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Thermoeconomic cost analysis of CO_2 compression and purification unit in oxy-combustion power plants

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ABSTRACT

High CO_2 purity products can be obtained from oxy-combustion power plants through CO_2 compression and purification unit (CPU) based on phase separation method. To identify cost formation process and potential energy savings for CPU, detailed thermoeconomic cost analysis based on structure theory of thermoeconomics is applied to an optimized CPU (with double flash separators). It is found that the largest unit exergy cost occurs in the first separation process while the multi-stage CO_2 compressor contributes to the minimum unit exergy cost. In two flash separation processes, unit exergy costs for the flash separator and multi-stream heat exchanger are identical but their unit thermoeconomic costs are different once monetary cost for each device is considered. For cost inefficiency occurring in CPU, it mainly derives from large exergy costs and thermoeconomic costs in the flash separation and mixing processes. When compared with an unoptimized CPU, thermoeconomic performance for the optimized CPU is enhanced and the maximum reduction of 5.18% for thermoeconomic cost is attained. To achieve cost effective operation, measures should be taken to improve operations of the flash separation and mixing processes.

1. Introduction

To mitigate the greenhouse effect on climate change, carbon capture and storage (CCS) technology is proposed as an effective and attractive pathway for restraining anthropogenic CO_2 emissions from coal-fired power plants. Generally, it can be divided into three main categories: post-combustion, pre-combustion, and oxy-combustion. Oxy-combustion is economic competitive and ready for commercial demonstration. It can be simply interpreted as a process that mixture of oxygen from air separation unit (ASU) and recycled flue gas primarily containing CO_2 and H_2O rather than air is used to combust with fuel, and then CO_2 can be easily separated from flue gas. For capturing CO_2 emissions from oxy-combustion power plants, CO_2 compression and purification unit (CPU) is used for removal of impurities in flue gas to obtain high-purity CO_2 products. From different requirements, various schemes for CPU without or with different purification units have been proposed for applications [1–3]. Compared with these options, the CPU using partial condensation method with double flash separators is chosen for oxy-combustion application since it is an auto-refrigerated process with characteristics of less power consumptions and lower capital costs.

Unfortunately, it would contribute to energy penalty [4–6], economic cost [7,8], and operating challenge [9,10] on oxy-combustion power plants since it consumes large energy and adds system complexity. To search energy saving method and reduce operating burden for CPU, several researches have been conducted, focusing on its thermodynamic and economic characteristics. Pipitone and Bolland [11] compared flash separation and distillation configurations based on simulations in SIMSCI PRO/II to remove impurities from flue gas in natural gas or pulverized fuel oxy-combustion power plant. Posch and Haider [12] identified the impact of main design parameters on the performance of two different CPU configurations. Ritter et al. [13] investigated six conceptual CPU configurations through energetic evaluation for reducing their specific energy consumption. Fu and Gundersen [14] simulated and compared three flash separation units through pinch and exergy analyses to obtain a suitable CPU with high thermodynamic performance. Further, techno-economic assessment [15] was conducted to screen the economic competitive process configuration for CO_2 purification. Jin et al. [16] presented single variable analysis and multi-variable optimization for CPU to find optimal operating conditions, and then deigned a double temperature control system for maintaining operation around desirable conditions.

Although the above studies have promoted the understanding of CPUs in oxy-combustion power plants, thermodynamic analysis and economic analysis for CPU are carried out separately which

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Nomenclature

Abbreviations

ASU	air separation unit
C	compressor
CCS	carbon capture and storage
Cooler	after-cooler
CPU	CO_2 compression and purification unit
HE1,2	first/second multi-stream heat exchanger
FS1,2	first/second flash separator
IEAGHG	International Energy Agency Greenhouse Gas
LCV114,119	throttle valves
MCC	multi-stage CO_2 compressor
MIX	mixer
OM (O&M)	operation and maintenance

Scalars

B	bifurcations/circles
C, c	investment cost (M$) and unit thermoeconomic cost ($/kJ)
E	exergy (kW)
E^{CH}	chemical exergy (kW)
E^{KN}	kinetic exergy (kW)
E^{PH}	physical exergy (kW)
E^{KN}	potential exergy (kW)
F	fuel exergy (kW)
f_m	total module factor
f_p	cost factor for internal pressure levels
H	annual operation hours (h)
L	load period (a)
i_A	load annual interest rate
J	junctions/rhombuses
k	unit exergy consumption
k^*	unit exergy cost (kW/kW)
k_Z	unit capital cost ($/s)
m	mass flow rate (kg/s)
N	numbers of parallel trains
P	pressure (bar)/product exergy (kW)
r	exergy rate
r_{OM}	O&M factor
r_p	cost ratio of operating pressure
T	temperature (°C)
V_{HE}	volume of a single-train heat exchanger (m^3)
W_{drum}	total weights of drums (kg)
Z	capital cost ($)

Greek letters

λ_A	average annual interest rate

Subscripts

0	reference state
a, i, j	number
F	fuel
in	inlet
out	outlet
P	product

cannot provide sufficient information for engineers. Fortunately, thermoeconomics that combines economic assessment and thermodynamic analysis by applying the concept of cost (an economic property) to exergy (an energetic property) can be applied since it is used for providing the system designers or operators with information not available through conventional energy analysis and economic evaluation but crucial to the design and operation of a cost effective system [17]. Thermoeconomics has been widely used in complex energy system like power plants to comprehend the process of cost formation from the input resource(s) to the final product(s). For conventional coal-fired power plant, Zhang et al. [18] applied exergy cost analysis to evaluate its performance, and then used thermoeconomic diagnose [19] to identify its malfunctions. Xiong et al. [20] considered thermoeconomic optimization to achieve the best balance between thermodynamic efficiency and economic cost for coal-fired power plant. Since increasing attention has been paid on CO_2 emission control, thermoeconomics has also been used to study CO_2 capture plants. Petrakopoulou et al. [21] performed thermoeconomic analysis to combined cycle power plant with chemical looping technology. Xiong et al. [22] presented a detailed thermoeconomic cost analysis of a 600 MWe oxy-combustion pulverized-coal-fired power plant. These researches provide good foundations for utilizing thermoeconomics for different applications.

However, very limited researches have been conducted to identify the cost formation process and then search cost effective operation for CPU. Therefore, the purpose of this paper is to implement this target using thermoeconomic cost analysis based on the structural theory of thermoeconomics. The paper is organized as follows. In Section 2, exergy calculation and exergy cost modeling with physical structure, fuel-product definition, characteristic equations and exergy cost equations are presented. Then, cost estimation and thermoeconomic cost modeling are presented in Section 3. Section 4 gives the results of exergy cost analysis and thermoeconomic cost analysis, and comparison of the thermoeconomic performance between optimized case and unoptimized case is discussed. Finally, a conclusion is given in Section 5.

2. Exergy cost analysis

2.1. Process description and exergy calculation

The schematic diagram of CPU, as described in Fig. 1, derives from an optimized case in our previous study [16] in which multi-variable optimization and control system design for CPU were conducted to obtain optimal operating conditions and maintain desirable operations through robust control. The system primarily consists of multi-stage CO_2 compressor (MCC), cold box in which first multi-stream heat exchanger (HE1), first flash separator (FS1), second multi-stream heat exchanger (HE2), second flash separator (FS2) are included, compressor (C) and after-cooler (Cooler). The feeding flue gas is compressed to 30 bar and then sent to cold box for removing impurities. In the first flash separation, flue gas is passed through HE1 and cooled down to −24.64 °C before entering into FS1 where the liquid CO_2 products are gained at the bottom whilst the top stream is cooled continually at HE2 to −55 °C and sent to FS2 in the second flash separation in which the second flow of CO_2 products is obtained from the FS2 bottom and vent gas is emitted from the FS2 top. Finally, the second CO_2 products is boosted and mixed with the first CO_2 products for storage or utilization. Different from the prototype proposed by the International Energy Agency Greenhouse Gas (IEAGHG) R&D programme [23], expansion process for vent gas and compression process for CO_2 products are not considered in this system.

Exergy (E) [24], defined as the maximum theoretical useful work obtained as the system state changes toward the dead state