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Optimal design and operation of pressurized oxy-coal combustion with a direct contact separation column

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A B S T R A C T

Simultaneous multi-variable gradient-based optimization is performed on a 300 MWe wet-recycling pressurized oxy-coal combustion process with carbon capture and sequestration. A direct contact separation column is utilized for practical and reliable low-temperature thermal recovery. The models for the components include realistic behavior like heat losses, steam leaks, pressure drops, and cycle irreversibilities. Moreover, constraints are used for technoeconomical considerations. Optimization involves 17 optimization variables and 10 constraints, with the objective of maximizing the thermal efficiency. The optimization procedure utilizes recent design rules and optimization procedures for optimal Rankine cycle performance speeding up the plant optimization process by eliminating variables and avoiding constraint violations. Moreover, the procedure partially alleviates convergence to suboptimal local optima. The basecase of the study is a comprehensively optimized cycle that utilizes a surface heat exchanger, a more thermodynamically-effective form of thermal recovery which however bears significant materials challenges. Upon optimization, the cycle utilizing the direct column is seen to be very attractive regarding efficiency and performance. Moreover, the optimization results unveil potential for reducing capital costs by eliminating the first carbon sequestration intercooled compressor and by showing possibilities of process intensification between the separation column and the carbon sequestration purification columns.

1. Introduction

The importance of emissions free power generation is motivated and discussed extensively in literature [1,2]. Clean and renewable power production is of high interest to both academic and industrial research aiming to make such technologies more affordable and reliable. However, the world's dependence on fossil fuels for power generation, especially coal due to its cheap price and abundance of reserves [3], is expected to continue at least till renewable power generation becomes more economically attractive.

Pressurized Oxy-Coal Combustion (OCC) with Carbon Capture and Sequestration (CCS) mitigates the emissions problem while relying on the cheapest fossil fuel [4–9]. In OCC the flue gas is mainly carbon dioxide and water vapor, and the latter can be separated by condensation. Flue gas cooling and condensation can be integrated to recover thermal energy, particularly latent, into the low temperature section of the power cycle, [5,6,8–10]. As flue gas pressure increases, the vapor dew point in the flue gas increases allowing for condensation to occur earlier and at a higher temperature. This increases the amount of recovered latent energy and increases its quality since it occurs at a higher temperature. Pressurizing the combustion process increases the compression requirements of the air separation and oxygen delivery process while reducing those for the carbon sequestration process, but also contributes in increasing the pressure losses and irreversibilities within the flue gas; the tradeoffs signify a presence of an optimum operation. Simultaneous multi-variable optimization, like the one dealt with in [9], is required to obtain the optimum operation and achieve an attractive cycle performance. Optimization in [9] contributes in significant efficiency increase, 0.82% points over the literature proposal of 10 bar combustor pressure [6], while simultaneously reducing the combustor's operating pressure, to the range of [3.75–6.25] bar, thus making the process more attractive and practical. Efficiency is 3.18% points higher than that of the atmospheric operation. Results also show the importance of the 15 other optimization variables in obtaining such efficiency improvements.

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Nomenclature

ASU air separation unit
CCS carbon capture and sequestration
FG-Rec-pri primary recycled flue gas
FG-Rec-sec secondary recycled flue gas
Cool-Gas flue gas at exit of HRSG
CSU carbon sequestration unit
DCSC direct contact separation column thermal recovery unit
DCSC-HX heat exchanger in DCSC
HRSG heat recovery steam generator
RHE recovery heat exchanger. Acid condensation occurs in RHE
FG-DCSC-in flue gas entering the DCSC
FG-RHE-in flue gas entering the RHE
FW feedwater
FW, Main main feedwater stream. Largest working fluid flow passing through the HRSG and entering the expansion line
FWH feedwater heater
FW-HRSG-in feedwater entering the HRSG. Same flowrate as FW, Main
FW-DCSC-in feedwater entering the DCSC
HHV higher heating value of coal (MJ/kg)
Hot-Gas flue gas entering the HRSG
HP-Pump high pressure pump
LHV lower heating value of coal (MJ/kg)
BLD Rankine cycle regeneration bleed
LP-Pump low pressure pump
OC oxy combustion
OCC oxy-coal combustion
RW-Sep-in recirculation water of the DCSC entering the separation column
Cool-Gas flue gas exiting the HRSG
FW-HRSG-in feedwater entering the HRSG
Comb-Gas-in flue gas entering the combustor
FW-Recov-out feedwater exiting the recovery unit, RHE/DCSC

Variables and constraints
BLD1_stage Bleed1 extraction stage
BLD2_stage Bleed2 extraction stage
BLD3_stage Bleed3 extraction stage
CO_2_Cap ratio of CO_2 capture to total produced
CO_2_purepurity of CO_2 captured
$\dot{m}$ mass flowrate (kg/s)
MITA minimum internal temperature approach (°C)
P pressure (bar)
P_{Comb} combustion pressure (bar)
$P_{Deaerator}$ deaerator pressure (bar)
$\dot{Q}$ duty transfer (MW)
T temperature (°C)
$\dot{Q}_{Comb}$ combustor duty (MW)
$q_{Deaerator}$ quality in deaerator tank

Pressure drop parameters
d recycling pipe diameter (m)
V bulk flue gas velocity (m/s)
ΔP_{HRSG} HRSG pressure drop (Pa)
ΔP_{pipe} recycling pipe pressure drop (Pa)
ε wall roughness (m)
f friction factor
L_{pipe} recycling pipes equivalent length (m)
$\dot{m}$ flue gas flowrate (kg/s)
μ dynamic viscosity (kg/m.s)
$\dot{Q}_{HRSG}$ total transferred duty in HRSG (MW)
Re Reynolds number
ρ density (kg/m^3)

The pressurized OCC cycle presented in [9] utilizes a recovery heat exchanger (RHE), which is a surface heat exchanger, for recovering thermal energy from the water vapor present in the flue gas. However, this type of heat exchanger is subjected to considerable amount of fouling and damage from the contaminated flue gas. While the surface heat exchanger is thermodynamically more efficient, it requires relatively more care and maintenance. A more practical form of thermal heat recovery which is less susceptible to fouling is a direct contact separation column (DCSC). Comparison of the capital cost between the two recovery units is out of the scope of this work and is not evaluated here; keeping in mind that the higher maintenance required for the surface exchanger might offset the cost analysis associated to the recovery section in favor of the DCSC.

Separation columns are used in various engineering and chemical processes [11], and in fact are used as part of the Carbon Sequestration Unit (CSU) in the OCC cycle, where the dry flue gas is purified from nitrogen and sulfur oxides and other contaminants. In general the separation process is performed by having two streams in a vertical counter flow arrangement where undesired substances in one stream are transferred to the other stream. In this study, a DCSC is used instead of a surface heat exchanger to condense water vapor from the flue gas and recover some of the latent and sensible energy.

Replacing the RHE with a DCSC changes the cycle's performance substantially. The DCSC utilizes an intermediate stream between the flue gas and the working fluid of the power cycle for the recovery process, leading to a less effective thermal recovery compared to an RHE. Therefore, the efficiency of the cycle with the DCSC is expected to decrease. The difference in the operation and performance of the two units mandates optimization of the operating conditions for the DCSC flowsheet, which are expected to be noticeably different than those for the RHE flowsheet.

Herein, multi-variable gradient-based optimization is performed for the model presented in [9] with a DCSC replacing the RHE. A similar methodology and approach are followed as those explained in [9], the optimization results of which are taken as the basecase of the current work. Recent design rules and optimization procedures [9,12,13], are incorporated and automated within the model. Detailed and high fidelity modeling of components and irreversibilities are also considered to accurately assess the concept's advantages and tradeoffs compared to the original RHE flowsheet and compared to other coal CCS technologies. The details of the model and the specifications are presented in Section 2. Section 3 describes the DCSC unit and presents its modeling approach and simulation analysis for the proper integration within the pressurized OCC flowsheet. Section 4 deals with the optimization formulation and describes the objective function, optimization variables, and optimization constraints. Results are shown in Section 5 where the influence of the critical variables on the cycle is analyzed. Results also suggest possibilities of capital cost reductions.

2. Flowsheet and model description

2.1. Power plant flowsheet

The flowsheet and model specifications studied here are identical to those of [9] with the exception of utilizing a DCSC instead of