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Coal- fired power plants with large-scale carbon capture systems are optimized using waste heat utilization to operate load-cycling

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ABSTRACT

Coal-fired power plants integrated with post-combustion carbon capture technology are selected as an effective way to meet the demand for electricity, and to ameliorate the environmental pollution caused by the burning of fossil fuels. However, there is energy loss in the coal-fired power plants integrated with large-scale carbon capture systems. To obtain the optimal system parameter of coal- fired power plants integrated with large-scale carbon capture systems, the inlet temperature of the stripper and the irreversibility of the system is first analyzed, followed by waste heat utilization. As renewable power generation deployment grows, fossil fuel plants, including coal-fired units with coupled carbon capture systems, are being forced to operate more flexibly. The performance of coal-fired power plants integrated with large-scale carbon capture systems under load-cycling operation conditions is analyzed. It turns out that the exergy efficiency of CPCC under 30%THA is the lowest, only 2.9%. The structures should be restructured under low load ratio.

Keywords: carbon capture and storage; load cycling operation conditions, exergy analysis; optimization

NONMENCLATURE

Abbreviations	
CCS	Carbon capture and storage
PCC	Post-combustion CCS
CPCC	Coal-fired power plants integrated with PCC
ESP	Electrostatic precipitator
DES	Desulfurizer
IDF	Induced draft fan
HT	Feedwater heater
Cond	Condenser
De	Deaerator
HP	High-pressure turbine
IP	Intermediate pressure turbine
LP	Low-pressure turbine
Symbols	
$\eta_{e,CPCC}$	The exergy efficiency of CPCC
$\dot{P}_{steam}$	The power output of CPCC, kW
$\dot{E}_{w,CO_2}$	The electricity of CO_2, kW
$\dot{m}_{coal}$	The supplied coal, $kg\cdot s^{-1}$
$e_{w,coal}$	The exergy of coal, $kJ\cdot kg^{-1}$
η_{abs}	the absorption rate
$\dot{m}_{FG,CO_2}$	the inlet mass flow rate of the absorber, $kg\cdot s^{-1}$
$\dot{m}_{TFG,CO_2}$	the inlet mass flow rate of the absorber, $kg\cdot s^{-1}$
R	the molar gas constant
T	the temperature, K
T_0	the temperature of the dead standard
y	the molar fraction
N	the molar flow rate, mol
$\dot{E}_w$	the exergy of matter, kW
$\bar{h}_i$	the molar enthalpy of component i, $kJ\cdot kmol^{-1}$
$\bar{s}_i$	the molar entropy of component i, $kJ\cdot kmol^{-1}\cdot K^{-1}$

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$\mu_{0,i}$	the dead standard chemical potential, kJ·kg^{-1}
Abbreviations	
APEN	Applied Energy
Symbols	
n	Year

1. INTRODUCTION

According to statistical review of world energy, coal-fired power plants still play an essential role to ensure the energy security and resilience of the power system [1], responsible for about 60% electricity production [2]. Coal is an indispensable pillar of the global energy mix due to its accessibility [3] and large quantities [4]. However, there are two sides of everything, and coal burning causes excessive CO_2 emissions. In 2022, CO_2 emissions associated with coal combustion amounted to 14.44 Gt [5], raising concern about the widespread diffusion of low-carbon technologies. Therefore, it is imperative to implement CO_2 reduction strategies for fossil fuel plants to mitigate global warming. This can be done by increasing the efficiency of energy conversion system and/or integrating with carbon capture and storage technology (CCS) [6].

With the advent of CCS application, the negative impact from burning fossil fuel is being mitigated, e.g., greenhouse [7]. Post-combustion CCS (PCC) is the most widely used approaches for coal-fired power plants compared with pre-combustion and oxy-combustion technologies because it is suitable for capturing CO_2 at low concentrations [8]. The initial PCC system is proposed by Bottoms [9]. After many studies, it was found that Monoethanolamine (MEA) is widely recognized as a crucial solvent for post-combustion capture technology, due to its fast reaction rate and relatively high separation selectivity with CO_2 [10].

Decreasing the energy required by the reboiler is one of the effective approaches to increase the integration power plants efficiency mainly by reducing the steam extraction. Throughout decades, PCC have been developed and its heat consumption can be as low as 3.0 GJ/t CO_2 [11] by optimizing the process [12]. Zhang et al.[13] proposed two improved PCC systems using flash evaporation and thermal vapor compression and to reduce the steam consumption and thus reduce efficiency penalty. The efficiency improvement of the integration system is about 0.1%. Xu et al. [14] introduced the system integration with three measures. As a result, the efficiency penalty of CO_2 capture is expected to decrease by 4.91%-points. Siefert et al. [15] conducted the exergy and economic analysis of two integration systems and raised some suggests to achieve reasonable values. However, the energy consumption of CCS is not static, and it increases with the increase of absorbing CO_2 [16].

Waste heat recovery is another effective way to increase decarbonization of power plants. In PCC, the heat of the condenser of the stripper, the solvent out from the stripper ,and the heat released in the compression process need to be cooled [17, 18], while the only solution that needs to be heated is the rich solution out from the absorber [19]. Enormous researches have been conducted to solve the considerable loss of low-grade heat in PCC. To recover the waste condensation heat, Song et al. compressed the vapor distillate stream to increase the fire-use rate [20]. The results showed that the energy consumption of PCC can be reduced to 1.78 MJ/kg CO_2. Li et al. [21] developed the MEA-based post-combustion capture process and optimized the process. It is that the CO2 avoided cost fell to \$75.1/t CO_2.

In summary, the energy consumption of PCC can be divided into two parts [22], one is the separation of CO_2 mainly related to heat consumption and the other is the subsequent treatment of CO_2, i.e., compression [23], which mainly requires electricity. The exergy analysis of PCC should be taken into consideration [24].

In order to address the instability associated with the rapid penetration of intermittent renewable power, coal-fired power plants, as the main dispatchable units in the current energy system, undertake peak shaving tasks in the power grid [25]. The coal-fired power plants integrated with PCC (CPCC) also need to be studied for load-cycling operation conditions [26]. To bridge the research gap, the energy and exergy of CPCC under different load conditions will be evaluated. Firstly, the models of CPCC are developed based on thermodynamic analysis. Then, temperature matching of each flow strand is performed to obtain the optimal CCS progress. Following that, the exergy flow of CPCC is analyzed under load-cycling operation conditions.

2. MODEL DEVELOPMENT

In this section, the coal-fired power plants and CCS models (including the compression system) are developed. Moreover, evaluation metrics are established based on the electricity and steam consumption of the carbon capture system.

2.1 *System description*

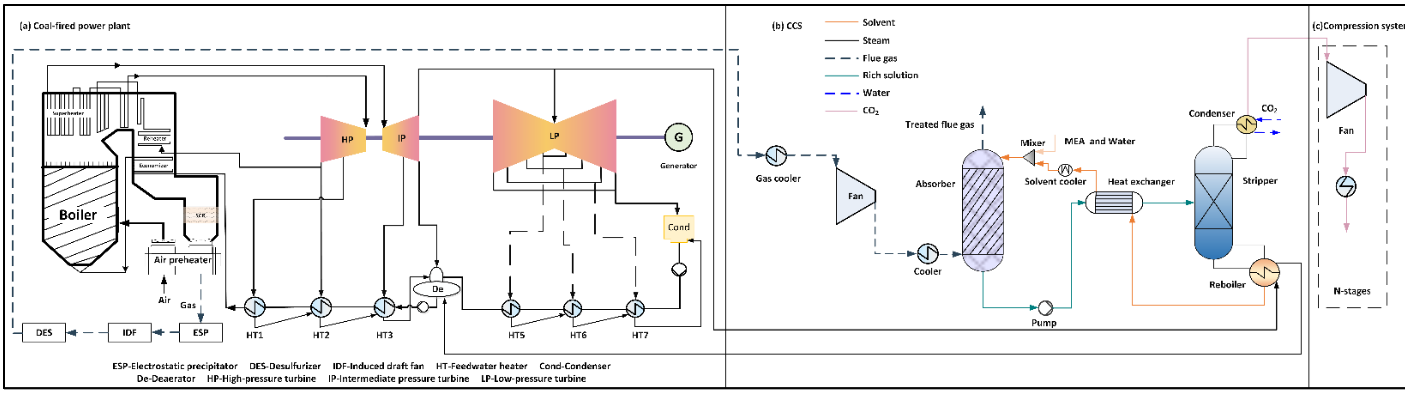

Fig. 1. Schematic of the proposed CPCC structure

Table 1. The parameters of CPCC

Items	Units	Value	Items	Units	Value
Lower heating value of coal of feed coal	kJ·kg^{-1}	22810	Mass flow rate of flue gas	kg·s^{-1}	771
Boiler efficiency	%	95	N_2	%	69.97
Main steam pressure	MPa	16.67	O_2	%	3.54
Main steam temperature	°C	538	H_2O	%	4.98
Reheat steam pressure	MPa	3.651	CO_2	%	21.51
Reheat steam temperature	°C	538	Pressure of the absorber	kPa	100
Condenser pressure	kPa	11	Pressure of the stripper	kPa	130
Generator efficiency	%	99	Inlet temperature of the absorber	°C	40
Gross efficiency	%	41.83	Inlet temperature of the stripper	°C	106

The proposed system can be split into three different subsystems, where the coal-fired power plants (a) is chosen as host unit and the MEA-based CCS (b) contains compression process (c), which shown in Fig. 1. The parameters of CPCC under 100%THA condition are listed in Table 1. A 630MW subcritical coal-fired power plants is selected as the host unit, which has 7 feedwater heaters. The feedwater heaters are numbered by the extraction pressure from highest to lowest. When the condensed water out from the reboiler flows into the feedwater system and heat recovery from CCS, the HT5-7 may be replaced, and the results of different feedwater system is compared in the section 3.

2.2 Hypothesis and mathematical model

The following hypothesis are assumed to develop the mathematical model.

1) The exhaust flue gas enters CCS after desulfurizer, denitrification and electrostatic precipitator, therefore the flue gas only contains N2, O2, H2O and CO_2.

2) The boiler exhaust process is simplified by considering only the process after the flue gas from the desulfurizer.

3) The outlet temperature of the gas cooler of CCS is 100kPa and 80 °C.

4) The pressure drop is ignored.

The proposed CPCC efficiency is determined and compared with the host power plants, which can be calculated as:

$$\eta_{e,CPCC}=\frac{\dot{P}_{steam}+\dot{E}_{w,CO_2}}{\dot{m}_{coal}*e_{w,coal}}, \quad (1)$$

where $\eta_{e,CPCC}$ is the exergy efficiency of CPCC; $\dot{P}_{steam}$ is the power output of CPCC, kW; $\dot{E}_{w,CO_2}$ is the exergy of CO_2, kW; $\dot{m}_{coal}$ is the supplied coal, kg·s^{-1}; $e_{w,coal}$ is the exegy of coal, kJ·kg^{-1}.

The absorption rate of CO2 is given by the change in mass of carbon dioxide at the inlet and outlet of the absorber as follows,

$$\eta_{abs}=\frac{\dot{m}_{FG,CO_2}-\dot{m}_{TFG,CO_2}}{\dot{m}_{FG,CO_2}}, \quad (2)$$

where η_{abs} is the absorption rate; $\dot{m}_{FG,CO_2}$ is the inlet mass flow rate of the absorber, kg·s^{-1}; $\dot{m}_{TFG,CO_2}$ is the inlet mass flow rate of the absorber, kg·s^{-1}.

The minimum work of CCS can be expressed by

$$W_{\min} = RT(\dot{N}_{CO_2,CO_2} * \ln(y_{CO_2,CO_2}) + \dot{N}_{CO_2,CO_2-CO_2} * \ln(y_{CO_2,CO_2-CO_2}) + \dot{N}_{TFG,CO_2} * \ln(y_{TFG,CO_2}) + \dot{N}_{TFG,TFG-CO_2} * \ln(y_{TFG,TFG-CO_2}) - \dot{N}_{FG,CO_2} * \ln(y_{FG,CO_2}) - \dot{N}_{FG,FG-CO_2} * \ln(y_{FG,FG-CO_2})) \quad , \quad (3)$$

where R is the molar gas constant, R=8.31 J·mol^{-1}·K^{-1}; T is the temperature, K; N is the molar flow rate, mol; y is the molar fraction; the subscripts CO_2, and −CO2 represents CO_2 and removal of CO_2, respectively.

The exergy of each stream can be calculated as

$$\dot{E}_W = \sum_{i=1}^{n} [\overline{h}_i - T_0 \overline{s}_i - \mu_{0,i}] \dot{N}_{i,\text{in}} \quad (4)$$

where $\dot{E}_w$ is the exergy of matter, kW; $\overline{h}_i$ is the molar enthalpy of component i, kJ·kmol^{-1}; $\overline{s}_i$ is the molar entropy of component i, kJ·kmol^{-1}·K^{-1}; $\dot{N}_{i,\text{in}}$ represents the moles of i constituents, kmol; $\mu_{0,i}$ is the dead standard chemical potential, kJ·kg^{-1} and T_0 is the temperature of the dead standard, T_0=298K.

3. RESULTS AND DISCUSSION

The inlet temperature of the stripper and the energy consumption of CCS is analyzed. Finally, the performance of CPCC is obtained.

3.1 The inlet temperature of the stripper under load-cycling operation conditions

When the stripper pressure is 130kPa, the heat consumption of the stripper under different inlet temperature is analyzed and the diagram of heat consumption with the changing of the inlet temperature is shown in Fig. 2. The total heat required for rich solution separation is provided partly by waste heat in the CCS and partly by steam. The amount of heat required to separate CO2 from a given stream is fixed, and if the rich fluid heater provides more heat, the desorption tower will require less heat. Thus, when CCS operates in 100%THA, 107°C is chosen as the inlet temperature for the stripper; when CCS operates in 50%THA, 105°C is chosen as the inlet temperature for the stripper.

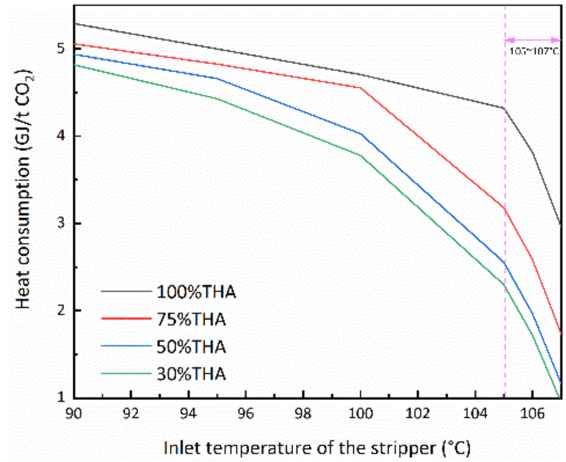

Fig. 2. Energy consumption varies with the inlet temperature

3.2 The energy distribution of CCS without heat exchange

When the inlet temperature of the stripper is 107°C and the carbon dioxide outlet pressure is 250 kPa, the energy diagram of CCS is shown in Fig. 3. The heat required by the rich solution heater (698,184kW) is higher than the heat released by the solvent cooler (612,363kW). Although the temperature of the top gas of the tower rises more after compression, the energy released decreases step by step. The energy and exergy data of each stream CCS is listed in Table 3 and the corresponding nodes are shown in Fig. 4.

The minimum work and the steam and electricity required by CCS under load-cycling operation conditions are listed in the Table 3. The absorption rate is 90%. Qstr means the heat required by the stripper and W_{CCS} means the electricity for driving pumps, fans and compressors. When the load ratio is 100%THA, Q_{str} is 441,773kW and

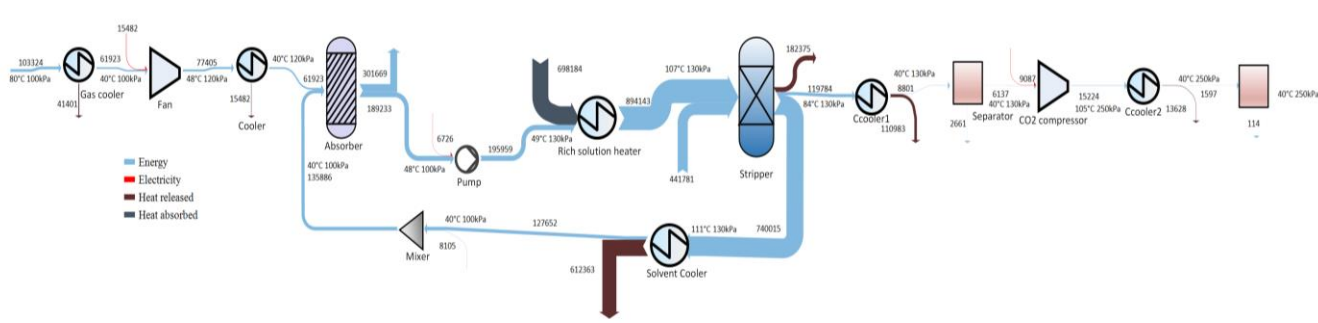

Fig. 3. Energy flow of CCS with compression

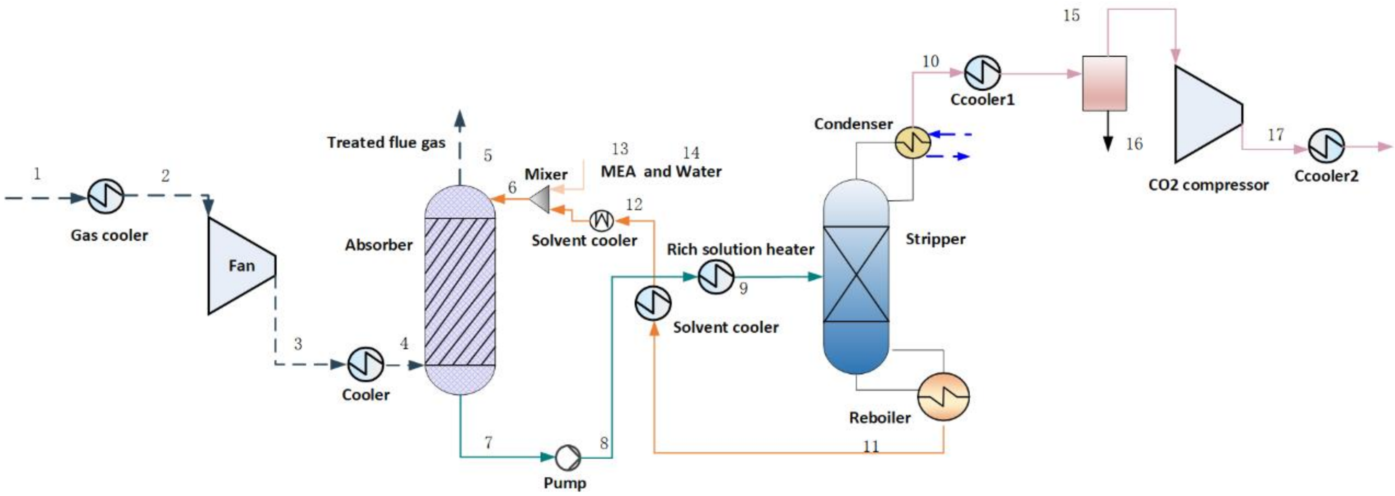

Fig. 4. Schematic of the proposed CCS structure

Table 2. The energy and exergy of each stream in CCS

	Unit	1	2	3	4	5	6	7	8
Tempreature	C	80	40	48	40	67	40	48	49
Pressure	kPa	100	100	120	100	100	100	100	130
Energy	kW	103320	61923	77405	61923	301670	135890	189233	195959
Exergy	kW	142420	138590	151180	138590	154320	184770	124155	129815
	Unit	9	10	11	12	13	14	15	17
Tempreature	C	107	84	111	40	40	40	40	186
Pressure	kPa	130	130	130	130	100	100	130	600
Energy	kW	894143	119784	740010	127667	32	8072	8801	14316
Exergy	kW	245732	44345	274198	187753	379	242	29961	36754

WCCS is 43,237kW. The exergy of electricity is more than the steam. Then, the performance of CPCC is analyzed.

Table 3. The data of CCS under load-cycling operation conditions

Load ratio/%	W_{min}/kW	Q_{str} /kW	W_{CCS} /kW
100	31770	441773	43237
75	22372	293616	22572
50	13872	154550	15410
30	8145	122569	10049

3.3 The performance of CPCC under load-cycling operation conditions

When the load ratio decreases, the steam extraction pressure does meet the stripper. Therefore, the exergy efficiency of 30%THA is the lowest, shown in Fig. 5. However, there is no more residual heat available in the CPCC.

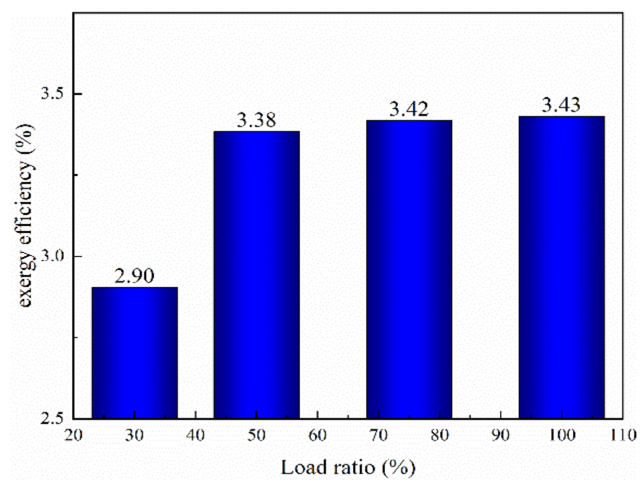

Fig. 5 Exergy efficiency of CPCC.

4. CONCLUSIONS

The coal-fired power plants integrated with CCS is a potential way to ensure clean power generation and support renewable energy integration. This paper has analyzed the energy flow of CCS without heat exchange and optimized the process and parameter of CCS. Then the performance of CPCC has analyzed under load-cycling operation conditions. The following conclusions can be drawn from this study.

1. The heat required by the rich solution is usually supplied by the solvent. However, this only makes it difficult to heat up to the optimum temperature. The inlet temperature of the stripper can benefit for decreasing the amount of extraction. The optimal temperature is related to the stripper pressure, and it varies in a small scale when the load ratio changes.

2. The heat required by the rich solution and the load ratio don't change in equal proportions previously. Moreover, the effect is exacerbated under low load ratio.

3. The exergy efficiency is the lowest, and the coupling system should be tuned for low load operation.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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