/log\left[(T_{so} - T_{ji})/(T_{si} - T_{jo})\right] \tag{5}$$

$$U_j = \left[d_o/(d_i \cdot h_j) + 1/h_s + R_s + d_o \cdot R_j/d_i + d_o \cdot log(d_o/d_i) \cdot R_t/2\right]^{-1} \tag{6}$$

$$L_j = \dot{m}_j \cdot \Delta H_j/(U_j \cdot \Delta T_{lm,j} \cdot \pi \cdot d_o \cdot NT_j) \tag{7}$$

4. Results and discussion

Figure 4 shows the geometrical results of the steam generator system. The superheater (purple) and the reheater (yellow) are placed in parallel, while the preheater and evaporator are placed in series (blue). The coil-wound Preheater&Evaporator consist of a shell with a height of 13.59 m and an internal and external diameter of 1.50m and 2.17m, respectively. On the other hand, the coil-wound Superheater&Reheater consist of a shell with a height of 9.72m and an internal and external diameter of 1.50m and 2.63 m, respectively. Inside the internal diameter of the shell could be added freeze-protection electric heater elements, enhancing temperature control over molten salt compared to traditional shell and tube heat exchangers.

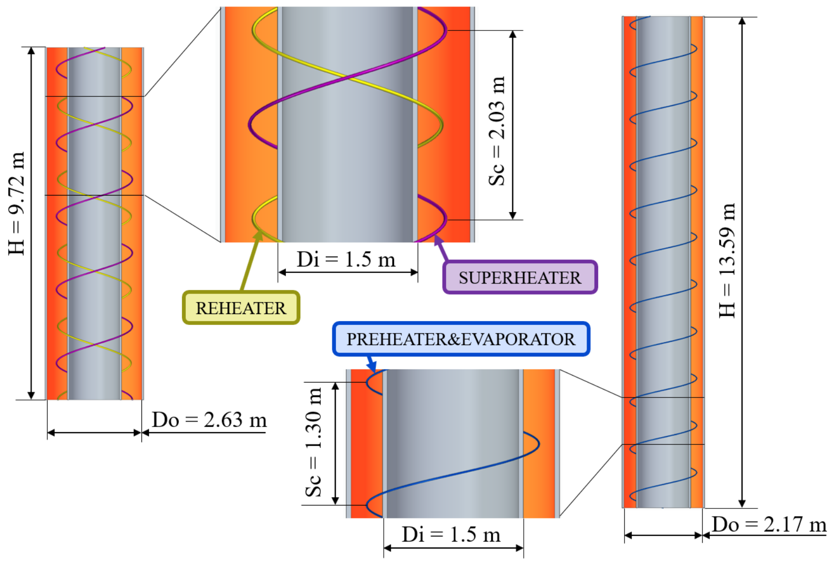

Figure 4. *Geometrical results of the steam generator system.*

4.1 Preheater&Evaporator

Table 2 and Table 3 show a comparison between the proposed Coil-Wound Preheater&Evaporator and the traditional shell and tube Tema F preheater and Tema E evaporator optimised by González-Gómez et al. [13]. By selecting the same type of tube, the number of tubes is reduced by a significant 77%, which means a smaller number of welds and, consequently, a reduction in cost and an improvement in reliability. The overall heat transfer coefficient is increased, reducing the heat exchange area by 31%. Molten salt pressure drop decreases by a significant 76% due to the coil-wound geometry, but water pressure losses are increased by 30% because of the high pressure drop of high quality vapour. Note that the effect of the molten salt pressure drop on the parasitic consumption of the plant is greater, as the flow rate of the molten salt is about 4 times higher than that of the steam.

Table 2. *Coil-Wound Preheater&Evaporator parameters compared to shell and tube.*

Parameter	**TEMA F Preheater**	**TEMA E Evaporator**	**Coil-wound Preheater&Evaporator**
Shell diameter, D_o (mm)	1600	1796	2171
Shell length, H (m)	11.04	9.43	13.59
Tubes ext. diameter, d_o (mm)	15.9	15.9	15.9
Tubes int. diameter, d_i (mm)	12.2	12.2	12.2
Tube pitch, PT_L=PT_R (mm)	23.9	20.7	20.7
Tube length, L_t (m)	22.08	18.86	61.70
Flow velocity (water), v_w (m/s)	0.61	2.53	$0.91 < v_w < 9.92$
Flow velocity (salt), v_s (m/s)	0.70	0.60	$0.67 < v_s < 0.71$
Conv. heat transfer coeff. (water), h_w (W/ºC·m2)	6598	27688	$10018 < h_w < 61639$
Conv. heat transfer coeff. (salt), h_s (W/ºC·m2)	4234	4200	$4381 < h_s < 5874$
Overall heat transfer coefficient, U (W/ºC·m2)	1448	1295	1540 2330

Table 3. *Coil-Wound Preheater&Evaporator performance compared to shell and tube.*

Parameter	**TEMA F PH + TEMA E EV**	**Coil-Wound PH&EV**	**Difference (%)**
Tubes number, NT (–)	1615 + 2737 = 4352	1000	-77.02
Pressure drop (salt), ΔP_s (kPa)	205 + 172 = 377	53 + 39 = 92	-75.60
Pressure drop (water), ΔP_w (kPa)	13 + 122 = 135	22 + 154 = 176	+30.37
Heat exchange area (shell), A (m^2)	1857 + 2597 = 4454	1746 + 1336 = 3082	-30.80

4.2 Superheater&Reheater

Table 2 presents a comparison between the traditional shell and tube U-shell type superheater and reheater optimised by González-Gómez et al. [13] and the proposed Coil-Wound Superheater&Reheater. The length and diameter of the superheater and reheater tubes are forced to be the same because both heat exchangers are arranged in parallel in the same shell. The reheater needs 54% less heat power than the superheater, hence the heat transfer area, and, in consequence, the number of tubes in the reheater should be lower. However, the reheated steam is less dense than the superheated steam, so the velocity of the reheated stream would be much higher than the superheated one. That explains why the velocity is unusually high in the reheater and low in the superheater. Point out that the velocity has an upper limit to ensure that erosion damage is not produced.

Selecting bigger tubes, the number of tubes is reduced by 65%, which means a great reduction of tube-to-tubesheet joints. The resulting overall heat transfer coefficient is slightly greater than the traditional shell and tube configuration, resulting in a modest 6% reduction of the heat exchange area. Molten salt pressure drop is significantly reduced by 88%. Owing to the unusually high and low velocities in the reheater and the superheater, the pressure drop in these heat exchangers is increased by 177% and decreased by 94%, respectively. Increasing the pressure drop of the reheater will affect the whole cycle, reducing the efficiency and electrical output of the cycle. However, the pressure drop of the reheater is below the maximum allowable pressure drop specified by the manufacturer of the steam power cycle, which is 2 bar [17].

Table 4. *Coil-Wound Superheater&Reheater parameters compared to shell and tube.*

Parameter	U-shell Superheater	U-shell Reheater	Coil-wound Superheater&Reheater	
Shell diameter, D_o (mm)	884	1010	2629	
Shell length, H (m)	10.41	11.05	9.72	
Tubes ext. diameter, d_o (mm)	15.9	25.4	31.8	
Tubes int. diameter, d_i (mm)	12.2	21.2	27.6	
Tube pitch, PT_L=PT_R (mm)	20.7	31.8	39.8	
Tube length, L_t (m)	20.81	22.09	32.6	
Flow velocity (water), v_w (m/s)	13.21	23.96	7.14	51.3
Flow velocity (salt), v_s (m/s)	0.65	0.50	0.44	
Conv. heat transfer coeff. (water), h_w (W/ºC·m2)	3649	1227	2084	2558
Conv. heat transfer coeff. (salt), h_s (W/ºC·m2)	5213	3656	3252	
Overall heat transfer coeff., U (W/ºC·m2)	1241	664	951	2330

Table 5. *Coil-Wound Superheater&Reheater performance compared to shell and tube.*

Parameter	U-shell SH + U-shell RH		Coil-wound SH&RH		Difference (%)	
Tubes number, NT (–)	1219 + 815 = 2034		462 + 252 = 714		-64.90	
Pressure drop (salt), ΔP_s (kPa)	149		18		-87.92	
Pressure drop (water), ΔP_t (kPa)	253	70	16	194	-94	+177
Heat exchange area (shell), A (m^2)	1133 + 1294 = 2427		1470 + 810 = 2281		-6.02	

5. Conclusions

The present work has introduced a novel design of a steam generator system based on a once-through steam generator composed of two coil-wound heat exchangers. The total steam generator heat exchange area is reduced by 22%, decreasing a significant 73% of the total number of tube-to-tubesheet joints, which are the most susceptible failure zone. Molten salts and main steam pressure drops are decreased by 79% and 51%, respectively, but the reheated steam pressure losses are increased by 177% due to the parallel superheater and reheater configuration.

Therefore, the thermal design results indicate that this novel design of steam generator system has better stationary performance than traditional shell and tube heat exchangers. In addition, the transitory performance would be much better because once-through steam generators permit fast load changes, coil tubes absorb high differential thermal expansions, and coil-wound heat exchangers allow part load operation.

In conclusion, this novel design of steam generator is a promising option for current and future solar power plants because the coil-wound once-through configuration could increase steam generator reliability and flexibility, reducing shutdown economic losses and increasing adjustment market returns for CSP plants. Further work will be done to develop a precise methodology to design coil-wound multi-stream heat exchangers and optimise a coil-wound once-through steam generator by means of an economic analysis.

Data availability statement

Data will be made available on request.

Author contributions

D. Pardillos-Pobo: Conceptualization, Methodology, Software, Visualization, Funding acquisition, Writing - original draft. P.A. González-Gómez: resources, Writing – review & editing, Funding acquisition. M. Berbey-Burgos: Writing – review & editing. D. Santana: Conceptualization, Resources, Writing – review & editing, Supervision, Funding acquisition.

Competing interests

The authors declare that they have no competing interests.

Acknowledgement

This research is funded under the projects: grant PID2021-122895OB-I00 funded by MCIN/AEI/ 10.13039/501100011033 and the ERDF A way of making Europe, grant TED2021-129326B-I00 funded by MCIN/AEI/ 10.13039/501100011033 and the European Union NextGenerationEU/PRTR, and the scholarship “Ayudas para la formación del profesorado universitario” (FPU-21/01212) awarded by the Spanish Ministerio de Educación, Cultura y Deporte (MECD).

References

1. Pablo Tapetado, Julio Usaola, “Capacity credits of wind and solar generation: The Spanish case”, Renew. Energy 143, 164-175, 2019. Doi: https://doi.org/10.1016/j.renene.2019.04.139
2. Ildo Agnetti, “Highly reliable steam generator system developed by John Cockerill Energy for peaker plants”, AIP Conf. Proc. 2303, 150001 (2020). Doi: https://doi.org/10.1063/5.0028683
3. Pablo del Río, Cristina Peñasco, Pere Mir-Artigues, “An overview of drivers and barriers to concentrated solar power in the European Union”, Renew. Sustain. Energy Rev. 81, 1019–1029, 2018. Doi: https://doi.org/10.1016/j.rser.2017.06.038
4. Sonja Wogrin, David Galbally, Andrés Ramos, “CCGT unit commitment model with first-principle formulation of cycling costs due to fatigue damage”, Energy 113, 227–247, 2016. Doi: https://doi.org/10.1016/j.energy.2016.07.014

5. Mark Mehos, Hank Price, Robert Cable, David Kearney, Bruce Kelly, Gregory Kolb, Frederick Morse, “Concentrating Solar Power Best Practices Study”, Technical Report No NREL/TP-5500-75763, 2020. Doi: https://doi.org/10.2172/1665767
6. Piotr Dzierwa, Dawid Taler, Jan Taler, Marcin Trojan, “Optimum heating of thick wall pressure components of steam boilers”, Proceedings of the ASME 2014 Power Conference, 2014. Doi: https://doi.org/10.1115/POWER2014-32080
7. Linde, “Coil-wound heat exchanger” (accessed 10/05/2022) URL: https://www.linde-engineering.com/en/images/Coil-wound-heat-exchangers_tcm19-407186.pdf
8. Tingting Wang, Guoliang Ding, Zhongdi Duan, Tao Ren, Jie Chen, Hui Pu, “A distributed-parameter model for LNG spiral wound heat exchanger based on graph theory” Appl. Therm. Eng. 81, 102–113, 2015. Doi: https://doi.org/10.1016/j.applthermaleng.2015.02.020
9. Yeon-Gun Lee, Jong-Won Kim, Goon-Cherl Park, “Development of a thermal-hydraulic system code, TAPINS, for 10 MW regional energy reactor”, Nucl. Eng. Des. 249, 364–378, 2012. Doi: https://doi.org/10.1016/j.nucengdes.2012.04.020
10. Genglei Xia, Yuan Yuan, Minjun Peng, Xing Lv, Lin Sun, “Numerical studies of a helical coil once-through steam generator”, Ann. Nucl. Energy 109, 52–60, 2017. Doi: https://doi.org/10.1016/j.anucene.2017.05.025
11. Qiang Lian, Wenxi Tian, Xinli Gao, Ronghua Chen, Suizheng Qiu, G.H Su, “Code improvement, separate-effect validation, and benchmark calculation for thermal-hydraulic analysis of helical coil once-through steam generator”, Ann. Nucl. Energy 141, 2020. Doi: https://doi.org/10.1016/j.anucene.2020.107333
12. Juergen Dersch, Jaime Paucar, Christian Schuhbauer, Axel Schweitzer, Alexander Stryk, “Blueprint for Molten Salt CSP Power Plant”, Final report of the research project “CSP-Reference Power Plant” No. 0324253, 2021. URL: https://elib.dlr.de/141315/ (accessed 10/05/2022)
13. P.A. González-Gómez, J. Gómez-Hernández, J.V. Briongos, D. Santana, “Thermo-economic optimization of molten salt steam generators”, Energy Convers Manag, 146, 228-243, 2017. Doi: https://doi.org/10.1016/j.enconman.2017.05.027
14. Xing Lu, Gaopeng Zhang, Yi-tung Chen, Qiwang Wang, Min Zeng, “Effect of geometrical parameters on flow and heat transfer performances in multi-stream spiral-wound heat exchangers”, Appl. Therm. Eng. 89, 1104-1116, 2015. Doi: https://doi.org/10.1016/j.applthermaleng.2015.04.084
15. Hao Yao, Guo Chen, Kailin Lu, et al. “Study on the thermal and geometrical parameters of helical coil once-through steam generator system”, Int. J. Adv. Nucl. React. Des. Tech. 3, 80-96, 2021. Doi: https://doi.org/10.1016/j.jandt.2021.07.001
16. Tang Q X, Chen G F, Yang Z Q, et al. “Numerical investigation on gas flow heat transfer and pressure drop in the shell side of spiral-wound heat exchangers”. Sci China Tech Sci, 2018, 61: 506–515. Doi: https://doi.org/10.1007/s11431-017-9176-9
17. J. Gómez-Hernández, P.A. González-Gómez, J.V. Briongos, D. Santana, “Influence of the steam generator on the exergetic and exergoeconomic analysis of solar tower plants”, Energy, 145, 313-328, 2018. Doi: https://doi.org/10.1016/j.energy.2017.12.129