SCO_2 closed Brayton cycle for coal-fired power plant: an economic analysis of a previous technical optimization

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ABSTRACT

The analysis of supercritical CO_2 Brayton cycle layouts have been performed by many scientific researchers over the years. These potential cycle layouts has advantages and drawbacks that depends on the context (application field, maximum and minimum parameter values, available heat…). In 2016, a preliminary study based on a sensibility analysis of a supercritical CO_2 for coal-fired power plant have been done to assess performance variations with cycle configurations [1]. This publication was dealing with several ways to improve the cycle performances regarding convenient cycle layout applied to coal-fired power plant. However, this preliminary study only focused on cycle performance improvements and did not take economic aspects into account.

INTRODUCTION

The main conclusions concerning the previous technical sensibility analysis [1] are the following: a recompression cycle is mandatory because the secondary compressor “partial flow” stream enable to gain significant efficiency (+4.5%pt compared to basic Brayton cycle layout without recompression stage). Furthermore, double reheat architecture (3 turbines) offers interesting efficiency improvement at “moderate” turbine inlet temperature (about +1.5%pt at 620°C turbine inlet temperature). In this context, the proposed power cycle architecture [1] that offers good performances with realistically selected material and components and that could require capital investment similar to that of existing “water-steam” coal power plants is illustrated in Figure 1.

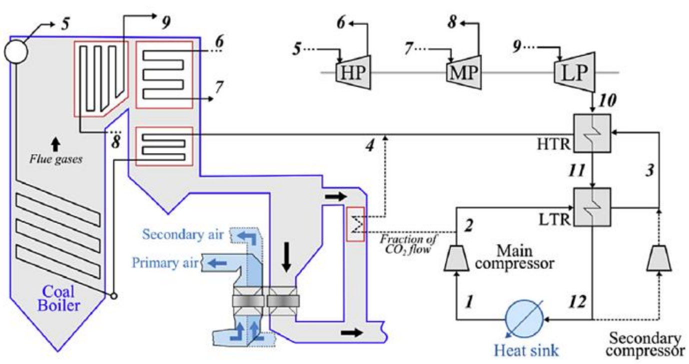

Figure 1: Process Flow Diagram (PFD) of suggested coal-fired power plant configuration in [1]

The operating conditions of this cycle are details in Table 1.

Table 1: Parameters of suggested sCO_2 coal-fired power cycle

Variable/parameter	Value(s)	Unit
Main compressor inlet temperature	32	°C
Main compressor inlet pressure	7.9	MPa
Main compressor outlet pressure	30	MPa
Turbine inlet temperature	620	°C
Pressure drop (every component)	0.1	MPa
LTR and HTR pinch	6	K
Air-gas heat exchanger pinch	30	K
Compressors isentropic efficiency	89	%
Turbine isentropic efficiency	93	%
Alternator/Motor electrical efficiency	99.6	%
Mechanical efficiency	98.5	%
Air preheating configuration	Case C	–
Number of recompression stages	1	–
Number of reheat stages	2	–

The pressure ratio of this cycle has been optimized to maximize the net cycle efficiency. Then, the best performances occurs at 7.9 MPa minimal cycle pressure (net cycle efficiency: 51.6 ± 0.1%) as depicted in Figure 2.

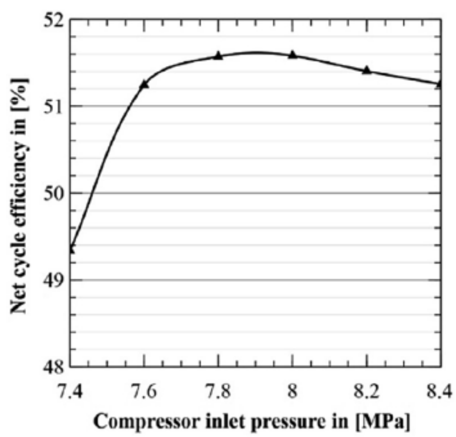

Figure 2: Net cycle efficiency as a function of main compressor inlet pressure [1]

OBJECTIVE

This paper intends to complete the described technical analysis done in 2016 [1] by achieving an economic evaluation of the described sCO_2 Brayton cycle architecture in order to assess the economic impact on a technical optimization result. The economic analysis is done by using equipment cost correlations found in literature (when available) or internally built (see methodology section below).

The present work is one of the preliminary studies that can further feed the future European Project “sCO_2-FLEX”. 10 European partners (academic and industrial) are involved is this project that aims at designing a highly flexible 25 MW (net electrical) sCO_2 Brayton cycle for coal-fired power plant integrated in a high renewable rate electrical network.

METHODOLOGY

The cost analysis of this study does not intend to give an accurate and absolute equipment costs. The aim of the economic analysis is to be able to compare different technical configuration to each other and to observe global trends. The economic evaluation method is based on the cost of main components (boiler, turbomachineries, recuperators, coolers). As a first economic assessment, this study only focuses on the Capital Expenditure (CAPEX).

The CAPEX is composed of direct costs (purchased equipment, piping, electrical, civil work, transport, direct installation, auxiliary services, instrumentation and control, site preparation) and indirect costs (mainly engineering, supervision, start-up) [2; 3]. All these costs can be directly linked to the "total costs of components". In this context, the CAPEX can be expressed as: $CAPEX(\$) = direct\ + indirect\ costs = (1 + x_1) \times direct\ costs = (1 + x_1 + x_2) \times total\ component\ cost$ where x_1 and x_2 are coefficients respectively fixed to 8% and 26% [2; 3].

Each component cost is expressed as follows: $cost_{component}(\$) = a \times (Parameter)^b \times f_p \times f_t$ where "a" and "b" are empirical coefficients that depend on components and f_p and f_t are pressure and temperature factors whose aim is to simulate the use of high grade material requirement (expensive material) when the maximal pressure and the temperature rise. The "parameter" represents the "characteristic power" of each component (heat duty for heat exchanger and boiler, and electricity power for turbomachineries).

Also, the specific cost (defined as the ratio of the CAPEX over the net power electrical production $specific\ cost\ (\$/kW_e) = CAPEX\ (\$)/Electrical\ production\ (kW_e)$) is used as "comparison criterion" to find the best economic solution.

This economic simplified model is used to assess the sCO_2 Brayton cycle CAPEX (and specific costs) of the proposed architecture used for the sensibility analysis plotted in Figure 2.

RESULTS AND DISCUSSION

The results of this study are plotted in Figure 3.

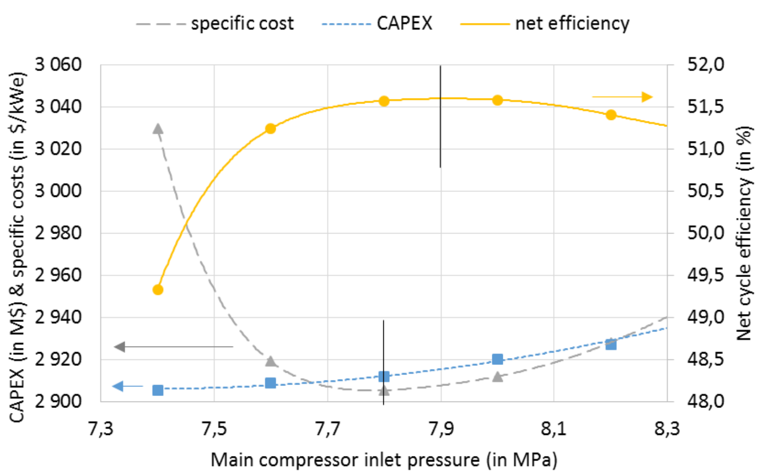

Figure 3: Net cycle efficiency [1] as a function of the main compressor inlet pressure (yellow solid line, right axis), CAPEX (blue dotted line, left axis) and specific costs (gray dashed line, left axis)

The yellow curve (solid line) is directly extracted from [1] (net cycle efficiency of the sCO_2 Brayton cycle described on Figure 1 as a function main compressor inlet pressure). As expressed above, the technical maximum performance appears for a main Compressor Inlet Pressure (CIP) of 7.9 MPa.

The CAPEX (blue dotted line) increases with the CIP. This is mainly due to the fact that the while the CIP increases, the low pressure turbine outlet temperature increases too while the compressor outlet temperature decreases, leading to High Temperature Recuperator (HTR) duty increase (and thus HTR cost rise). The specific costs (gray dashed line) shows a minimum around a CIP value of 7.8 MPa which differs from the performance optimum.

These results shows that the economic evaluation of sCO_2 Brayton cycles is complementary and the sole technical performance criteria is not sufficient to expected the best economic solution. Thus economic evaluation can lead to different solution, especially when comparing several solutions. That is why further development of this methodology are foreseen in our team.

PERSPECTIVES

As mentioned in this study, the economic model is first version of a very simplified structure and it has not been carried out for accurate and absolute cost assessment. However, it can be used for cycle comparison and first observed results are interesting since it can be seen that the economic optimum does not fit the performance optimum. Also, the economic assessment of this paper only focuses on the CAPEX.

In this context, two main perspectives can be expected: first, improvement of the economic model (refinement of component cost models, addition of Levelized Cost Of Electricity (LCOE) module…) and then, application of the cost evaluation method on the whole sensibility analysis carried on in the related paper [1] in order to assess the economic impact of suggested cycle technical improvements (e.g. the number of reheats).

REFERENCES

[1] Mounir Mecheri and Yann Le Moullec, Supercritical CO_2 Brayton cycles for coal-fired power plants, Energy, Volume 103, 2016, Pages 758-771, ISSN 0360-5442 https://doi.org/10.1016/j.energy.2016.02.111

[2] Antonio C. Caputo, Mario Palumbo, Pacifico M. Pelagagge, Federica Scacchia, Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables, Biomass & Energy, 28, pp 35-51 http://dx.doi.org/10.1016/j.biombioe.2004.04.009

[3] SungHo Park, JoonYoung Kim, MunKyu Yoon, DongRyul Rhim, ChoongSub Yeom, Thermodynamic and economic investigation of coal-fired power plant combined with various supercritical CO_2 Brayton power cycle, Applied Thermal Engineering 130, pp 611-623, https://doi.org/10.1016/j.applthermaleng.2017.10.145