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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

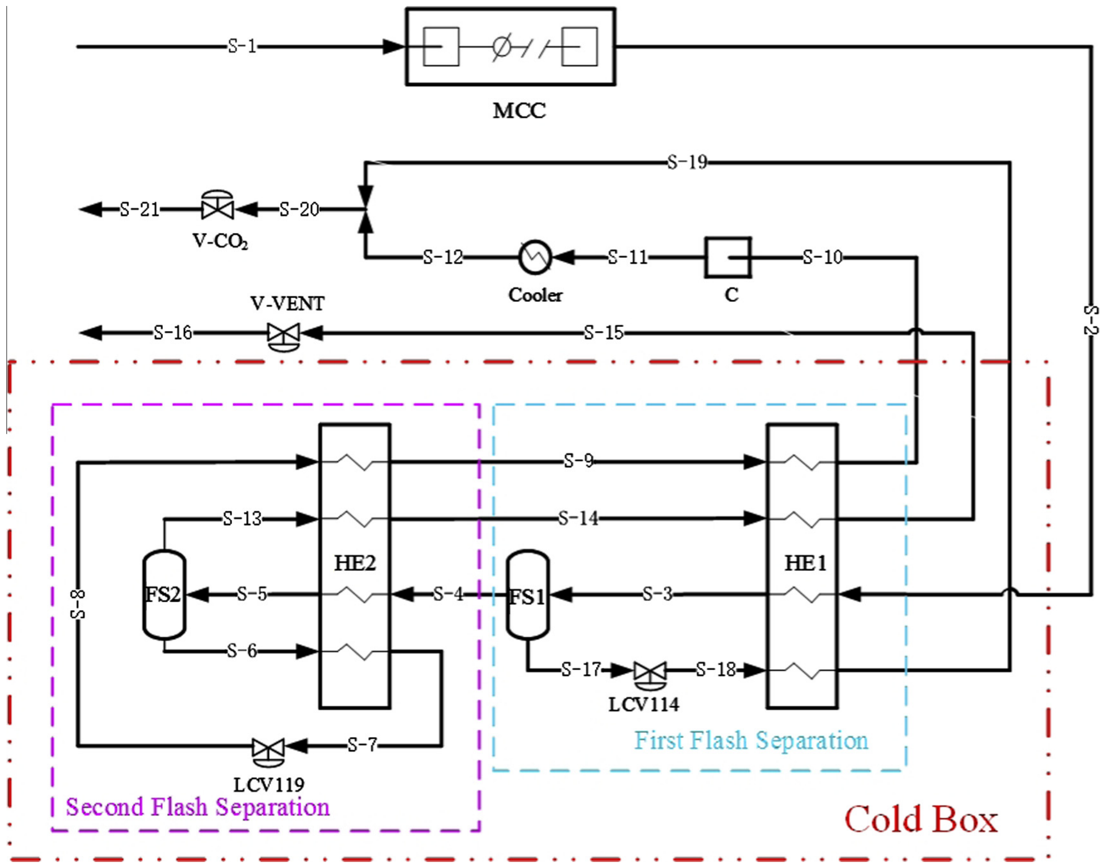

Fig. 1. Schematic diagram of the CO_2 compression and purification unit.

reversibly when excluding other heat sources, is firstly calculated to form fuel-product definition. The total exergy (E) is the sum of physical exergy (E^{PH}), chemical exergy (E^{CH}), kinetic exergy (E^{KN}), and potential exergy (E^{PT}). For thermodynamic system like CPU, only E^{PH} and E^{CH} are left for calculation since E^{KN} and E^{PT} are normally small and can be neglected. Physical exergy [24] (E^{PH}, defined as the maximum theoretical useful work obtained as a system passes from its initial state (T and P) to the environment state (T_0 and P_0)) and chemical exergy [24] (E^{CH}, raised from the departure of the chemical composition of a system from the environment) are calculated since detailed model, process simulation results with thermodynamic parameters (composition, flow rate, temperature, pressure and enthalpy), and exergy calculation procedures can be found in our previous study [16]. Table 1 lists operating conditions whilst Table 2 summarizes exergy values (E_i, i = 1–21) for the corresponding streams denoted as $S-i$ (i = 1–21) to calculate exergy resources (fuels and products).

2.2. Exergy cost modeling

The fuel-product definition is introduced to convert physical structure into productive structure. "Product" is named as the productive purpose of a process device measured in terms of exergy whilst "fuel" is the consumed exergy flow to create the product [17,22]. Following the fuel-product definitions for typical devices [17,22,24], equations for fuel and product exergies of main devices in CPU are listed in Table 3. MCC and C are fueled by net work to boost the inlet pressure to the require outlet pressure for corresponding flows. Physical separation process occurs in flash separators (FS1 and FS2) from one flow to vent and product flows, while an opposite process appears in mixer from two fuel flows to one product. For multi-stream heat exchangers (HE1 and HE2), exergy is removed from the hot streams and then supplied to the cold streams.

Different from physical structure, productive structure indicates the resource distribution throughout the plant for achieving the final aim of production. Fig. 2 describes a possible productive structure diagram of CPU when a low aggregation level which would reflect more information of cost formation with high accuracy is adopted here. Besides physical "plant components" represented by squares, rhombuses (junctions, Jj, j = 1–3) and circles (bifurcations, Ba, a = 1–4) are introduced to allow join and distribute the flows among the different devices. Junctions reflect that the products of two or more components are united to form the fuel of other component while bifurcations represent that an exergy flow is distributed between two or more components. For J1, F_{10} (E_9-E_{10}) and F_{12} ($E_{14}-E_{15}$) from B3, and F_8 ($E_{18}-E_{19}$) from B1 are combined with P_1 from MCC to form the fuels for HE1. B1 distributes the products of HE1 into F_3, F_6, and F_{15} (E_{19}) as the fuels of FS1, C, and MIX, respectively. F_9 (E_5-E_4) from B2, F_{13} (E_6-E_7) and F_{14} ($E_{13}-E_{14}$) from B4, and F_{11} (E_8-E_9) from B3 are mixed in J2 to act as the fuel of HE2. Then, junctions and bifurcations can be helpful for establishing structural equations to form a part of exergy cost model and thermoeconomic cost model.

The set of characteristic equations, which express each inlet flow (F_i) as a mathematical function of the outlet flows (P_i) for all the productive structure process units and internal parameters (x), i.e., $F_i = g_i(x_i,P_i)$, form the thermoeconomic model which represents the productive structure in the way of mathematics. From the characteristic equations presented in Table 4, unit exergy consumption k_i (defined as the ratio of fuel to product in terms of exergy, $k_i = F_i/P_i$) and exergy rate r_i (known as the portion of the ith flow of fuel in the product of the corresponding jth junction, $F_i = r_iP_j$) can be obtained and then used as known data in exergy

Table 1
Detailed stream conditions for CO_2 compression and purification unit as sketched in Fig. 1.

Stream no. Composition, mol.%	$S-1$	$S-2$	$S-3$	$S-4$	$S-5$	$S-6$	$S-7$
CO_2	82.40	82.40	82.40	63.68	63.68	95.59	95.59
O_2	4.19	4.19	4.19	8.54	8.54	1.27	1.27
N_2	9.50	9.50	9.50	19.78	19.78	2.08	2.08
Ar	3.90	3.90	3.90	8.00	8.00	1.06	1.06
CO (ppm)	31	31	31	65	65	7	7
SO_2 (ppm)	14	14	14	2	2	4	4
SO_3 (ppb)	83	83	83	1	1	2	2
NO (ppm)	20	20	20	40	40	11	11
NO_2 (ppb)	38	38	38	1	1	2	2
Temperature, °C	50	30.33	−24.64	−24.64	−55.00	−55.00	−44.38
Pressure, bar	1.10	29.90	29.72	29.72	29.45	29.45	29.24
	$S-8$	$S-9$	$S-10$	$S-11$	$S-12$	$S-13$	$S-14$
CO_2	95.59	95.59	95.59	95.59	95.59	24.00	24.00
O_2	1.27	1.27	1.27	1.27	1.27	17.57	17.57
N_2	2.08	2.08	2.08	2.08	2.08	41.78	41.78
Ar	1.06	1.06	1.06	1.06	1.06	16.62	16.62
CO (ppm)	7	7	7	7	7	136	136
SO_2 (ppm)	4	4	4	4	4	0	0
SO_3 (ppb)	2	2	2	2	2	0	0
NO (ppm)	11	11	11	11	11	75	75
NO_2 (ppb)	2	2	2	2	2	0	0
Temperature, °C	−55.62	−44.38	16.72	89.50	40.00	−55.00	−44.38
Pressure, bar	8.74	8.54	8.23	18.59	18.49	29.45	29.17
	$S-15$	$S-16$	$S-17$	$S-18$	$S-19$	$S-20$	$S-21$
CO_2	24.00	24.00	97.49	97.49	97.49	96.91	96.91
O_2	17.57	17.57	0.69	0.69	0.69	0.87	0.87
N_2	41.78	41.78	1.21	1.21	1.21	1.48	1.48
Ar	16.62	16.62	0.60	0.60	0.60	0.74	0.74
CO (ppm)	136	136	4	4	4	5	5
SO_2 (ppm)	0	0	24	24	24	17	17
SO_3 (ppb)	0	0	149	149	149	104	104
NO (ppm)	75	75	4	4	4	6	6
NO_2 (ppb)	0	0	68	68	68	47	47
Temperature, °C	16.83	16.79	−24.64	−31.21	16.71	23.84	23.73
Pressure, bar	28.90	28.80	29.72	18.80	18.49	18.49	18.39

Table 2
Exergy streams for CO_2 compression and purification unit, kW.

Stream	E_1	E_2	E_3	E_4	E_5	E_6	E_7
E^{PH}	266.21	38493.08	44597.22	17637.46	22082.80	12422.41	12036.76
E^{CH}	74652.45	74652.45	74652.45	24871.75	24871.75	22205.80	22205.80
E	74918.66	113145.53	119249.67	42509.22	46954.55	34628.22	34242.56
	E_8	E_9	E_{10}	E_{11}	E_{12}	E_{13}	E_{14}
E^{PH}	11752.50	6512.85	6042.42	8543.14	8228.64	8029.95	7942.65
E^{CH}	22205.80	22205.80	22205.80	22205.80	22205.80	4297.80	4297.80
E	33958.30	28718.65	28248.22	30748.94	30434.45	12327.75	12240.45
	E_{15}	E_{16}	E_{17}	E_{18}	E_{19}	E_{20}	E_{21}
E^{PH}	7781.96	7774.14	25684.72	25465.96	18400.29	26570.78	26524.71
E^{CH}	4297.80	4297.80	51056.86	51056.86	51056.86	73251.07	73251.07
E	12079.77	12071.95	76741.57	76522.82	69457.15	99821.85	99775.78

Table 3
Fuel-product definitions for the corresponding components in analyzed plant.

No.	Component	Fuel	Product
1	MCC	$F_1 = W_{MCC}$	$P_1 = E_2 - E_1$
2	HE1	$F_2 = (E_9 - E_{10}) + (E_{14} - E_{15}) + (E_{18} - E_{19})$	$P_2 = E_3 - E_2$
3	FS1	$F_3 = E_3$	$P_3 = E_4 + E_{17}$
4	HE2	$F_4 = (E_{13} - E_{14}) + (E_6 - E_7) + (E_8 - E_9)$	$P_4 = E_5 - E_4$
5	FS2	$F_5 = E_5$	$P_5 = E_6 + E_{13}$
6	C&Cooler	$F_6 = W_C$	$P_6 = E_{12} - E_{10}$
7	MIX	$F_7 = E_{12} + E_{19}$	$P_7 = E_{21}$

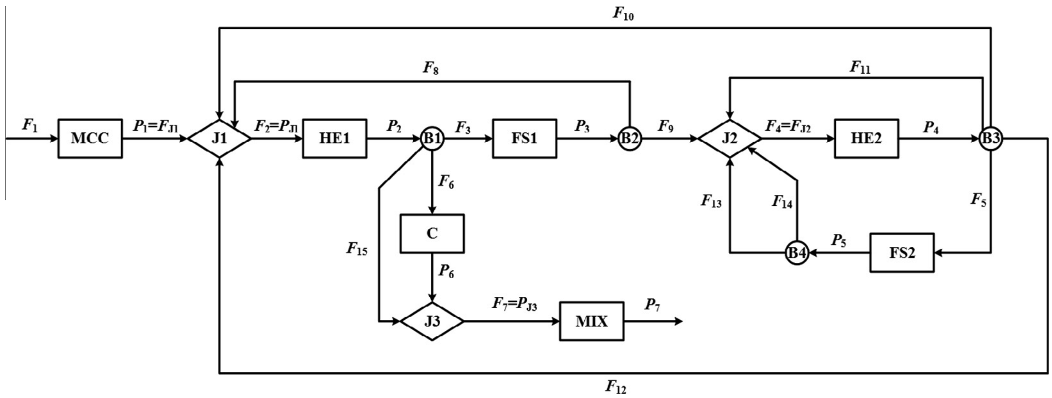

Fig. 2. Productive structure of the CO_2 compression and purification unit.

Table 4
Characteristic equations and exergy cost equations for all components.

No.	Component	Characteristic equation	Exergy cost equation
1	MCC	$F_1 = g_{F_1}(x_1,\ P_1) = k_1P_1$	$k^*_{P_1} = k_1k^*_{F_1}$
2	HE1	$F_2 = g_{F_2}(x_2,\ P_2) = k_2P_2$	$k^*_{P_2} = k_2k^*_{F_2}$
3	FS1	$F_3 = g_{F_3}(x_3,\ P_3) = k_3P_3$	$k^*_{P_3} = k_3k^*_{F_3}$
4	HE2	$F_4 = g_{F_4}(x_4,\ P_4) = k_4P_4$	$k^*_{P_4} = k_4k^*_{F_4}$
5	FS2	$F_5 = g_{F_5}(x_5,\ P_5) = k_5P_5$	$k^*_{P_5} = k_5k^*_{F_5}$
6	C&Cooler	$F_6 = g_{F_6}(x_6,\ P_6) = k_6P_6$	$k^*_{P_6} = k_6k^*_{F_6}$
7	MIX	$F_7 = g_{F_7}(x_7,\ P_7) = k_7P_7$	$k^*_{P_7} = k_7k^*_{F_7}$
8	J1	$P_1 = g_{P_2}(x_8,\ P_{J_1}) = r_1P_{J_1}$ $F_8 = g_{F_8}(x_8,\ P_{J_1}) = r_8P_{J_1}$ $F_{10} = g_{F_{10}}(x_8,\ P_{J_1}) = r_{10}P_{J_1}$ $F_{12} = g_{F_{12}}(x_8,\ P_{J_1}) = r_{12}P_{J_1}$	$k^*_{J_1} = r_8k^*_{P_3} + r_{10}k^*_{P_4} + r_{12}k^*_{P_4} + r_1k^*_{P_1}$
9	J2	$F_9 = g_{F_9}(x_9,\ P_{J_2}) = r_9P_{J_2}$ $F_{11} = g_{F_{11}}(x_9,\ P_{J_2}) = r_{11}P_{J_2}$ $F_{13} = g_{F_{13}}(x_9,\ P_{J_2}) = r_{13}P_{J_2}$ $F_{14} = g_{F_{14}}(x_9,\ P_{J_2}) = r_{14}P_{J_2}$	$k^*_{J_2} = r_{11}k^*_{P_4} + r_{13}k^*_{P_5} + r_{14}k^*_{P_5} + r_9k^*_{P_3}$
10	J3	$P_6 = g_{P_6}(x_{10},\ P_{J_3}) = r_6P_{J_3}$ $F_{15} = g_{F_{15}}(x_{10},\ P_{J_3}) = r_{15}P_{J_3}$	$k^*_{J_3} = r_{15}k^*_{P_2} + r_6k^*_{P_6}$
11	B1	$P_2 = g_{P_2}(x_{11},\ F_3,\ F_6,\ F_{15})$	$k^*_{P_2} = k^*_{F_3} = k^*_{F_6} = k^*_{F_{15}}$
12	B2	$P_3 = g_{P_3}(x_{12},\ F_8,\ F_9)$	$k^*_{P_3} = k^*_{F_8} = k^*_{F_9}$
13	B3	$P_4 = g_{P_4}(x_{13}, F_5, F_{10}, F_{11}, F_{12})$	$k^*_{P_4} = k^*_{F_5} = k^*_{F_{10}} = k^*_{F_{11}} = k^*_{F_{12}}$
14	B4	$P_5 = g_{P_5}(x_{14},\ F_{13},\ F_{14})$	$k^*_{P_5} = k^*_{F_{13}} = k^*_{F_{14}}$

cost and thermoeconomic cost equations. Actually, the exergy cost equation for an energy system or a component can be expressed as below [22].

$$k^*_P \cdot P_i = \sum_{j=1}^{n} k^*_{F_j} F_j \qquad (1)$$

in which, k^* (kW/kW) is unit exergy cost which means the amount external exergy resources in producing one unit exergy of a flow, the subscript F and P represent fuel and product, respectively.

3. Thermoeconomic cost analysis

3.1. Cost estimation

Before thermoeconomic cost analysis, necessary considerations and assumptions are established as follows for cost estimation of each device in CPU which then can be used as the required "economic factor" cost in the thermoeconomic cost equations. (1) Combined with steady-state simulation results [16] and the detailed economic analysis method [15] for CPU, investment cost equations for the corresponding devices can be formulated. (2) Eq. (2) calculates the investment costs of MCC (C_{MCC}) and C (C_C) where m is the mass flow rate (kg/s), P_{in} and P_{out} are the outlet pressure and inlet pressure (bar), respectively. (3) In Eq. (3) for estimating investment cost of sub-ambient heat exchangers (HE1 and HE2), f_m means the total module factor that converts the purchase cost into the total investment cost, N represents the numbers of parallel trains, C_{volume} is the cost per unit volume, V_{HE} (m^3) is the volume of a single-train heat exchanger, and r_p is the cost ratio of operating pressure. (4) The investment cost of flash drums (FS1 and FS2) can be calculated as illustrated in Eq. (4), in which f_p is the cost factor for internal pressure levels and W_{drum} (kg) is the total weights of drums. (5) Since the investment costs of cooler and mixer are small compared to that those of compressors and sub-ambient heat exchangers, they are expected to be negligible in this study.

$$C_{MCC(or\ C)} = m\left[(0.13 \times 10^6)m^{-0.71} + (1.40 \times 10^6)m^{-0.60}\ln(P_{out}/P_{in})\right] \qquad (2)$$

$$C_{HE} = f_m N r_p C_{volume} V_{HE} \qquad (3)$$

$$C_{drum} = 3.5 \times 73 f_m f_p W_{drum}^{-0.34} \qquad (4)$$

Table 5
Thermoeconomic cost equations for all the components in CPU.

No.	Component	Thermoeconomic cost equation
1	MCC	$c_{P_1} = k_1 c_{F_1} + k_{Z_1}$
2	HE1	$c_{P_2} = k_2 c_{F_2} + k_{Z_2}$
3	FS1	$c_{P_3} = k_3 c_{F_3} + k_{Z_3}$
4	HE2	$c_{P_4} = k_4 c_{F_4} + k_{Z_4}$
5	FS2	$c_{P_5} = k_5 c_{F_5} + k_{Z_5}$
6	C&Cooler	$c_{P_6} = k_6 c_{F_6} + k_{Z_6}$
7	MIX	$c_{P_7} = k_7 c_{F_7}$
8	J1	$c_{J_1} = r_8 c_{P_3} + r_{10} c_{P_4} + r_{12} c_{P_4} + r_1 c_{P_1}$
9	J2	$c_{J_2} = r_{11} c_{P_4} + r_{13} c_{P_5} + r_{14} c_{P_5} + r_9 c_{P_3}$
10	J3	$c_{J_3} = r_{15} c_{P_2} + r_6 c_{P_6}$

3.2. Thermoeconomic cost modeling

In order to calculate capital cost (Z) for building thermoeconomic cost model, the investment costs for devices in CPU should be converted as unit time cost which is stated as below: for a device i with an investment cost C_i and a load period L year (18 [22] in this paper), its monetary cost in unit time, Z_i (\$/s)), is formulated as below [22].

$$Z_i = C_i * \left[\frac{((1/L) + \lambda_A + r_{\mathrm{OM}})}{H * 3600}\right] \tag{5}$$

where r_{OM} means the O&M factor for CPU in oxy-combustion power plant (1.5% [25] is adopted in this study), H means the annual operation hours (5000 h [25] in this paper), and λ_A means the average annual interest rate based on the "equal principal of the law" which can be calculated as below [22].

$$\lambda_A = i_A \times \frac{(1 + 1/L)}{2} \tag{6}$$

in which, i_A is the load annual interest rate and 5.94% [25] is chosen in this study.

After determining Z as discussed above, thermoeconomic cost equation for device i in CPU can be expressed as follows:

$$c_P \cdot P_i = \sum_{j=1}^{n} c_{F_j} F_j + Z_i$$

where c (\$/kJ) means unit thermoeconomic cost which defined as the monetary cost expanded in producing one unit exergy of a flow [22]. Table 5 summarizes thermoeconomic cost equation for the components in CPU, where the $k_{Z,i}$ denoted as unit capital cost formulating as $k_{Z,i} = Z_i/P_i$. Here, the unit exergy cost of feeding flue gas is 6.91×10^{-6} \$/kJ, which derives from results of thermoeconomic cost analysis a 600 MWe oxy-combustion power plant [22].

4. Results and discussion

4.1. Exergy cost

Table 6 lists exergy cost results for all components in CPU. Consistent with exergy analysis results conducted in the previous study [16] that main exergy destruction (defined as the difference between fuel exergy and product exergy) occurs in compressors and heat exchangers, unit exergy consumptions are mainly presented in compression and heat transfer processes, which are ranked in the order of MCC, C&Cooler, HE2 and HE1. For unit exergy cost, it is quite distinctive from the results of exergy analysis that the largest unit exergy cost occurs in second heat exchanger and second flash separator whilst the unit exergy cost for MCC is minimum. Another interesting finding is that the unit exergy cost for heat exchanger equals to that of flash separator, which is attributed to only physical separation process in flash separator. When considering exergy cost (means that the product of unit exergy cost and exergy value for the corresponding flow) for components in CPU, main consumptions are ascribed to flash separation (47,437.39 kW for first flash separator and 379,075.55 kW for second flash separator) and mixing (447,394.60 kW for mixer) processes. Therefore, measures for potential energy savings in flash separation and mixing processes should be taken to make CPU operate more cost effective.

4.2. Thermoeconomic cost

As shown in Table 7, investment costs for different devices in CPU are obtained based on above cost estimation equations (see Eqs. (2)–(4)), and unit thermoeconomic costs are calculated from a set of thermoeconomic cost equations (see Table 4) discussed in Section 3.2. Similar with economic analysis results for CPU in other study [15], the total investment costs are 57.35 M\$ which the investment cost of compressors (MCC and C) accounts about 92.33%. Inversely, the unit thermoeconomic cost for MCC is the minimum value among all components while the unit thermoeconomic cost for second flash separator is the maximum. Although the distribution of unit thermoeconomic cost for all components is consistent with that of unit exergy cost, the unit thermoeconomic cost for heat exchanger does not equal to that of flash separator due to the effects of different monetary costs for the corresponding components. From the results of thermoeconomic cost (defined as the product of unit thermoeconomic cost and exergy value for the corresponding flow), main inefficiency still concentrates on flash separation and mixing processes, which then approaches for improving their operating performance should be considered.

4.3. Comparison with the unoptimized CPU case

As discussed in the previous study [16], multi-variable optimization with four objective variables (MCC discharge pressure,

Table 6
Exergy cost calculation results for CPU.

No.	Component	F	P	k	r	k_F^*	k_P^*
1	MCC	64783.93	38226.87	1.695	0.442 (r_1)	1.000	1.695
2	HE1	7696.78	6104.14	1.261	0.305 (r_6)	3.157	3.981
3	FS1	119249.67	119250.79	1.000	0.512 (r_8)	3.981	3.981
4	HE2	5712.61	4445.33	1.285	0.438 (r_9)	6.282	8.073
5	FS2	46954.55	46955.97	1.000	0.034 (r_{10})	8.703	8.073
6	C&Cooler	3082.84	2186.23	1.410	0.516 (r_{11})	3.981	5.613
7	MIX	99891.60	99775.78	1.001	0.012 (r_{12})	4.480	4.484
8	J1	–	–	1.000	0.038 (r_{13})	3.157	3.157
9	J2	–	–	1.000	0.009 (r_{14})	6.282	6.282
10	J3	–	–	1.000	0.695 (r_{15})	4.478	4.478

Table 7
Investment cost and thermoeconomic cost for the components in CPU.

No.	Component	Investment cost, M$	c_P (10^{-5} $/kJ)
1	MCC	46.11	0.989
2	HE1	2.54	3.402
3	FS1	0.69	3.405
4	HE2	0.71	7.235
5	FS2	0.46	7.241
6	C&Cooler	6.84	6.569
7	MIX	0	4.372
8	J1	–	2.512
9	J2	–	5.559
10	J3	–	4.367

MCC outlet temperature, FS1 temperature, and FS2 temperature) and three operating constraints (CO_2 product purity, CO_2 recovery rate, and CO_2 triple point temperature) were conducted to minimize the specific power consumption (defined as the ratio of total power consumption including power consumption in MCC and *C* to total CO_2 recovered) for CPU. Different from exergy analysis for validating the effectiveness of the selected multi-variable optimization method, exergy cost and thermoeconomic cost analyses for unoptimized case are also conducted for comparison. Fig. 3 presents a comparison of unit exergy costs for all components in two cases. It is found that similar distribution for unit exergy cost is obtained that the largest irreversibility results from first flash separation process while MCC contributes to the smallest effects on thermodynamic performance of CPU. After optimization, the thermodynamic efficiency for CPU is improved because the unit exergy cost for all components in optimized case are lower than that in unoptimized case except for MCC which is almost the same

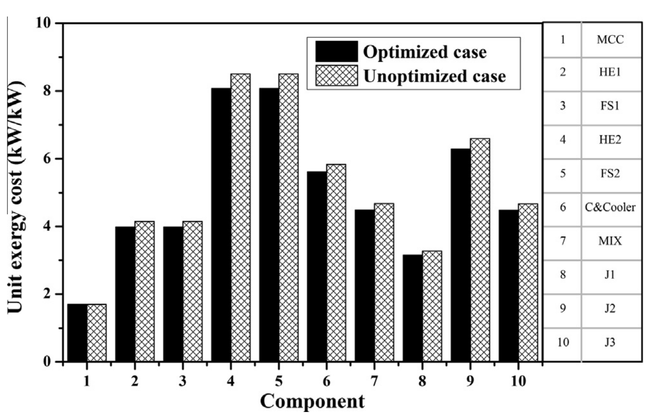

Fig. 3. Comparison of exergy costs for all components in two CPU cases.

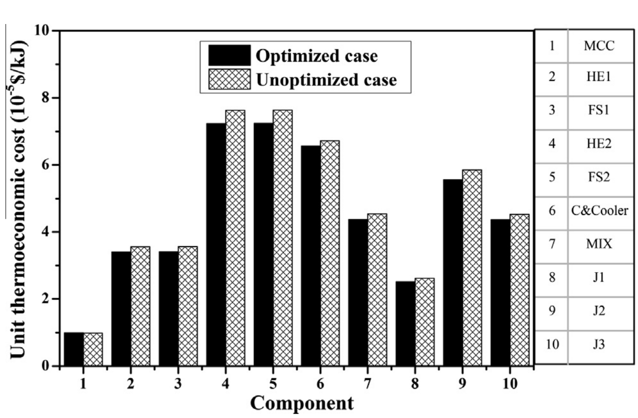

Fig. 4. Comparison of thermoeconomic costs for all components in two CPU cases.

between these two cases, and the biggest reduction of unit exergy cost can be 5.06%.

Fig. 4 illustrates comparison of thermoeconomic cost analysis results for two cases, which also finds that the proportion for each component is similar between optimized case and unoptimized case. When multi-variable optimization is applied, unit thermoeconomic costs for all components are reduced under the optimal operating conditions. The sequence of energy savings in component is in the way of second heat exchanger, second flash separator, first heat exchanger, first flash separator, mixer, C&Cooler and MCC, which the highest improvement is 5.18%. Thus, the thermoeconomic performance for CPU based on multi-variable optimization is further enhanced.

5. Conclusion

Detailed thermoeconomic cost analysis based on the structure theory of thermoeconomics for an optimized CO_2 compression and purification unit (CPU) in oxy-combustion power plants is firstly performed in this paper. Exergy calculation based on process simulation from our previous study is conducted for all streams in CPU to lay the foundation for exergy cost analysis. Then, thermoeconomic cost analysis is carried out when investments costs for all devices in CPU are estimated. Comparison of thermoeconomic performance between optimized CPU and unoptimized CPU is presented to further validate the selected multi-variable optimization method.

For unit exergy consumption, the largest one comes from multi-stage CO_2 compressor (MCC) while other components are ranked in the order: compressor & cooler (C&Cooler), second multi-stream heat exchanger (HE2), and first multi-stream heat exchanger (HE1). From exergy cost results, MCC has minimum effects on unit exergy cost while second flash separation contributes to the largest unit exergy cost for CPU. Interestingly, the unit exergy costs of flash separator and multi-stream heat exchanger are identical in two flash separation processes. In addition, main inefficiency results from flash separation and mixing processes when exergy cost for all components are compared. With respect to thermoeconomic cost analysis, unit thermoeconomic cost primarily occurs in second flash separator while that of MCC is still the minimum value. Although the unit thermoeconomic cost for heat exchanger does not equal to that of flash separator since monetary costs are considered for all components, flash separation and mixing processes still lead to main cost inefficiency in CPU. When compared to optimized case, similar exergy cost and thermoeconomic cost distributions in the unoptimized case are obtained even though more penalties are produced. The maximum improvement for unit exergy cost and unit thermoeconomic cost can be reached to 5.06% and 5.18%, respectively.

The research uncovers the cost formation from feeding flue gas to CO_2 products, and then provides useful information for energy savings in CPU. Searching reasonable operating condition for flash separation and mixing processes in CPU is recommended as main measures to obtain cost effective operation for CPU.

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