Optimization of a Decoupled Combined Cycle Gas Turbine Integrated in a Modular Multi-Tower Solar Power Plant

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1. Introduction

The CAPTure project is aimed at developing and combining various innovative concepts of next-generation CSP plants in order to maximize their overall efficiency and dispatchability, all of which are key factors towards competitiveness on the power market. This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 640905.

With the Modular Multi-Tower Decoupled Solar Combined Cycle concept developed in CAPTure, a small solar-driven gas turbine is located atop each modular tower. An innovative volumetric air receiver uses a primary loop of atmospheric air as heat transfer fluid. The primary air heats the gas turbine's working air by means of a fixed-bed regenerative system. The waste heat from the exhaust of all gas turbines is recovered through one or two heat transfer fluids (in order to cover the whole temperature range) that are also used as media of a centralized thermal storage system. The heat extracted from this direct storage system is then converted into dispatchable power through a mutualized, industrial-scale steam turbine. As part of the project, various validation-scale prototypes of the key elements as well as a complete unit including a solar receiver and a gas turbine will be developed and tested.

The objective of this paper is to assess various design options regarding the design of the power cycle of a utility-scale plant based on the modular multi-tower decoupled solar combined cycle concept developed in the CAPTure project.

2. Topping cycle (i.e. gas turbine) including primary air loop and regenerative system

2.1. Layout envisioned – Simulations performed

Thermoflex models were built in order to match the thermal performances of a 50 kWe topping pilot gas turbine and to be able to discuss the underlying hypotheses. A TIT of 850°C (obtained without supplementary firing) and a pressure ratio of about 10 were considered. Realistic hypotheses were made regarding the compressor and expansion polytropic efficiencies. A multi-shaft gas turbine layout was considered (low pressure, high pressure and power turbine) with an intercooling between the LP and HP compressors. The main design options and the key parameters were compared, thermal performance being the main criterion.

The regenerative system was simulated as a heat exchanger. Two hypotheses (very optimistic: 1% and rather conservative: 10%) were made regarding the leakage rate and the relative pressure losses affecting the primary air loop.

2.1. Main results

The main results are summarized on Table 1 below.

	1% leakage & ΔP/P	**10% leakage & ΔP/P**
Gross efficiency	16.8 %	16.5 %
Net efficiency	16.3 %	12.9 %
Auxiliary consumption	3.5 % of gas turbine elec. output	22.8% of GT elec. output

Table 1 – Gross and net efficiencies and auxiliary consumption of the topping cycle depending on the leakage rate and the relative pressure loss of the regenerative system on the primary air side

The relative pressure loss of the regenerator on both sides (primary air and working air) is by far the most critical parameter regarding the performances of the topping cycle. Conversely, the impact of the leakage rate affecting the primary air loop is rather low.

3. Combined cycle including direct storage system inserted between topping cycle and HRSG

3.1. Layouts envisioned – Simulations performed

A complete utility-scale combined cycle was modelled, still using the Thermoflex software. As in § 2 above, a TIT of 850°C was considered, as well as 1% and 10% leakage rates and pressure drop ratios on the primary air side. An 85% polytropic efficiency (realistic for a ~10 MWe gas turbine) was considered for both the compression and the expansion. Regarding the bottoming cycle, three layouts were considered that can be characterized by the heat recovery steam generator (HRSG) and the heat transfer fluids: 1) 3-pressure reheat HRSG with binary salt and medium-temperature oil; 2) 3-pressure reheat HRSG with ternary salt and low-temperature oil; 3) 2-pressure reheat HRSG with ternary salt only.

Only the bottoming cycle produces dispatchable power (thanks to the intermediate storage system): about 100 MWe that account for roughly half (depending on the configuration) of the total power output. The steam characteristics of the 3-pressure steam cycle are as follows: HP 100 bar/480°C, reheat 24 bar/480°C, LP 3.35 bar/226°C.

3.2. Main results

The main results are summarized on Table 2 below.

Heat transfer fluid / Storage medium	Bottoming cycle	Share of dispatchable power	1% leakage & ΔP/P		10% leakage & ΔP/P	
			Gross eff.	Net effic.	Gross eff.	Net effic.
Binary salt + mid-T oil	3P-Reheat	57.7%	43.1%	40.5%	42.6%	37.2%
Ternary salt + low-T oil	3P-Reheat	50.0%	41.9%	39.8%	41.2%	35.9%
Ternary salt only	2P-Reheat	46.4%	40.7%	38.8%	40.1%	35.3%

Table 2 – Gross and net efficiencies of the power cycle depending on the performances of the regenerative system and the configuration of the intermediate storage system and the bottoming cycle

Layout 1), however the most expensive and hazardous, provides the highest fraction of dispatchable power (i.e. output of the bottoming cycle) and the best overall net efficiency (about 40%). Layout 2) uses a largely reduced volume of cheaper oil; its heat rate is 1.8% higher than that of layout 1). Layout 3) is the cheapest and its heat rate is 4.4% higher than that of layout 1).

4. Key Conclusions

The main conclusions of this study are as follows:

- The performances of the regenerative system have a critical impact on the performances of the plant;
- With TIT~850°C, the efficiency is not higher than that of current Rankine steam cycles (~42%). Other studies showed that a reheat on the topping cycle increases the cycle efficiency by about 3 percentage points. However, the need of a second regenerator would greatly increase the plant's complexity.

References

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