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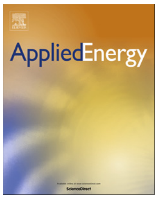

Application of optimal design methodologies in retrofitting natural gas combined cycle power plants with CO_2 capture

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HIGHLIGHTS

- A new approach is proposed for retrofitting NGCC power plants with CO2 capture.
- HTI techniques are developed for improving heat recovery in NGCC power plants.
- EGR techniques are developed to increase the process overall energy efficiency.
- The proposed methods are efficient for practical application.

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ABSTRACT

Around 21% of the world's power production is based on natural gas. Energy production is considered to be the significant sources of carbon dioxide (CO_2) emissions. This has a significant effect on the global warming. Improving power plant efficiency and adding a CO_2 capture unit into power plants, have been suggested to be a promising countermeasure against global warming. This paper presents a new insight to the application of energy efficient technologies in retrofitting natural gas combined cycle (NGCC) power plants with CO_2 capture. High fidelity models of a 420 MW NGCC power plant and a CO_2 capture plant with CO_2 compression train have been built and integrated for 90% capture level. These models have been then validated by comparisons with practical operating data and literature results. The novelty of the paper is to propose optimal retrofitting strategies to minimize the efficiency penalty caused by integrating carbon capture units into the power plant, including (1) implementing heat transfer intensification techniques to increase energy saving in the heat recovery steam generator (HRSG) of the power plant; (2) extracting suitable steam from the HRSG to supply the heat required by the capture process, thus on external heat is purchased; (3) employing exhaust gas recirculation (EGR) to increase the overall energy efficiency of the integrated process, which can benefit both power plant (e.g. increasing power plant efficiency) and capture process (e.g. reducing heat demands). Compared with the base case without using any integrating and retrofitting strategies, the optimal solution based on the proposed approaches can provide sufficient heat to CO_2 capture process, and keep the same power generation. The optimal solution shows that, the flue gas flow-rate is reduced 33% in the inlet of CO_2 capture process, heat demand in CO_2 capture decreases 4.3%, heat output from the power plant increases from 0 MW to 133 MW, and more than 22% of profit is obtained in the integrated system. This demonstrates the validity and efficiency of the proposed approaches in retrofitting existing NGCC power plants with CO_2 capture.

1. Introduction

Population growth and technological development in the world, has led to an energy demand that has been increased proportionally. The main sources to produce energy have been power plants, which operate on different types of fuel. However, power plants produce large amounts of greenhouse gas emissions such as carbon dioxide (CO_2), which has a significant effect on the global warming, raising the earth's temperature. Reducing CO_2 emission in power plants has been widely investigated by using combined cycle technologies to improve power plant efficiency and employing carbon capture and storage (CCS) unit to mitigate CO_2.

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Nomenclature

Indices

ex	exchanger

Sets

EX	set of all exchangers
$EX_{ec\&sh}$	set of all economisers and superheaters
EX_{ev}	set of all evaporators

Parameters

ΔT_{min}	minimum temperature difference approach (°C)
EXA_{ex}	designed area of exchanger *ex* (m^2)
CF'_{ex}	estimated flow rate of cold stream in an evaporator (kg/s)
$CFCP_{ex}$	heat-flow capacities (the multiplication between heat capacity and flow-rate) of cold stream in exchanger *ex* (kW/K)
CTI'_{ex}	initial inlet temperatures of cold streams in exchanger *ex* (C)
CTO'_{ex}	initial outlet temperatures of cold streams in exchanger *ex* (C)
$HFCP_{ex}$	heat-flow capacities (the multiplication between heat capacity and flow-rate) of hot stream in exchanger *ex* (kW/K)
HTI'_{ex}	initial inlet temperatures of hot streams in exchanger *ex* (°C)
HTO'_{ex}	initial outlet temperatures of hot streams in exchanger *ex* (°C)
$LMTD'_{ex}$	initial logarithmic mean temperature difference in exchanger *ex* (°C)
M	a sufficient large positive number
$MAXEU_{ex}$	upper bound of heat transfer coefficient of intensified exchanger *ex* (kW/m^2 °C)
$MAXNU_{ex}$	upper bound of heat transfer coefficient of exchanger *ex* without intensification (kW/m^2 °C)
$MINEU_{ex}$	lower bound of heat transfer coefficient of intensified exchanger *ex* (kW/m^2 °C)
$MINNU_{ex}$	lower bound of heat transfer coefficient of exchanger *ex* without intensification (kW/m^2 °C)

Variables continuous

AEB_{ex}	positive variable, energy balance differences between hot stream and cold stream in exchanger *ex* (kW)
BEB_{ex}	positive variable, energy balance differences between hot stream and cold stream in exchanger *ex* (kW)
CF_{ex}	flow rate of cold stream in an evaporator (kg/s)
CHI_{ex}	enthalpy of inlet cold stream in an evaporator (kJ/kg)
CHO_{ex}	enthalpy of outlet cold stream in an evaporator (kJ/kg)
CTI_{ex}	inlet temperatures of cold streams in exchanger *ex* (°C)
CTO_{ex}	outlet temperatures of cold streams in exchanger *ex* (°C)
$DACTI_{ex}$	positive variable, differences between initial and updated temperatures for cold stream inlet (°C)
$DACTO_{ex}$	positive variable, differences between initial and updated temperatures for cold stream outlet (°C)
$DAHTI_{ex}$	positive variable, differences between initial and updated temperatures for hot stream inlet (°C)
$DAHTO_{ex}$	positive variable, differences between initial and updated temperatures for hot stream outlet (°C)
$DBCTI_{ex}$	positive variable, differences between initial and updated temperatures for cold t stream inlet (°C)
$DBCTO_{ex}$	positive variable, differences between initial and updated temperatures for cold stream outlet (°C)
$DBHTI_{ex}$	positive variable, differences between initial and updated temperatures for hot stream inlet (°C)
$DBHTO_{ex}$	positive variable, differences between initial and updated temperatures for hot stream outlet (°C)
EU_{ex}	heat transfer coefficient of intensified exchanger *ex* (kW/m^2 °C)
HBA_{ex}	positive variable, heat transfer differences between streams and exchanger in exchanger *ex* (kW)
HBB_{ex}	positive variable, heat transfer differences between streams and exchanger in exchanger *ex* (kW)
HTI_{ex}	inlet temperatures of hot streams in exchanger *ex* (°C)
HTO_{ex}	outlet temperatures of hot streams in exchanger *ex* (°C)
NU_{ex}	heat transfer coefficient of exchanger *ex* without intensification (kW/m^2 °C)
Obj	objective value
U_{ex}	overall required heat transfer coefficient of exchanger *ex* (kW/m^2 °C)

Binary

EN_{ex}	1 if tube inserts are implemented in exchanger *ex*; otherwise, it is 0

Natural gas power plants are typical electricity generation processes that can be divided into two types: open cycle gas turbine (OCGT) and combined cycle gas turbine (CCGT). The OCGT is also called Brayton cycle, consisting of a power generator unit coupled with a gas turbine through a shaft. It can be used to produce power with 35–42% efficiency based on the lower heating value (LHV). The second type of natural fired gas turbine (CCGT) has the same basic elements of the OCGT, but employs a heat recovery steam generator (HRSG) to recover the heat from the exhaust gas to produce extra power. Over the last few decades, CCGT become popular compared with OCGT, because of the higher power production with higher plant efficiency [1]. The HRSG is one of the components that has significant exegetic losses. Therefore, optimization of the HRSG operating parameters (such as number of pressure levels, and steam pressures, temperatures and flowrates) can increase the efficiency of combined cycle plants. Cihan et al. [2] used thermodynamic optimization to determine the optimum values of the operating parameters to minimize exergy losses in the HRSG they considered. Ameri et al. [3] utilized exergy analysis for optimizing HRSG operating parameters to improve the plant performance by reducing the exergy destruction of the HRSG. Bassily [4] also found that increasing steam outlet temperature, and reducing stack temperature and temperature difference of heat exchangers can mitigate the HRSG irreversibility. Sanjay [5] dealt with thermodynamic analysis of CCGT with single (B1P), dual (B2P), and triple pressure (B3P) bottoming cycle configuration. They stated that the advantages of B3P included the highest plant-efficiency and plant-specific work, and the least non-dimensionalized exergy destruction and process irreversibility in the HRSG.

Compared with the technologies of improving energy efficiency in power plants, CO_2 capture and storage (CCS) is the most efficient methodology to reduce CO_2 emissions directly. CCS can be applied by different techniques to mitigate the CO_2 from the power plants, either by capturing the CO_2 from the fuel before entering the combustion (called pre-combustion) or by capturing the CO_2 from the exhaust. The latter, depending on the oxidant that is used in the combustion, can be divided into the Oxy fuel technique (using

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