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Supercritical Carbon Dioxide Power Cycles with Oxy-Combustion Capture: Towards a New Improved Cycle Layout for Energy Production

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The aim of this work is to introduce a new power cycle that could be a promising technology for increasing thermal efficiency, reducing cost of electricity while capturing nearly-all CO_2 emissions. This cycle is based on existing supercritical CO_2 oxy-fuel technologies, incorporating significant improvements in the process layout. The cycle is based on semi-closed loop recompression Brayton cycle that uses supercritical CO_2 as the working fluid dramatically reducing energy losses compared to steam- and air-based traditional cycles. The oxy-combustion capture allows a full capture of carbon emissions through an air separation unit that provides pure oxygen to the system with cold energy integration of LNG. The proprietary feature of the new cycle is the recompression-based architecture, that increases the efficiency of the heat recuperative system. Promising results were obtained from first phase simulations: a 63 % LHV thermal efficiency for a 300 MW power plant, compared to a 59 % in the most efficient technology available on the market. First economic estimations show a 71.7 €/MWh LCOE, lowering the one from existing cycles. The balance between an increase in capital cost and a reduction in fuel demand was evaluated to ascertain the competitiveness of this advanced power cycle.

1. Introduction

In order to achieve carbon neutrality objectives, many works have been initiated either to integrate CO_2 capture systems into thermal power plants by minimizing the energy penalty (Hagi et al., 2014) or for the integration into the electricity network of renewable energy sources through the advanced concept of Power-to-Gas (PtG) plant via the transient storage of energy vectors (Kezibri and Bouallou, 2017). More recently, research carried out on supercritical carbon dioxide (s-CO_2) Brayton cycle has had promising results. This type of cycle presents notorious advantages with respect to traditional power systems such as gas Brayton cycle and Rankine steam cycle. The steam Rankine cycle suffers from the low compactness of turbine and condenser while the gas Brayton cycle endures the low cycle efficiency. The s-CO_2 Brayton cycle, characterized with high compactness and high efficiency, can compensate these two issues and it has been considered as one of the most promising alternatives for power conversion systems in many industrial applications (Fan et al., 2022).

As any thermodynamic power cycle, the s-CO_2 cycle receives heat (Q_{hot}) from a hot source at a temperature T_1, it releases heat (Q_{cold}) to a cold sink at T_2 while it produces work (W_{net}) through a power engine.

Heat sources in s-CO_2 power cycles con vary widely. Supercritical CO_2 power cycle can be applied to convert the energy from solar power, nuclear reactor, fossil fuel, waste heat, fuel cell and geotherm. In present work, we focus on the cycles that use fossil fuels as a heat source, which provides the cycle with a great flexibility to cope with the intermittence of renewable energy sources.

The working fluid in the power engine is almost pure CO_2 and it normally operates above the critical point (30.98 °C and 7.38 MPa). Variation of thermodynamic properties of carbon dioxide are show in Figure 1 for a constant pressure of 7.4 MPa (slightly over the critical one). Data is referred to the NIST (National Institute of Standards and Technology) Standard Reference Database 23.

It can be clearly appreciated that from 31 °C there is a strong variation in the fluid properties. In particular, the high-density of s-CO2 near the critical point is used in the inlet of the compressor in the power cycle. It has been

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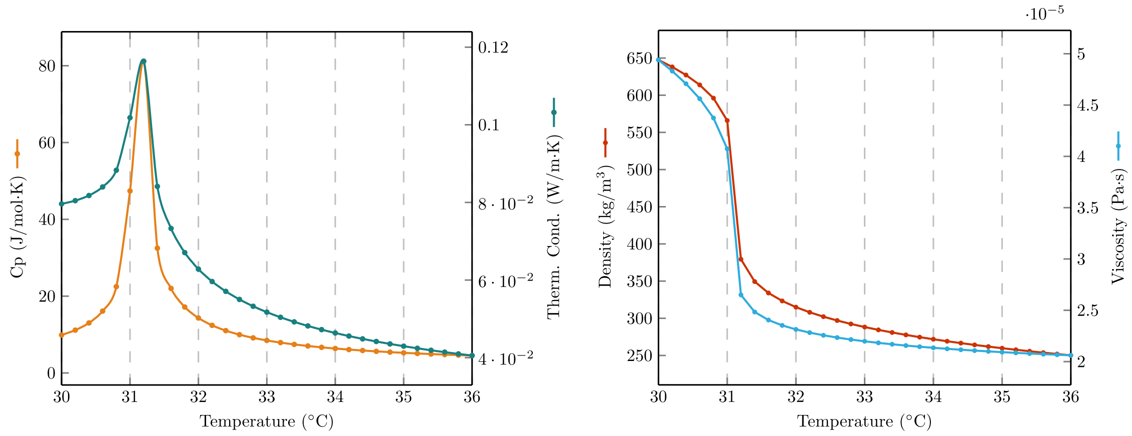

Figure 1: Thermophysical properties of s-CO_2 at 7.4 MPa. Data: NIST Standard Reference Database 23

shown that a significant valley of compressor work consumption locates near the Pcr, which entails the feature of high cycle efficiency (Fan et al., 2022). The heat sink is usually refrigeration water at ambient conditions. This is due to the high availability, the low cost and the minimum temperatures reached in the cycle. Nevertheless, other cooling fluids could be used in order to reduce the process water consumption. Liquefied natural gas (LNG) is a promising fluid for energy integration in the process. After transportation, LNG must be regasified in order to be sold in domestic pipelines or used in industrial facilities. The low temperatures of LNG (-160 °C) could be used for cooling purposes in the power generation cycles.
The thermal efficiency (η) of a power cycle is a measure of how well the cycle converts thermal energy into mechanical work. The formula for thermal efficiency is given by:

$$\eta = \frac{W}{Q_{\text{hot}}} = \frac{\sum W_{\text{out}} - \sum W_{\text{in}}}{Q_{\text{hot}}} \quad (1)$$

Where: η is the thermal efficiency, W_{net} is the network output of the cycle and Q_{hot} is the heat input to the system from the heat source.
A great number of research works in the topic has arisen in recent years. Fan et al. (2022) carried out extensive review on the advances and technical issues of supercritical carbon dioxide power systems. White et al. (2021) presented the theoretical background and classification of different s-CO_2 power cycles as well as the challenges related to the equipment design and materials (turbomachinery, recuperative heat exchangers). Crespi et al. (2017) categorized different cycle configurations of cycles for the s-CO_2 power system.

2. Supercritical-CO_2 power cycles state of the art

2.1 Power Cycle Layouts

The basic configuration for the s-CO_2 Brayton cycle is schematic in Figure 2a. The simple Brayton recuperated cycle (SBR) is composed by five principal components: heater, turbine, compressor, recuperator and cooler. This s-CO_2 power system presents the feature of high efficiency compared to a traditional gas Brayton cycle. The recuperator provides a simple energy integration in the process, since is used to transfer heat from the hot exhaust leaving the turbine to the cold fluid leaving the compressor.

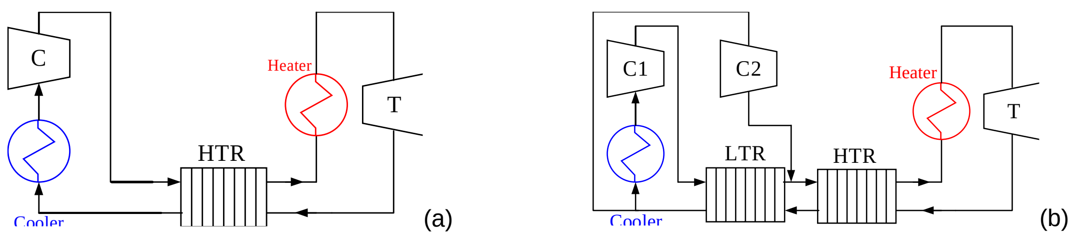

Figure 2: Schematic of a simple Brayton recuperated cycle (a) and a Recompression cycle (b)

Within the recompression cycle (Figure 2b), the recuperation is divided into a high-temperature recuperator (HTR) and a low-temperature recuperator (LTR), by introducing an auxiliary compressor. The purpose of this compressor is to bypass a fraction of the main flow from the heat-rejection process and main compressor, which

reduces the heat-capacity rate ($\dot{m}c_p$) within the high-pressure side of the low-temperature recuperator. This helps offset the mismatch in the heat capacities of the hot and cold fluids within the LTR, reducing the irreversibility compared to the simple recuperated cycle.
The recompression cycle assisted with reheat (RC-RH) is schematic in Figure 3. The RC-RH divides the expansion process and introduces an intermediate reheating process. This increases the average temperature of heat addition, and hence cycle efficiency, and increases the turbine exhaust temperature, which increases the potential internal heat recovery within the recuperator.

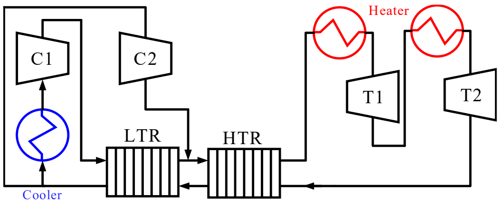

Figure 3: Schematic of a supercrital CO_2 recompression-reaheated cycle

2.2 Oxy-combustion s-CO_2 existing technologies

An oxy-fuel combustion capture is a type of carbon capture in which the fuel is combusted in the presence of nearly pure (approximately 98 %) oxygen to ensure that the products of combustion (flue gas) contain CO_2 and water with only trace amounts of other gases. This allows a simple separation by condensation of the combustion products, obtaining stream rich in CO_2 to be stored underground or sold. The main challenge with this method is separating oxygen from air. Technological innovations in this process such us 'chemical looping combustion' for the s-CO_2 cycles are under development (Saqline et al., 2023).
Allam et al. (2017) developed a highly regenerative supercritical cycle called "NET Power cycle" which is a CO_2 oxy-fuel power cycle that utilizes hydrocarbon fuels while inherently capturing nearly all atmospheric emissions at a cost of electricity that is highly competitive. The proprietary system achieves these results through a semi-closed-loop, high-pressure, low-pressure-ratio recuperated Brayton cycle that uses supercritical CO_2 as the working fluid.

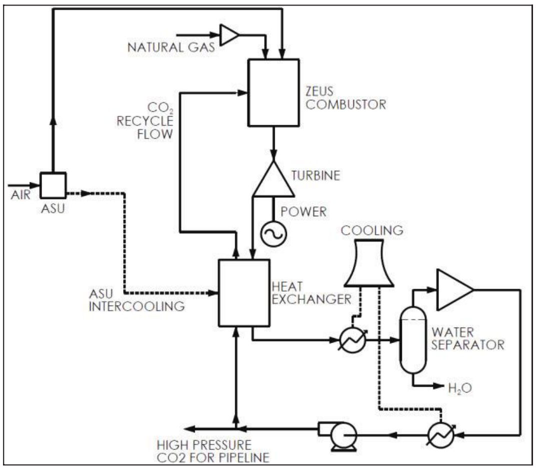

Figure 4: Proprietary NET Power Natural Gas Cycle

Figure 4 is a simplified flow scheme for a unit burning natural gas. The cycle includes a high pressure oxy-fuel combustor that burns a fossil fuel in a pure oxygen stream to provide a high-pressure feed stream to a power turbine. An economizer heat exchanger transfers heat from the high temperature turbine exhaust flow to a high-pressure CO_2 recycle stream that flows into the combustor, diluting the combustion products and lowering the turbine inlet temperature to an acceptable level. The turbine exhaust flow is cooled to a temperature below 70 °C in the economizer heat exchanger and then further cooled to near atmospheric temperature in an ambient air cooler or with cooling water. Liquid water derived from water or hydrogen in the fuel is separated, and the remaining stream of predominantly CO_2 is compressed to the required high pressure. The recycle stream is then reheated in the economizer heat exchanger before returning to the combustor. The net CO_2 product is removed from the recycle stream at a high purity and pressure for delivery to an export CO_2 pipeline.

For a more detailed explanation of the cycle and the process operating conditions and compositions of each stream refer to the report (IEA, 2015) published by the International Energy Agency. This report gathers complete reviews of the available oxy-combustion cycle options, in particular, there is a section covering the 'NET Power case'. The results of the thermodynamic calculations validated by NET Power indicate a net electric efficiency of 58.8 % for the NET Power cycle, being the highest one of the supercritical CO_2 systems evaluated. The economic analysis also shows that the NET Power cycle has the lowest levelized cost of electricity (LCOE) of 73.8 €/MWh for a system with full CO_2 capture at pipeline conditions. NET Power, owned by 8 Rivers Capital., is developing the first full-scale 300 MWe natural gas Allam Cycle plant, currently in the design phase and expected to be operational by 2026 (NET Power, 2022).

3. Towards a new technology for power production systems

In this work, a more efficient technology for power production based on a s-CO_2 oxy-fuel cycle is presented.

3.1 Description of the process

Figure 5 shows a simplified process flow diagram (PFD) of the cycle. A natural gas stream is combusted in presence of an oxidant stream composed mainly of O_2 and CO_2. The combustor has an inlet of a pure recycled CO_2 stream which purpose is to lower the combustion flame temperature in order to prevent material damage. Gases leaving the combustor at high temperature and pressure pass through a power turbine with a pressure ratio of 10, generating electricity.

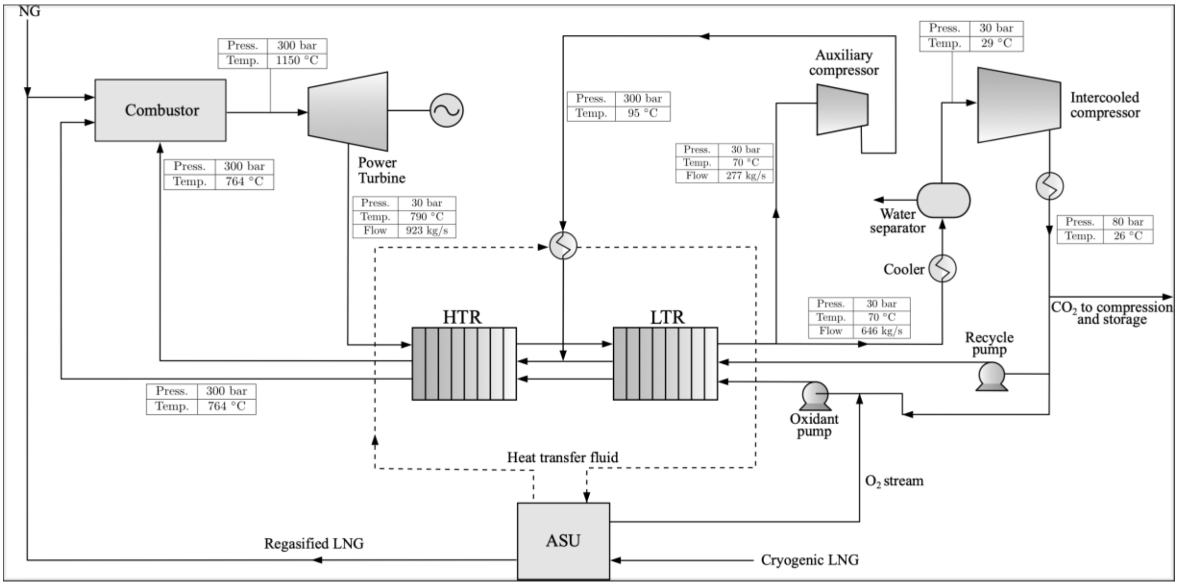

Figure 5: Process Flow diagram of the new thermodynamic s-CO_2 cycle

The turbine exhaust gases are cooled in a recuperative heat exchangers system. This system is composed of two equipment: a high temperature recuperator (HTR) and a low temperature recuperator (LTR). Both are multi-flow heat-exchangers in which an energy integration between streams takes place. Flue gases are cooled while transferring heat to streams that need to be preheated before being recycled to the combustor or turbine.

After passing through the LTR, the flow is divided into two streams. The main stream is cooled in a condenser reaching nearly ambient conditions, allowing water content of the stream to be separated from the main flow. Then, gases are compressed in a multi-stage intercooled main compressor. The auxiliary stream is compressed in an auxiliary compressor at higher temperature and heated by a heat transfer fluid that carries waste heat from the air separation unit.

The last cooler from the compression train on the main stream allows the fluid to enter in the liquid region, making pumping possible. Here, the flow is divided again in a recycling stream and an oxidant stream. The oxidant CO_2 stream is mixed with oxygen coming from the ASU and it is pumped to the combustor and preheated in the recuperative system. The net CO_2 product is removed from the recycle stream at a high purity (97.8 %) and pressure for delivery to an export CO_2 pipeline. The recycling stream is pumped and heated in the LTR. Before entering the HTR, it is mixed with the flow leaving the auxiliary compressor. After passing through the HTR, the supercritical CO_2 is recycled to the combustor.

In the traditional cycle, there is a significant imbalance between the heat liberated by the low-pressure turbine exhaust and the heat required to raise the temperature of the high pressure recycle stream, due to the large increase in the specific heat of CO_2 in the high pressure stream. The purpose of this compressor is to bypass a fraction of the main flow reducing the heat-capacity rate ($\dot{m}c_p$) within the high-pressure side of the LTR. This helps offset the mismatch in the heat capacities of the hot and cold fluids within the LTR, reducing the process irreversibility and hence improving cycle efficiency. While this does complicate the system, the thermal efficiency increases enough to offset the economic cost and complexity of the added components. The split fraction is determined according to parameter sensibility studies carried out to optimize cycle efficiency. Optimum value of split fraction x_{rc} is near 0.3, which is consistent with previous works (Fan et al., 2022).
As mentioned before, a significant quantity of heat is required to raise the recycle CO_2 temperature from the auxiliary stream. A very convenient source of heat can come from the air compressors of the cryogenic air separation plant that produces the oxygen stream used in the oxy-fuel combustor. These compressors can be operated adiabatically with no inter-cooling. The total adiabatic power input to the recycle CO_2 stream produces an equivalent drop in required fuel energy input (Allam et al., 2017).
The air separation unit is an energy-intensive part of the overall process. In order the reduce consumption, a cold energy integration with cryogenic LNG is proposed to act as a service fluid in the cryogenic distillation towers. The low temperatures (-160 °C) can be used for cooling the air flow and at the same time serving the purpose of regasifing the LNG. This regasified LNG is used as fuel in the combustor of the power cycle together with natural gas coming for the grid.

3.2 Energy Conversion Equations

The energy conversion in the components of the new cycle can be described by the following basic equations:

$$Q_{heater} = \dot{m} \cdot (h_{out} - h_{in}) \quad (2)$$

$$W_{turbine} = \dot{m} \cdot (h_{in} - h_{out}) \quad (3)$$

$$W_{compressor} = \dot{m} \cdot (h_{out} - h_{in}) \quad (4)$$

$$Q_{recuperator} = \dot{m} \cdot (h_{out} - h_{in}) \quad (5)$$

These equations outline the fundamental energy conversion processes occurring in each cycle component.

3.3 Results of process simulations

For this research, process simulations have been performed using Aspen Hysys v.12 and Peng-Robinson was selected as the EOS for predicting thermodynamic fluid proprieties, since it has been proven to provide the best empirical match to the operational region of Allam Cycle operation.
The existing oxy-combustion s-CO_2 technologies presented in Section 2.2, were used as benchmarks in our simulations and comparative analysis. These benchmarks allowed to evaluate the improvements and advantages of our proposed cycle in terms of thermal efficiency and economic viability. The accompanying table (Table 1) synthesizes the outcomes of the simulation.

Table 1: Expected values of key cycle parameters comparison

Cycle attribute	Expected Value New Cycle	Expected Value Allam Cycle
Turbine outlet flow	923 kg/s	923 kg/s
Turbine inlet condition	300 bar at 1,150°C	300 bar at 1,158°C
Turbine power output	439 MW	Confidential
CO_2 compression power	87 MW	77 MW
ASU power consumption	56 MW	56 MW
Net power output	295 MW	303 MW
Heat thermal input	471 MW	511 MW
Cycle thermal efficiency	63 %	59 %

The achieved efficiency of 63 % in our innovative energy production process surpasses the original Allam Cycle's efficiency of 54-59 %. This notable improvement underscores the success of our approach in optimizing energy utilization and enhancing overall system performance.
As evident from the results, the observed increase in efficiency can be primarily attributed to a reduction in the heat demand through combustion. In other words, this improvement would lead to a decreased requirement for natural gas in the process, consequently lowering costs. This is particularly significant given the market's pronounced volatility, and the demonstrated decrease in natural gas demand. This drop in fuel consumption not

only enhances the environmental sustainability of the process but also presents a cost-effective strategy in response to the fluctuating market conditions.

3.4 Economic analysis

This proposed cycle demonstrates superior thermal efficiency compared to the existing Allam cycle, with the incorporation of an additional component, namely the compressor. Although this augmentation results in a higher initial capital investment, the enhanced thermal efficiency translates into a reduced demand for fuel to generate an equivalent power output. The balance between increased capital expenditure and diminished operational costs must be evaluated to ascertain the competitiveness of this advanced power cycle.
The Levelized Cost of Electricity (LCOE) is calculated using the following formula (2)

$$\mathrm{LCOE} = \frac{\text{Total Costs}}{\text{Total Electricity Generated}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{6}$$

Total Costs' encompass all relevant costs associated with the project over its lifespan, including initial capital costs (I_t), operational and maintenance expenses (M_t), and fuel expenditures (F_t). 'Total Electricity Generated' represents the cumulative electricity output (E_t) over the project's operational life (n).
Since the proposed cycles are compared with a same power output, the Total Electricity Generated is essentially the same. The only difference between both cycles is in the Total Costs. The New Power cycle has a 7,8 % reduction in fuel input, while the annualized increase in CAPEX is estimated in only 5 %. These two opposing effects result in an LCOE of about 71.7 €/MWh for the proposed system, lower than the one of NET Power.

4.4 Carbon footprint

The carbon footprint associated with the proposed process is expected to align closely with that of the Allam cycle, both exhibiting an equivalent CO2 emission rate of 20.9 kg/MWh in relation to net power production. Even if the new power cycle consumes less CH_4, the oxy-combustion capture entails nearly no CO_2 emissions in both cases. It is important to acknowledge that the new cycle introduces a larger physical footprint due to the incorporation of a greater number of components, each of smaller individual sizes.

4. Conclusions

Supercritical CO_2 oxy-combustion power cycles offer an alternative to continue using hydrocarbon fuels for electricity production at a competitive cost and with a low carbon footprint associated. The novelty of this article lies in the integration of re-compression layout configuration to existing s-CO2 oxycombustion power cycles. The new recompression s-CO_2 cycle entails an increase in thermal efficiency enough to offset the economic cost and complexity of the added components. Further research on the subject should be encouraged in order to find not only academic but also industrial solutions for the power generation sector.

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