POLITECNICO
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SCUOLA DI INGEGNERIA INDUSTRIALE
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Executive Summary of the Thesis

Operating strategies to tackle the effect of the increase of ambient temperature on the performance of dry-cooled coal power plants based on supercritical CO2 power cycles

Laurea Magistrale in Energy Engineering - Ingegneria Energetica

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Academic year: 2021-2022

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1. Introduction

Nowadays one of the biggest challenges is the battle against climate change. This situation is mainly caused by the greenhouse gases emissions from the energy sector and is therefore pressing to shift towards more sustainable energy sources. However the transitioning towards renewable energy sources cannot be immediate as their intermittent nature may cause problems to the grid operation[2]. Conventional plants could foster the integration of renewable energy sources (such as wind and solar) by providing fluctuating back-up power, however these plants are currently not able to work with such flexible operation and is therefore necessary to develop new power cycle technologies.

2. sCO2-Flex project

The sCO2-Flex project is an EU-funded H2020 research project developed within the previously presented scenario, it aims to design a dry-cooled sCO2 Brayton cycle power plant capable of satisfying the EU objectives in term of efficiency and flexibility. Other objectives are also the reduction of greenhouse gas emissions, residue disposal and, above all, water consumption. Supercritical CO2 cycles for power generation are gaining a large interest from industry, institution and academia. The advantages of the sCO2 power cycles can be see in comparison to the Ultra Super Critical (USC) steam cycle technology, defined as its possible competitor in the future energy market. This new kind of power plant can do better with respect to USC since they show potential higher efficiency, compactness of the turbomachinery, no need of water treatment, high performance in part-load and fast transients. However not only advantages comes from transitioning towards supercritical CO2 cycles, as in the proximity to the critical point the thermodynamic conditions change significantly even with slight variations. This could lead to problems in the components operation, specifically the main compressor[1]. The cycle configuration selected for the 25Mwel sCO2-Flex plant is a recompressed Brayton cycle with HTR Bypass, depicted in Figure 1.

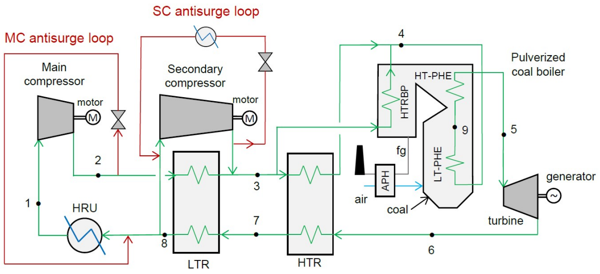

Figure 1: Plant layout: Recompressed cycle with HTR bypass configuration[3].

A significant component that needs to be highlighted in the layout is the air cooled Heat Rejection Unit (HRU). Thanks to this component it will in fact be possible to reduce by 100% the water consumption of the cycle. However, differently from water-cooled HRU that can benefit from a relatively stable minimum temperature of the cooling medium, for dry-cooled units the ambient temperature variation on daily and seasonal base can affect the cycle minimum temperature with a consequent impact on sCO2 power plant performance and operability. The HRU is able to tackle this problem in a reduced way. Acting on the rotational speed of the fans is possible to change the CO2 set point temperature, but there is an upper limit to this intervention set at 125% of the design rotational speed. Simulations assessed that this range of operation is useful only from design ambient temperature to a maximum temperature of 22°C. The objective of this thesis was to find feasible operating strategies able to tackle the effect of the ambient temperature increase on the performance of a dry-cooled coal power plant based on supercritical CO2 power cycles.

3. The effect of ambient temperature increase

The ambient temperature increase is a major problem of dry-cooled sCO2 power plants. In the previous paragraph it is stated that the HRU is able to mitigate this problem only if the increase does not exceeds the value of +2°C from the nominal conditions of 20°C. Therefore, above the value of 22°C the Compressor Inlet Temperature will increase. From Figure 2 is possible to notice that due to the operation in the supercritical region the density will significantly decrease with the increase of the CIT.

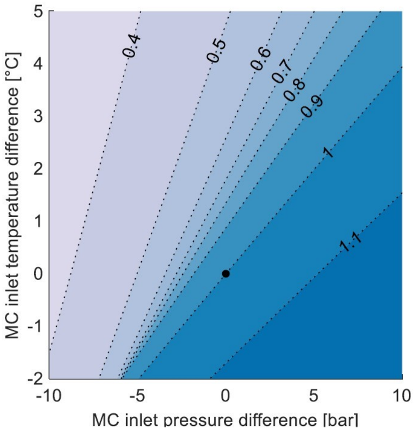

Figure 2: Ratio between the local density of CO2 and the density at main compressor inlet point in nominal conditions[3].

This situation will lead to an abrupt increase of the main compressor volumetric flow rate, this will cause the operating point of the main compressor to reach the upper limit of its performance map (see Figure 4). In order to tackle this problem a strategy is initially proposed that however shows numerous limitations at high ambient temperatures. The strategy, that will be denominated *Standard strategy*, divide the operation in four different operative region and different solutions are proposed depending on the region, Figure 3.

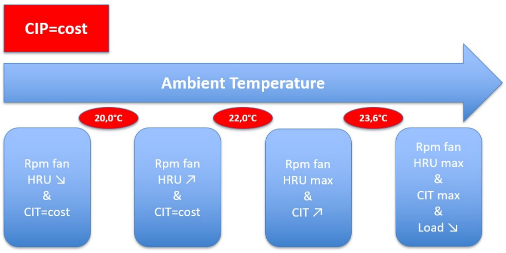

Figure 3: Standard operating strategy.

With T_{amb} lower than the design conditions (20°C), and T_{amb} higher than design and lower than 22°C is suggested the variation of the HRU fan in order to avoid changes of the main compressor inlet conditions. In the first case the RPM will need to decrease while in the latter to increase. At 22°C the HRU fan rotational speed reaches its upper limit, therefore when T_{amb} is between 22°C and 23.6°C the CIT will increase until it reaches the upper limit of the compressor map. Afterwards (T_{amb}>23.6°C) in order to keep the the operating point inside the compressor maps the thermal input (Load) is decreased. The compressors curve of operation is showed in Figure 4 and 5.

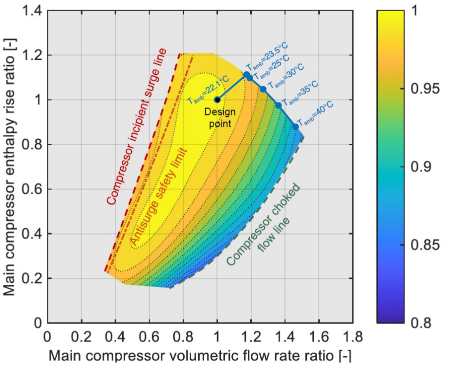

Figure 4: Main compressor operating points as a function of the ambient temperature[4].

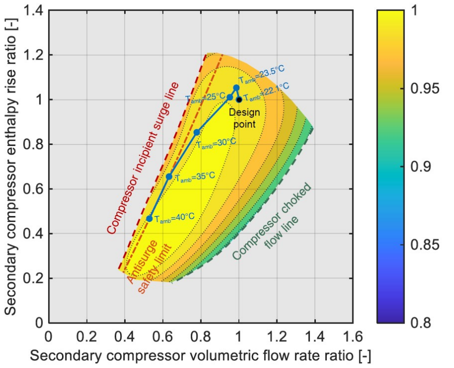

Figure 5: Secondary compressor operating points as a function of the ambient temperature[4].

The significant reduction of the maximum electric power produced by the plant as showed in Figure 6 where is possible to highlight that at 35°C the plant will be able to supply only around 30% of its nominal value.

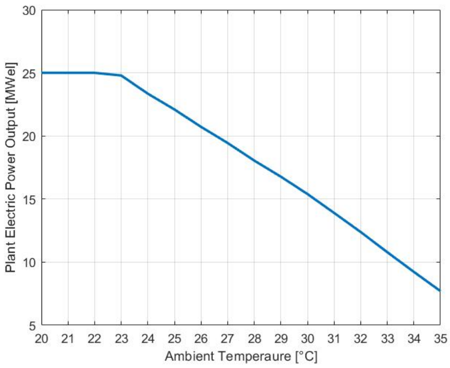

Figure 6: Maximum electric power produced.

This strategy shows, specially for a peaker plant, a critical problem, thus other strategies needs to be investigated.

4. Alternative operating strategies at constant minimum pressure

It was previously assessed how the increase of ambient temperature is critical for the dry-cooled sCO2 cycles operation and that the standard operating strategy is not able to successfully tackle this problem, it is therefore necessary to find new strategies to be adopted. The first mentioned in this work mean to exploit the characteristic of the compressors showed in Figure 5. Is in fact possible to notice that while the main compressor suffers from an increase of the volumetric flow rate the secondary shows the opposite situation.This operating strategy consists in the variation of the split ratio as the ambient temperature increase. This could make possible to redirect the excessive flow rate of the main compressor to the secondary, preserving the system operability at higher temperatures without limiting the fuel mass flow rate. The split ratio is defined as the percentage of the mass flow rate of the total that is processed by the main compressor.

4.1. $\Delta T_{mix,LTR}$ and Split Ratio

However for simulation purposes operating on the Split Ratio is not immediate and is chosen to use $\Delta T_{mix,LTR}$ instead because it is simpler to impose from a numerical point of view. $\Delta T_{mix,LTR}$ corresponds to the temperature difference of the two streams at the outlet of the LTR cold side and outlet of secondary compressor. However this regulation shows a strong limit in its range of regulation due to the secondary compressor operation. In Figure 7 is possible to notice that the mass flow redirected to the secondary compressor has a huge impact on its performance. At 100% Load when the $\Delta T_{mix,LTR}$ reaches the value of 19.1°C the upper limit of the map is reached, and proceeding further it will exit from the performance map.

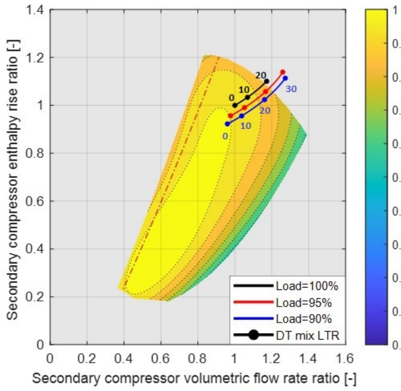

Figure 7: Secondary compressor performance maps at variable Load and $\Delta T_{mix,LTR}$ operation

4.2. Operating strategy considering $\Delta T_{mix,LTR}$ variation

In this paragraph the first alternative operating strategy is presented. The suggested operation is based on the standard strategy, except for the last corrective action. As showed in the scheme in Figure 8 when the compressor reaches the upper limit of the performance map three different options are available with different $\Delta T_{mix,LTR}$ (5°C,10°C,15°C). For each route is then reduced the heat input in order to operate on the limit of the performance map.

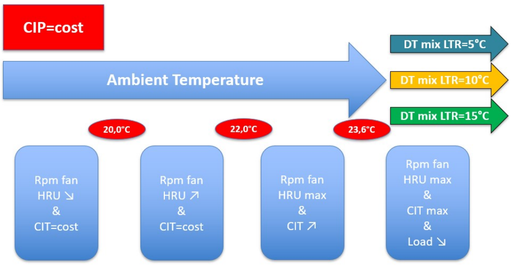

Figure 8: $\Delta T_{mix,LTR}$ variation operating strategy.

Unfortunately this solution doesn't present significant results showing in Figure 9 a maximum power generated curve fairly similar to the standard operation strategy.

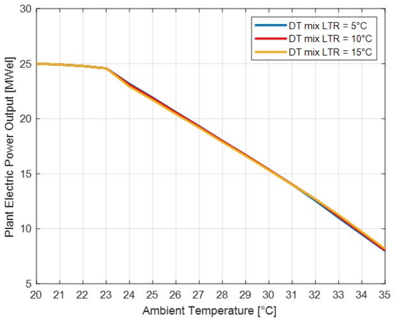

Figure 9: Maximum electric power produced at different values of $\Delta T_{mix,LTR}$.

5. Alternative operating strategies at variable minimum pressure

In Figure 2 is possible to notice that increasing the main Compressor Inlet Pressure is theoretically possible to counteract the effect of the increase of the CIT and keep the density value around the nominal value. Therefore this paragraph propose a viable operating strategy thanks to a controlled regulation of the main compressor inlet condition, made possible via the variation of the HRU fan rotational speed for the CIT and varying the plant inventory for the CIP. In order to do that the simulation will be structured in matrixes of operating conditions. For each load a new matrix will be generated and each matrix is defined by all the possible couple of compressor inlet operating conditions as showed in Figure 10.

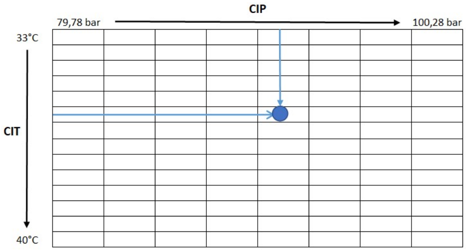

Figure 10: Explanatory compressor inlet temperature and pressure matrix in the simulation.

The matrices will also present limits defined by areas that marks some couples of inlet operating points as unfeasible. The limits in question are operation limits that correspond to operating conditions that exceeds the compressor limit and HRU operation limits that are function of the ambient temperature and exclude the operating point when the HRU surpasses its limit on the fans.

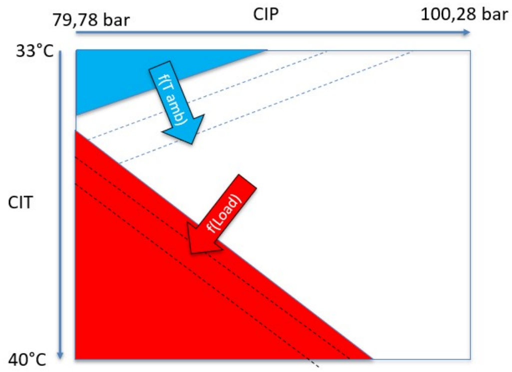

Figure 11: Area of the unfeasible operation points, in red the operations that exceeds the compressor limits and in light blue the point excluded by the HRU operation.

5.1. Maximum power generated

Thanks to the simulation and the limits previously assessed the curve of operation will be generated thanks to the new operation strategy also schematized as following:

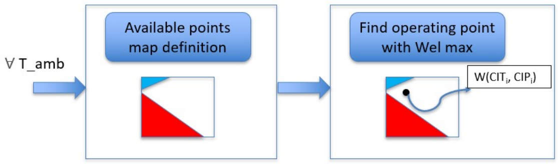

Figure 12: Operating strategy with controlled compressor inlet.

This strategy showed large improvements in term of power production, is in fact possible to notice in Figure 13 that in this new case the power only slightly deviates from the nominal conditions. In comparison to the standard operating strategy the new one allows to obtain additional 3.9 MWel at 26°C and 11.4 MWel at 32°C.

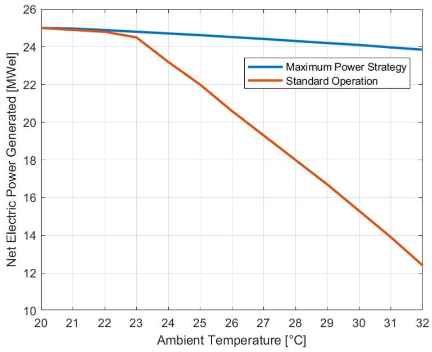

Figure 13: Maximum electric power at standard and controlled compressor inlet strategies.

However this solution present also a problem: the increased power production derived from an increase of the maximum pressure of the cycle, that deviates from the nominal values continuing to increase. Thus causing mechanical problems.

5.2. Pressure constraint

Is therefore necessary to find a new operating curve. Therefore to the previous strategy is added another limit that erase the operating conditions that presents a maximum cycle pressure higher than the nominal one. The same strategy as before is then followed, however in this situation is possible that the limits occupy the whole map. In that situation the load is decreased until feasible points are found.

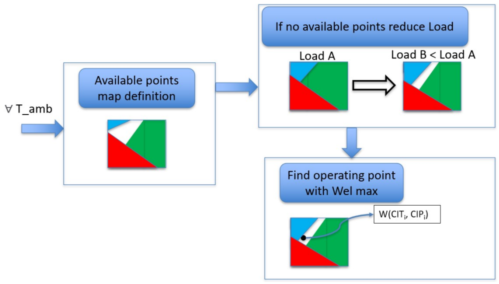

Figure 14: Operating strategy with controlled compressor inlet and maximum pressure limit.

The obtained curve showed to possess interesting operating performance. In Figure 15 is in fact possible to notice that despite having a power lower than the one previously computed it is still much higher than the standard operation since it allow us to obtain additional 3.0 MWel at 26°C and 9.0 MWel at 32°C.

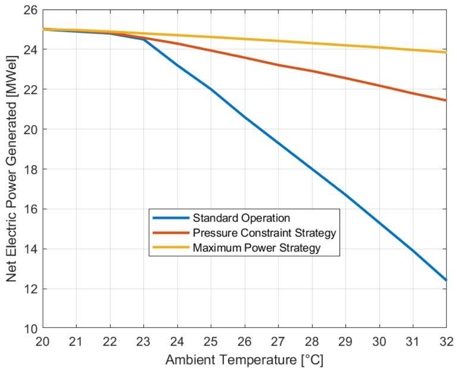

Figure 15: Maximum electric power produced at maximum and pressure constraint strategy

After further analysis is assessed that the curve obtained from this last strategy doesn't present any noticeable limitation. Therefore, a controlled operation of the compressor inlet condition with a maximum pressure limit can be considered the optimal strategy.

5.3. No inventory variation strategy

The strategy previously assessed is already an optimal result in order to tackle the effect of the increase of the ambient temperature. However, is considered interesting to evaluate another strategy where the inventory tank is removed and therefore there is no inventory variation in the cycle. In this configuration the regulation will be made only acting on the CIT and the CIP will vary accordingly, this translates into a line of feasible operating points for each map as showed in the scheme in Figure 16.

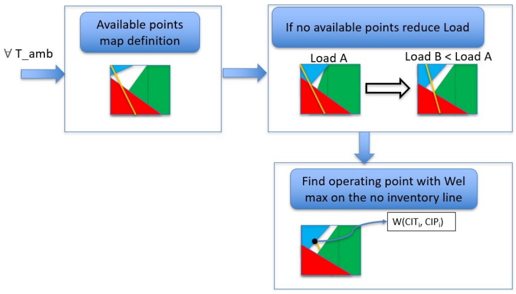

Figure 16: Operating strategy with no inventory variation.

The strategy is therefore similar to the previous one apart from the feasible points that will not be scattered across the map but only on the yellow line. In Figure 17 is showed the power production of the three strategies investigated.

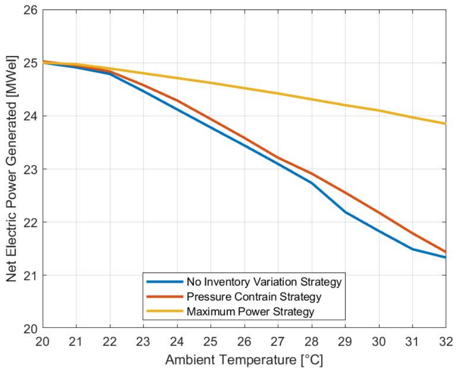

Figure 17: Maximum electric power at different operating strategies.

It is possible to notice that the strategy defined as optimal and the one with no inventory variation have fairly similar results. It thus seems that the regulation of the CO2 inventory at variable ambient temperature could be avoided without any significant performance penalization.

6. Conclusions

The study aimed to find feasible operating strategies able to tackle the effect of the ambient temperature increase on the performance of a dry-cooled coal power plant based on supercritical CO2 power cycles. The analysis showed that in order to obtain valid solutions a regulation of both Compressor Inlet Temperature and Compressor Inlet Pressure is needed. This will be possible acting respectively on the RPM of the HRU fan and the inventory of the plant. Thanks to this approach it is possible to significantly mitigate the problem, even if it results necessary to limit the increase of cycle maximum pressure which would tend to exceed the nominal value. An optimal strategy has been thus identified, and it resulted that is possible to operate till the value of 32°C of ambient temperature with a power production of 21.4 MWel in opposition to the 12.4 MWel of the standard case.

Moreover from the analysis of the inventory it is showed that in case of ambient temperature variation of the plant is possible to reach values similar to the optimal strategy without an inventory tank. Further studies could focus on this possibility but is usually not recommended, since without inventory it will not be possible anymore to operate at partial load thus losing some of the advantages of the sCO2-Flex cycle. This result on the operation strategy at different ambient temperature could open the sCO2 Brayton cycle to CSP applications. They are in fact usually placed in hot and dry locations where the impact of the ambient temperature on the cycle will be significant.

7. Acknowledgements

The sCO2-Flex project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.

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