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Preliminary assessment of sCO_2 power cycles for application to CSP Solar Tower plants

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Abstract

This work presents a preliminary thermodynamic assessment of three different supercritical CO_2 (sCO_2) power cycles integrated in a high temperature solar tower system, working up to 800°C. An indirect cycle configuration is considered with KCl-$MgCl_2$ molten salt as heat transfer fluid (HTF) in the solar receiver and a two tanks thermal energy storage (TES) system. The most promising cycle configuration is selected, optimizing the cycle turbine inlet temperature to achieve the best compromise between cycle and receiver efficiency. An estimate of the yearly energy yield of the proposed power plant is finally performed, indicating the possibility of reaching solar-to-electric efficiency of about 17.5%.

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Max 6 keywords: Supercritical carbon dioxide, sCO_2, solar tower, solar energy CSP

1. Introduction

Concentrating Solar Power (CSP) can play a fundamental role in the near future energy scenario, providing carbon-free, renewable and dispatchable electric energy to meet the increasing world energy demand. Although the Levelized Cost of Electricity of this technology is still non-competitive (ranging from 150 to 200 €/kWh_{el}[1]), a number of research programs are addressing its development and evolution[2][3]. Among the different CSP technologies, solar towers (ST) are the most promising in terms of potential LCOE reduction[2] thanks to the high concentration ratio that can be reached (from 500 to 2000), allowing for increased maximum temperatures and high efficiency thermodynamic conversion power cycles. Nowadays, about 430 MW_{el} of commercial ST plants are operating (mainly in Spain and in the US), while other 430 MW_{el} are under construction in China, US, Chile and South Africa and other 1500 MW_{el} are in the planning phase[4]. All the ST currently in operation are based on traditional Rankine steam cycles for the conversion of the thermal power. Supercritical carbon dioxide (sCO_2) cycles coupled with high temperature solar receivers are recognized to be a promising technology to reduce costs and at the same time increase the conversion efficiency. In this work, a preliminary thermodynamic

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assessment of three different sCO_2 power cycles, exploiting heat collected in a high temperature solar tower system is carried out. The maximum investigated temperature is set at 800°C. An indirect cycle configuration is assumed, where KCl-$MgCl_2$ molten salts are used as heat transfer fluid (HTF) in the solar receiver, allowing for a lighter receiver design (with cost benefits respect to a high pressure direct sCO_2 receiver) and allowing an easier integration with a Thermal Energy Storage (TES). The most promising cycle configuration is selected, optimizing the Turbine Inlet Temperature (TIT) to achieve the best compromise between cycle and receiver efficiency. An estimate of the yearly energy yield of the proposed power plant is also performed.

Nomenclature

p	pressure, bar	HT	High temperature
T	temperature, °C	PB	Power Block
DNI	Direct Normal Irradiance, kWh/m^2	SF	Solar Field
LT	Low Temperature	TES	Thermal Energy Storage
FOM	Figure of Merit	TIT	Turbine Inlet Temperature
HTF	Heat Transfer Fluid	W	Power, W

2. Design performance

2.1. Power Cycle

Three different sCO_2 power cycles, following the literature proposals of[5][6][7] have been investigated, evaluating their performance as function of the Turbine Inlet Temperature (TIT) and optimizing the other cycle parameters while setting 250 bar as turbine inlet pressure. The three selected options are Recompression (RR), Partial Cooling (PC) and Recompression Main Compression Intercooling (RMCI) cycles. All cycles are regenerative and their layouts are reported in Fig.1, while the main design assumptions are reported in Table 1.

In each cycle, the different sCO_2 streams exiting the regenerators and compressors have the same temperature, in order to minimize the irreversibility losses, while the minimum cycle pressure is optimized. In the PC and the RMCI also the intermediate pressure level is optimized through the RPR parameter, defined as:

$$RPR = \left(\frac{p_{max}}{p_{int}} - 1\right) \Big/ \left(\frac{p_{max}}{p_{min}} - 1\right) \qquad (1)$$

The heat rejection system is based on dry coolers, working with ambient temperature of 40°C, with a pressure drop of 2% on the CO_2 side and with electrical fan consumptions ($W_{aux,PB}$) assumed equal to 1.25% of the rejected heat. A schematic of the power cycles inserted in the overall system is also reported in Fig.1.

Table 1. Main assumptions for the power cycle simulation

Parameter	Value	Parameter	Value
Turbine inlet pressure (bar)	250	$\Delta p/p$ primary Heat Exchanger	0.015
Minimum temperature (°C)	51	$\Delta p/p$ heat rejection Heat Exchanger	0.02
LT/HT regenerator effectiveness	0.93/0.95	Compressor/Turbine isoentropic efficiency	0.89/0.93
$\Delta p/p$ Hp/Lp side of regenerator	0.01/0.015	Mechanical/Electrical efficiency	0.99/0.99

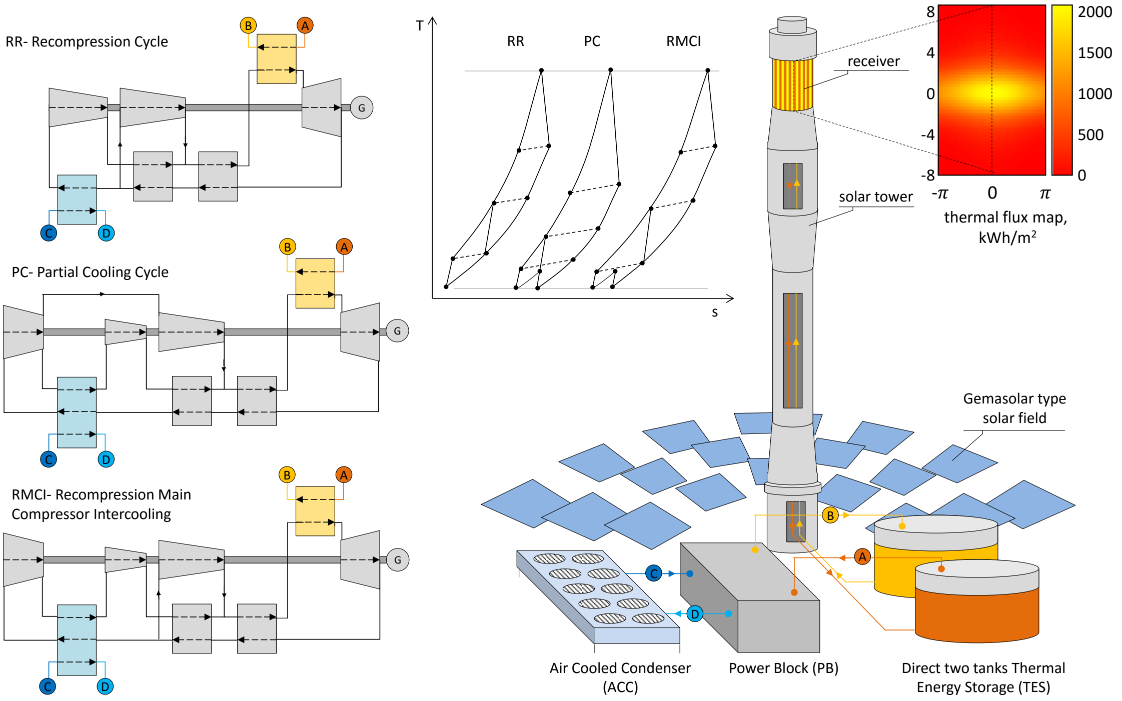

Fig. 1. Investigated sCO2 cycles layouts and overall system schematic

2.2. Tower and receiver

The solar field and the receiver geometry were assumed similar to the one of the Gemasolar plant, consistently with previous works[8][9][10]: the surrounding solar field consists of 2650 canted heliostats of 110 m^2 each, concentrating the solar radiation onto a tubular external receiver with a diameter of 8 m and 16 m high. The Solar Multiple is 2.8. The nominal optical efficiency and the map of heat flux concentrated on the receiver were computed with DELSOL3 [11] at solar noon on the spring equinox (March 21st) for the location of Sevilla (37°42' N, 5°9' W, DNI=2090 kWh/m^2-y). The calculated optical efficiency is 66.8%, assuming for simplicity all the heliostats aiming at the equator of the receiver [8]. The main geometrical parameters of the receiver are reported in Table 2 while the design heat flux map is the one reported in [10] and also shown in Fig. 1.

Table 2. Main characteristics of the ST receiver for a Gemasolar type plant.

Parameter	Value	Parameter	Value
Receiver height above ground (m)	138	Number of panels	16
Receiver Diameter, m	8	Number of tubes per panel	38
Receiver Height, m	16	Tube external diameter, m	0.0395
Number of flow path	2	Salts pump overall efficiency	0.75

In order to reach temperatures above 800°C, a preliminary screening of potential HTFs was performed, based on costs, required pumping power and heat exchange characteristics. The most suitable HTF and storage media is KCl-$MgCl_2$ salt, whose main characteristics are reported in Table 3. The selected material for the receiver was INCOLOY 800 HT, considered a good candidate to withstand the required temperatures, although detailed studies about its long-term chemical stability vs. the selected salt are not available.

Table 3. Main characteristics of the selected molten salt[12].

Parameter	Value	Parameter	Value
Molar Composition	67%KCl/33%$MgCl_2$	Viscosity @ 700°C (cP)	1.44
Solidification temperature (°C)	426	Thermal conductivity @ 700°C (W/m-K)	0.39
Boiling temperature (°C)	>1418	FOM (forced convection, turbulent)	5.66
Density @ 700°C (kg/m^3)	1593	FOM(heat exchanger area)	39.7
Specific Heat @ 700°C (kJ/kg-K)	1.1555	Estimated Cost (€/kg)	0.26

A simplified thermal resistance model [13] adapted from [14] was used for the evaluation of the receiver thermal losses. The model was initially tested for the Gemasolar operating temperatures (290°C-565°C), with Solar Salts as HTF: although no performance data are available for the Gemasolar receiver, the obtained thermal efficiency of 84.3% appears to be in the range of efficiencies reported by [14][15]. For the present study, the thermal performance of the receiver as function of the TIT were computed assuming a constant ΔT of 15°C between the selected salts and the sCO_2 in the primary heat exchanger. A rigorous analysis should consider an optimized number of flow paths as function of the molten salts ΔT and mass flow rate, however, the effect of a different flow paths arrangement on the receiver efficiency is limited as reported in [16] and thus a fixed number of flow paths was considered. On the contrary a more marked effect can be highlighted for the molten salts circulation pumping power ($W_{aux,\mathrm{SF}}$) and thus calculation was performed assuming the same tube mass flow rate of the Gemasolar case and taking into account also the tower height.

3. Results

The three plant layouts are compared on the basis of the nominal power output, while a more detailed year simulation is carried out only for the most promising plant configuration.

3.1 Nominal results

In Fig.2 the cycle gross efficiency, the receiver thermal efficiency and the system net power ($W_{NET} = W_{cycle} - W_{aux,SF} - W_{aux,PB}$) is reported for thethree cycles as function of the TIT: it is possible to highlight the contrasting effects of the TIT on the cycle efficiency and the receiver thermal efficiency resulting in a maximum power output for each investigated plant.

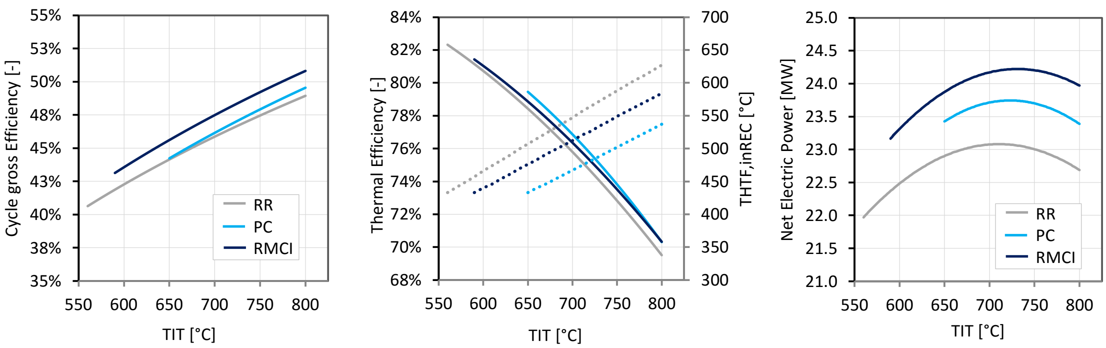

Fig. 2. (Left) Cycle Gross efficiency, (Center) Receiver efficiency and (Right) net power of the three investigated cycles layouts as function of the TIT.

A maximum net electric power of about 24.2 MW_{el} was obtained by the RMCI cycle for a TIT temperature of 730°C, with a corresponding solar to electric efficiency of about 23.4%. The receiver thermal efficiency is of 74.7%, with molten salts rising their temperature in the receiver from 534°C up to

745°C, while the cycle gross efficiency is of about 48.5%. The RMCI cycle with a TIT of 730°C was thus selected for the yearly simulation.

3.3. Yearly results

The yearly simulation was performed on hourly basis using the DNI and ambient temperature data available in [17]. The optical efficiency as function of Azimuth and Zenith is the same reported in [18] and obtained with DELSOL 3. The receiver thermal efficiency was assumed to be function of both the solar power and the heat flux distribution on the receiver. In order to limit the number of simulations, the thermal efficiency was computed for nine different sun positions and for each hour of the year the closest irradiation map was selected. A schematic of the nine different flux maps selection procedure is reported in Fig.3, Left: thanks to the N-S solar field and receiver symmetry the same maps can be used either before or after solar noon. In Fig.3, Right, the thermal efficiency for the different maps is computed as function of the incident thermal power.

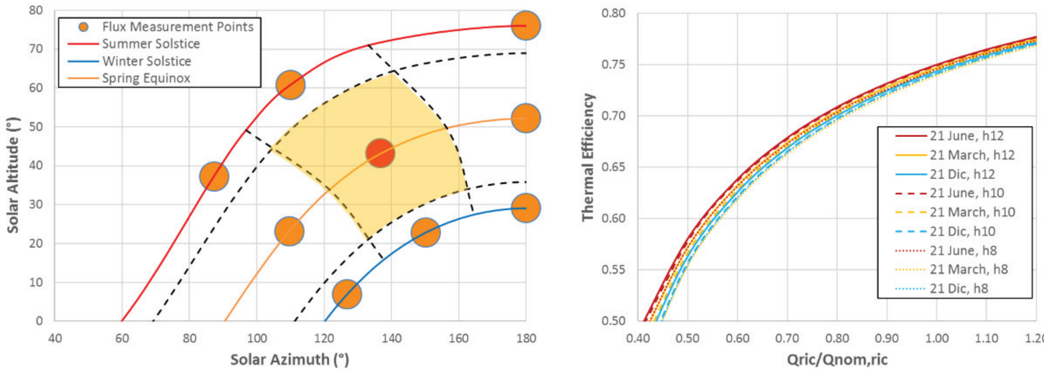

Fig. 3. (Left) Nine flux reference maps and selection procedure and (Right) thermal efficiency as function of the incident thermal power on the receiver for the nine reference maps.

Assuming a large TES size similar to the one of the Gemasolar (13h), allows the power block to operate at nominal molten salt mass flow rate throughout the year. The minimum cycle temperature and pressure are also kept constant assuming a variable consumption of the heat rejection system. Fan consumption is calculated based on the power consumption at 40°C ($W_{aux,PB,40}$), according to the following correlation obtained from preliminary design of the required dry coolers [19]:

$$W_{aux,PB,T_x} = (0.189 + 0.015T_{amb} - 9.45 \cdot 10^{-4}T_{amb}^2 + 2.70 \cdot 10^{-5}T_{amb}^3)W_{aux,PB,40} \quad (2)$$

The molten salts pumping power for every hour was determined taking into account the HTF flow variation. The yearly results for the MRCI case are reported in table 4, according to the chain of efficiencies, as suggested in [20].

Table 4. Yearlyresultsfor the RMCI case (in brackets the nominal efficiency values).

Parameter	Value	Parameter	Value
Yearly Optical Efficiency (%)	60.95 (66.8)	Yearly Solar Field Aux Efficiency (%)	97.87 (97.96)
Yearly Thermal Efficiency (%)	60.80 (74.7)	Yearly Solar-to-Electric Efficiency (%)	17.51 (23.4)
Yearly Net PB Efficiency (%)	48.29 (47.90)	Yearly Net Electric Energy (GWh)	106.7

The yearly solar-to-electric efficiency of 17.5% is comparable with the one that was obtained for a standard Gemasolar type plant (18.2%), underlying how the advantages in terms of PB conversion efficiency are counterbalanced by the limited receiver thermal performance.

4. Conclusions

This work discussed a preliminary assessment of the application of different (sCO_2) power cycles to high temperature solar tower system, working up to 800°C. The analysis focused on the plant energy balances, assuming an indirect cycle configuration using KCl-$MgCl_2$ molten salt as high temperature fluid in the receiver, integrated with a Thermal Energy Storage system, and adopting radiations maps derived through the simulation of a Gemasolar-type solar field. The most promising cycle configuration turns out to be a RMCI cycle, with an optimized TIT of 730°C, which achieves the best compromise between cycle and receiver efficiency. The yearly energy yield is of 106.7 GWh, with a solar-to-electric efficiency of 17.5%. The obtained efficiency is comparable with the one estimated for a Gemosalar type power plant, based on Rankine cycle (18.2%): this result shows how the advantage achieved in the power cycle is counterbalanced by the poor receiver performances. The strong performance decay of the receiver for low incident radiation suggests a possible advantage on yearly basis for lower design TIT, requiring further analyses. Alternative solutions to enhance the overall efficiency can be based either on direct sCO_2 receivers or on the use of different HTF, allowing for more compact and highly efficient receivers design (e.g. liquid sodium receivers). From an economic point of view, the cost savings on the power block [7] have to be compared with the increased cost of the receiver and of the TES.

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