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Shell coal IGCCS with carbon capture: Conventional gas quench vs. innovative configurations

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ABSTRACT

The Shell coal integrated gasification combined cycle (IGCC) based on the gas quench system is one of the most fuel flexible and energy efficient gasification processes because is dry feed and employs high temperature syngas coolers capable of rising high pressure steam. Indeed the efficiency of a Shell IGCC with the best available technologies is calculated to be 47–48%. However the system looses many percentage points of efficiency (up to 10) when introducing carbon capture. To overcome this penalty, two approaches have been proposed. In the first, the expensive syngas coolers are replaced by a "partial water quench" where the raw syngas stream is cooled and humidified via direct injection of hot water. This design is less costly, but also less efficient. The second approach retains syngas coolers but instead employs novel water–gas shift (WGS) configurations that requires substantially less steam to obtain the same degree of CO conversion to CO_2, and thus increases the overall plant efficiency. We simulate and optimize these novel configurations, provide a detailed thermodynamic and economic analysis and investigate how these innovations alter the plant's efficiency, cost and complexity.

1. Introduction

In a world with a rapidly expanding appetite for energy and rising concentrations of greenhouse gases, the use of coal as a primary energy source engenders both heightened interest and concern. Coal is the most abundant and least expensive fossil fuel, but also the most carbon intensive. Various gasification technologies enable the conversion of coal into a synthesis gas that can be further processed into common energy carriers such as electricity and synthetic fuels (e.g. hydrogen, natural gas, and liquid transportation fuels). Gasification also provides some of the least costly methods for large scale CO_2 capture for sequestration in deep geologic formations away from the atmosphere.

Numerous studies indicate that bituminous coal-based electric power with CO_2 capture is less costly using integrated gasification combined cycles (IGCC) instead of standard pulverized coal (PC) steam electric plants [1,2]. For lower rank subbituminous coals and lignites, which comprise fully half of the world's coal reserves [3], the relative economics are less clear. To help clarify this issue, we investigate the thermodynamic and economic performance of three different variants of one particular type of coal-based IGCC plants that is likely to be able to economically convert *all* coals into electricity and other energy carriers: pressurized, entrained flow, oxygen-blown gasification, with coal drying and dry feeding into the gasifier. All plants in this work use bituminous coal; a forthcoming study addresses the effect of coal rank on plant performance and economics.

Commercial plants of this type (e.g. that use the Shell Coal Gasification or Siemens Fuel Gasification Process) typically employ high temperature heat exchangers to cool down the hot (about 900 °C) synthesis gas by generating high pressure steam prior to syngas cleaning and chemical processing. In plants with CO_2 venting, the high cost of these "syngas coolers" (SC) is generally offset by significantly increased plant efficiency. However, costly syngas coolers are often not well matched to CO_2 capture, which requires a relatively moist syngas; much of the generated steam must be used for syngas humidification required by the downstream water–gas shift (WGS) reaction necessary for high levels of CO_2 capture. In this regard, dry feed gasifiers are at a disadvantage relative to coal–water slurry fed gasifiers (e.g. GE Energy and ConocoPhillips E-Gas^{TM}) which generate a more humid syngas; often, additional steam is not required prior to WGS. To address this issue, Shell recently filed a patent application for a "partial water quench" whereby the hot raw syngas is cooled by direct water injection [4]. This system both humidifies the syngas and eliminates the costly high temperature syngas coolers.

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Nomenclature

Abbreviations and symbols

AGR	acid gas removal
AR	as received
ASU	(stand-alone, cryogenic) air separation unit
BOP	balance of plant
COMPR	compressor
COMPR	compressor
COND	condenser
CCR	annual capital charge rate
CCS	CO_2 capture and storage
dp	infinitesimal pressure drop, bar
ECON	economizer
ECN	Energy Research Centre of the Netherlands
GE	general electric
GT	gas turbine
HHV	high (or gross) heating value
HP	high pressure (∼140–170 bar)
HT	high temperature
HRSC	heat recovery steam cycle
HRSG	heat recovery steam generator
IDC	interest during construction
IGCC	integrated gasification combined cycle
L/G	liquid-to-gas mass ratio
LEAP	Laboratorio Energia Ambiente Piacenza
LCOE	levelized cost of electricity
LHV	lower (or net) heating value
LLT	extra low temperature
LP	low pressure (3–15 bar)
LT	low temperature
MDEA	N-methyl-diethanolamine
MP	medium pressure (20–50 bar)
NETL	National Energy Technology Laboratory
NG	natural gas
O&M	operation and maintenance
p	absolute pressure, bar
PC	pulverized coal (steam electric power plant)
pp	percentage points
q	mass flow rate, kg/s
QC	a particular plant configuration, defined below
QW	quench water
RH	reheat
SC	syngas cooler
SC	a Shell IGCC equipped with a conventional two-stage sour WGS unit for CCS, as defined in Section 2
SE	a Shell IGCC equipped with the novel ECN WGS unit for CCS, as defined in Section 2
SN	a Shell IGCC equipped with an innovative high efficiency WGS unit for CCS, as defined in Section 2
SV	a Shell IGCC without CCS, as defined in Section 2
S/CO	steam-to-CO mole ratio
SCOT	Shell Claus offgas treating
SG	synthesis gas, or syngas
SH	superheater
ST	steam turbine
TIT	turbine inlet temperature, °C
TOT	turbine outlet temperature, °C
TPC	total overnight plant cost
TPI	total plant investment (TPC + IDC)
T_{sat}	saturation temperature, °C
v	specific volume, m^3/kg
VGV	variable (air inlet) guide vanes
WGS	water–gas shift
x_A	volume fraction of component A
ΔT	temperature difference, K
ΔT_{TIT}	TIT de-rating, K
η	polytropic efficiency

Researchers at the Energy Research Centre of the Netherlands (ECN) have recently developed an advanced WGS design that significantly reduces the flow of steam required for conversion of CO and H_2O to CO_2 and H_2 [5]. This system, which is modeled and optimized in this study, has recently been implemented at pilot scale at NUON's Buggenum IGCC plant in the Netherlands. In addition, we investigate an alternative advanced WGS layout specifically designed and optimized to further minimize the steam consumption and thus the carbon capture penalty.

This study compares the thermodynamic and economic performance of a bituminous coal-based IGCC plant using Shell gasification technology – with and without CO_2 capture – using either the standard gas quench or the partial water quench as syngas cooling method and either the conventional two-stage sour WGS or one of the two advanced WGS designs. The plants are designed, modeled in detail and optimized to maximize the net electric efficiency, using both exergy analysis and numerical optimization algorithms. Our goal is to understand what the preferred IGCC design is for dry feed, entrained flow gasifiers with relatively high levels of carbon capture (>90%).

2. Methodology

We model four cases, three with CO_2 capture:

SV – a ***S***tandard (i.e. with syngas coolers) Shell coal gasifier-based IGCC plant with syngas coolers and CO_2 ***V***enting,
SC – a ***S***tandard Shell IGCC plant with CO_2 capture that uses a ***C***onventional two-stage WGS unit,
SE – a ***S***tandard Shell IGCC plant with CO_2 capture that uses the advanced ***E***CN WGS design,
SN – a ***S***tandard Shell IGCC plant with CO_2 capture that uses an optimized ***N***ew WGS configuration derived from the ECN design,
QC – a partial water ***Q***uench Shell IGCC plant with CO_2 capture, using a ***C***onventional two-stage WGS unit.

This research entailed seven primary tasks: (1) building a detailed model of the Shell coal gasification process using Aspen Plus chemical process modeling software [6], (2) calibrating the model by matching key component data and process flows to the detailed information provided in Refs. [7–9] which describe standard Shell- and Prenflo-based IGCC plants using bituminous coal, (3) investigating the optimal design of a partial water quench + wet scrubber + WGS system for Shell IGCC with CO_2 capture, (4) building the ECN WGS and coupling it to a standard Shell IGCC plant, (5) simulating the General Electric (GE) 9FB gas turbine (burning H_2-rich syngas) using the "Gas/Steam" (GS) simulation code developed at Politecnico di Milano and presented in [10,11,15,18], (6) configuring and optimizing the layout of the heat recovery steam cycle (HRSC) for each plant using a new method developed by Martelli [12,13] that maximizes the power output of the steam cycle, and (7) adding the cost framework required for a full techno-economic comparison between cases. Given that the first generation of IGCC power plants with CO_2 capture are likely to be operated as base-load plants, analyses of load-following performance and off-design calculations were not performed in this study. Indeed, commercially available gasification processes and