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Thermodynamic analysis and numerical optimization of the NET Power oxy-combustion cycle

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HIGHLIGHTS

- Complete thermodynamic analysis and optimization of the NET Power oxy-combustion cycle.
- Detailed process simulation developed in Aspen Plus.
- Optimization-based sensitivity analyses performed to find the key design variables.
- Optimal cycle features a net electric efficiency (LHV basis) of 54.80% with 100% CO_2 capture.

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ABSTRACT

This paper presents a thorough thermodynamic analysis and optimization of the NET Power cycle (also called Allam cycle), a natural-gas-fired oxy-combustion cycle featuring nearly 100% CO_2 capture level, very high net electric efficiency, and potentially near-zero emissions level. The main goals of this study are the systematic optimization of the cycle for the maximum efficiency, and the quantification of the effects of the modelling assumptions and equipment performance on the optimal cycle variables and efficiency. An Aspen Plus flow-sheet featuring accurate first-principle models of the main equipment units (including cooled turbine) and fluid properties (equation of state) has been developed. The influence of the cycle variables on the thermodynamic performance of the cycle is first assessed by means of sensitivity analyses. Then, the cycle variables, which maximize the net electric efficiency, are determined with PGS-COM, a black-box numerical optimization algorithm, linked to the simulation software. The corresponding maximum cycle efficiency is equal to 54.80% (with 100% CO_2 capture), confirming the outstanding performance of the NET Power cycle. Moreover, the optimization indicates the existence of promising combinations of the cycle variables which lead to reduced component costs (due to the lower operating pressures and temperatures) of the most critical components, without considerably affecting the net electric efficiency. The analysis also indicates that the cooling medium temperature, the power consumption of the air separation unit, the effectiveness of the regenerator and the effectiveness of the turbine cooling system are the main factors influencing the cycle efficiency.

1. Introduction

Among the available carbon capture technologies, turbine-based oxy-combustion cycles appear to be a promising mid-term solution for the production of electricity from natural gas. The oxy-combustion technology is based on a thermodynamic cycle in which the fuel is burned in a combustor with an oxidant stream composed mainly of pure oxygen. In a conventional plant the combustion is performed using air as oxidant, but the significant amount of nitrogen contained dilutes considerably the CO_2 in flue gases. It is well known that this is one of the major drawbacks affecting the energy consumption related to CO_2 Capture and Storage [1,2]. On the other hand, thanks to the removal of nitrogen from the oxidant, oxy-combustion cycles deal with working fluids featuring higher CO_2 concentrations, which may reduce the energy intensity of CO_2 separation. Nowadays, among the most interesting solutions proposed in literature for oxy-combustion cycles there are the ones based on CO_2-rich and H_2O-rich streams as working fluids. In the former case CO_2 capture is performed simply by splitting part of the main flow, while in the second case water condensation produces a stream rich in carbon dioxide, which then can be

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Nomenclature

Acronyms	
ASU	air separation unit
BWR-LS	Benedict-Webb-Rubin-Lee-Starling
CCL	CO_2 capture level
CES	clean energy system
COT	combustor outlet temperature
CPSO	constrained particle swarm optimizer
EoS	equation of state
GHG	greenhouse gases
GSS	generating set search
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycles
LHV	lower heating value
LT	low temperature
PGS-COM	particle generating set-complex algorithm
PR	Peng-Robinson
pvT	pressure-specific volume-temperature
SCOC-CC	Semi-Closed Oxy-Combustion Combined Cycle
SRK	Soave-Redlich-Kwong
TBC	thermal barrier coating
TIP	turbine inlet pressure
TIT	turbine inlet temperature
TOT	turbine outlet temperature
Symbols	
A	surface area
c	load coefficient of the turbine stage
c_p	specific heat capacity
EXP	adiabatic expander
h	heat transfer coefficient
HX	multi-flow heat exchanger
k_{ij}	binary interaction coefficient
m	mass flow rate
M_0	Mach number
MIX	mixer
p	pressure
Q	thermal power
St	Stanton number
T	temperature
u	pitchline velocity
U	overall heat transfer coefficient
v	velocity
V	volumetric flow rate
W	mechanical power
x	mole fraction
β	pressure ratio
γ	specific heat capacities ratio
ε	effectiveness of the convective cooling system
η	efficiency
θ	defined as $(\gamma - 1)/\gamma$

easily captured via partial condensation (however in both cases a further purification step may be required depending on CO_2 purity specifications).

Over the last 30 years, different layouts have been proposed, including the Semi-Closed Oxy-Combustion Combined Cycle (SCOC-CC) [3], the MATIANT cycle [4], the NET Power cycle [5,6], the Graz cycle [7] and the CES cycle [8]. The SCOC-CC, MATIANT and NET Power cycles use CO_2 as diluent to limit both the combustion and turbine inlet temperatures, while the Graz and the CES cycles use H_2O.

The basic idea of the SCOC-CC cycle is to use pure oxygen provided by a cryogenic air separation unit (ASU) as oxidant in the combustor of a gas turbine combined cycle, and to recycle a fraction of the generated CO_2 so as to moderate the turbine inlet temperature. Since the plant does not feature any gas stack, all the generated CO_2 (as well as pollutants) is captured (CO_2 capture level = 100%). For the SCOC-CC cycle, Chiesa and Lozza [9] estimated, in an Integrated Gasification Combined Cycles (IGCC) configuration, a net electric efficiency of 39%, while Lozza et al. [10] calculated a net electric efficiency equal to 46.17%. Riethmann et al. [11] developed a supercharged SCOC process reaching a net plant efficiency up to 50%, as a result of several sensitivity analyses covering different ranges of hot gas temperatures, pressure ratios and supercharge factors.

The MATIANT cycle consists of a combination of a supercritical CO_2 cycle and a higher temperature regenerative reheated gas cycle (using a CO_2-rich working fluid). Similarly to the SCOC-CC cycle, all the generated CO_2 is captured. Yantovski et al. [12] proposed a MATIANT cycle (named "quasicombined COOPERATE cycle") reaching an electric efficiency of 52%. Then Yantovski [13] compared it against conventional power plants from a techno-economic point of view, estimating, for the former, an electric efficiency of 54.3% for the case with nearly zero CO_2 emissions. Mathieu and Nihart [14] presented a sensitivity analysis of the MATIANT cycle showing the effects of different parameters on the plant net electric efficiency. They reported an overall efficiency of 44.2% for the best case.

Allam et al. [15] developed a highly regenerative supercritical cycle called "NET Power cycle" or "Allam cycle". The turbine inlet temperature is controlled by recycling a large amount of supercritical CO_2 to the combustor while heat recovery of the turbine exhaust gases is performed using a multi-flow heat exchanger (the regenerator). A detailed description of the cycle is reported in Section 2. In [16] the developers estimated a cycle efficiency for natural gas combustion of 59% for the single combustor scheme (without reheat) and about 57.5% for the double combustor scheme (with reheat).

An alternative option is the Graz Cycle, which integrates a high temperature Brayton cycle (made by a compressor a combustor and cooled turbine handling a mixture of H_2O and CO_2 as working fluid), with a low temperature steam cycle (made by a high pressure turbine, a low pressure turbine, a condenser, and a Heat Recovery Steam Generator). Starting from the original scheme published in [7], different improvements have been proposed over the last twenty years by the researchers of the Graz University of Technology. For instance, Sanz et al. [17] proposed the "S-Graz" cycle featuring a higher steam content compared to the original layout thanks to the adoption of different cycle parameters. A net electric efficiency of 57.7% was assessed by the authors. Later, Jericha et al. [18] developed and designed a new scheme with condensation of the H_2O-CO_2 mixture at atmospheric pressure which allows to improve the heat transfer process in the condenser. Jericha et al. [18] assessed an overall efficiency of about 54%.

The CES cycle is essentially an internal combustion steam cycle using the injection of steam and liquid water in the combustor to moderate the firing temperature. Pure oxygen is used as oxygen and natural gas (or other fuels) as fuel. At the exit of the combustor, the mixture of H_2O and CO_2 expands in a turbine (eventually with reheat) and then it is cooled down in a water condenser. Anderson et al. [19] discussed the technological evolution of the CES cycle, by