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The Mechanism and Potential for Reducing Energy Consumption of CO_2 Capture in Power System

Yawen Zheng[1,2], Lin Gao[2*], Song He[1,2]

1 Laboratory of Integrated Energy System and Renewable Energy, Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China

2 University of Chinese Academy of Sciences, Beijing100049, China

ABSTRACT

Rather high energy penalty of CO_2 capture is the critical gap deterring the deployment of CCS technologies in last twenty years. Deeper understand of mechanism of energy consumption for CO_2 capture will lay the basis for reducing the energy consumption. Accordingly, this paper introduced a thermodynamic analysis method with new criterion to reveal the mechanism of energy consumption in power system integrating CO_2 capture from new angle. Coal-fired power plant with post-combustion had been taken as the typical case and some enlightening results had been achieved. Although energy consumption for separation process is generally recognized as the dominant part of capture penalty, deterioration of energy utilization in power system due to providing energy for CO_2 separation is nonnegligible, which also exhibits attractive potential for energy saving in some cases. For separation efficiency improvement, the ceiling of 50% separation efficiency indicates as low as 5.9 percentage points penalty (with CO_2 compression), and the CO_2 capture cost of around 24 \$/t CO_2 can be anticipated for 50% separation efficiency.

Keywords: CO_2 capture, Energy consumption, Post-combustion, Evaluation

NONMENCLATURE

Abbreviations	
CFPP	Coal-fired power plant
PCC	Post-combustion
PCC	Post-combustion
Symbols	
P_{net}, MW	Net output power
EC_{CO2}, MJ/kg	Energy consumption of CO_2 capture
E_{sep}, MJ/kg	Energy consumption of CO_2 separation
E_{int}, MJ/kg	Energy consumption of system integration
R_{ex}	Exergy ratio of extracted steam to main steam

1. INTRODUCTION

As the only way that can realize low carbon utilization of high carbon fuel, CCS has been recognized as the important option of technology package for climate change mitigation [1]. Among CCS chain, CO_2 capture is the most energy and cost intensive part accounting more than 70% energy consumption and cost [2], which is the critical gap deterring the deployment of CCS.

To the present, post-combustion capture is the most mature and suitable technology for existing coal-fired power plants for emission reduction, which has attracted numerous attention in the literature. There are two main ways in reducing capture energy consumption, including improving separation technology and optimizing the system performance of power system with CO_2 capture.

As the kernel process of CO_2 capture, separation technology is undoubtedly the focus in the field of reducing energy consumption, whose aim is to selectively separate CO_2 from mixed gases. For the specific separation technology, chemical absorption is the technology of choice for post-combustion capture [3-8] with many years of industrial experiences, and it is a popular option adopted by most of CCS demo projects. Generally, chemical absorption technology separates

CO_2 by the chemical reaction of the given absorbent and CO_2. The most common absorbent in the chemical absorption process is 30 wt% aqueous monoethanolamine (MEA) [9-14]. The reported lowest reboiler duty of 30% MEA for flue gas mitigation with a 10-15% CO_2 concentration is ~3.6-4.0 GJ/t CO_2 [15-19]. With the innovation of absorbents, such as amine blends, multi-phase absorbents, non-aqueous solution and ionic liquid etc., the reboiler duty of chemical absorption has significantly reduced from higher than 3.5 GJ/t-CO_2 to lower than 2.5 GJ/t-CO_2, approaching a 50% separation efficiency [20].

Different from optimization of the separation process, another research hotspot for reducing capture energy consumption is optimizing the system performance of CO_2 capture system. For post-combustion capture, there are several methods in improving the system performance. Liu et al. [21] studied various heat integration strategies in enhancing the performance of 600 MW coal-fired power plants with CO_2 capture, including optimizing steam extraction location, utilizing waste heat from CO_2 capture and compression process etc.. Results indicated that the efficiency penalty of the best case decreases to 9.75%. Wang et al. [7] proposed a new CO_2 capture system driven by double absorption heat transformer. Through the absorption heat transformer, low-temperature steam is upgraded into a higher energy level to match the temperature of CO_2 regeneration. Results shown that with 90% CO_2 capture, the thermal efficiency of the power plant is enhanced by 1.25 percentage points compared with traditional method.

Despite hotspot had focused on separation technologies and system integration respectively, the relationship and the internal interaction between these two approaches are worthy of more attention. For example, it's apparently that the energy consumption for CO_2 separation do not equal to the system penalty. Accordingly, what's the relationship between these two indicators, and what's the connotation of difference value between them. Answers to these questions will lead to better understand of CO_2 capture technology, and then, suggesting the direction for energy consumption reduction. So, the purpose of this paper is to clarify the characteristics of separation innovation and system integration, to reveal the interaction between them, to evaluate the potential and to identify the role of each approach.

2. METHODOLOGY

2.1 The separation process and the capture system

Part of reason for ignorance to the difference and interaction between separation and system integration may come from the ambiguous boundary between separation and capture in the literatures. Nevertheless, defining separation and capture clearly and exploring the relationship between them are the premise and basis for understanding the energy consumption of capture.

CO_2 separation is a process index as the kernel course of CO_2 capture technology, which specifically referring to separating CO_2 from the mixed streams. Chemical absorption for post-combustion capture is a representative separation process. Comparatively, CO_2 capture is a systematic technology, which not only includes separation process, but also includes the integration between the separation and the emission source.

2.2 Analysis and evaluation methodology for CO_2 capture

For CO_2 capture system, the penalty of thermal efficiency ($\Delta\eta$) is the most commonly adopted evaluation indicators in the literatures for the evaluation of system performance. The absolute decline in efficiency of capture system compared with the reference system without CO_2 capture relates to the penalty of thermal efficiency, which can be expressed as:

$$\Delta\eta=\eta_{p,r}-\eta_{p} \tag{1}$$

Where η_p and $\eta_{p,r}$ are the power generation efficiency for system with and without CO_2 capture.

Corresponding to the definition of CO_2 separation and capture, the energy consumption of CO_2 capture consists of both the separation energy consumption and the penalty paid for integrating separation into the system. Thus, the CO_2 capture energy consumption can be expressed as:

$$EC_{\mathrm{CO2}} = E_{\mathrm{sep}} + E_{\mathrm{int}} \tag{2}$$

As indicated by equation (2), the capture energy consumption can be divided into two parts, the former part indicated by E_{sep}, donates the energy directly used by CO_2 separation, including the heat or work consumed in separation process, and the later part donates the penalty paid in system integration, which can be looked as energy consumption indirectly caused by CO_2 separation. EC_{CO2} is difference between the output work of the capture system and the reference system, and E_{sep} can be obtained by calculating the energy used by separation process. Thus, equation (2) can be further expressed with considering different energy types:

$$EC_{CO2} = E_{sep} + E_{int} = (\sum W + \sum Q\eta_w) + E_{int} \quad (3)$$

where W and Q represent work and heat consumption in CO_2 separation process, respectively; η_w represents the conversion efficiency of heat to work, and correspondingly, $Q\eta_w$ indicates the turbine work that could have been done by the extracted steam.

Compared to EC_{CO2} and E_{sep}, the physical meaning of E_{int} is not quite clear. It can be obtained by (EC_{CO2}-E_{sep}). It's understandable that it represents the penalty that not directly consumed by separation process, but still paid due to CO_2 capture. It not only depends on the interaction between CO_2 capture and power generation, but also highly related to the characteristics of different capture technology. Understanding of this value may inspire the innovation of CO_2 capture technology. Furthermore, an indicator, which is the ratio of the separation energy consumption and the system penalty, is defined by equation (4).

$$\eta_d = \frac{E_{sep}}{E_{sep} + E_{int}} \quad (4)$$

η_d can represent the level of integrating CO_2 capture into energy system, which can be named as integration efficiency and can be used to guide the optimization of the system.

3. *MODEL DEVELOPMENT OF COAL-FIRED POWER PLANT (CFPP) WITH POST-COMBUSTION (PCC)*

A simplified diagram of CFPP with PCC is given in Fig.1 with the key parameters listed in Table 1. The CFPP with gross power of 600 MW is adopted in this study with main steam parameters of 600℃ and 24.2 MPa, where coal combustion, feed water heating, power generation, flue gas desulfuration and CO_2 capture are the key units. The simulation is conducted with Aspen Plus software and the results of thermal efficiency and flue gas parameters are listed in Table 1.

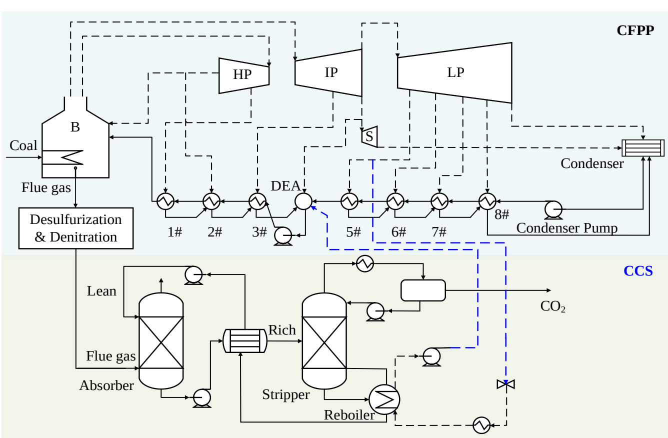

Fig. 1. System flowchart of CFPP with CCS

Table 1 Overall performance of 600 MW CFPP

Parameters	Value	Parameters	value
P_{net}/MW	611	Flue gas mass flow (kg/s)	653.5
Boiler feed water/(t/hr)	1315	Flue gas temp. (℃)	120
Main steam flow/(t/hr)	1600	Flue gas pressure (bar)	1.01
Main steam pressure/MPa	24.2		
Main steam temp. /℃	600	Component (vol.%)	
Reheat pressure/MPa	4.2	H_2O	5.4
Reheat temp./℃	600	CO_2	13.2
Exhaust steam pressure/MPa	0.006	N_2	76.1
Thermal efficiency/%	43.7	O_2	5.2

The isentropic efficiency of steam turbine is a function of steam mass flow rate under the off-design condition. When CO_2 capture is introduced in coal-fired power plant, the drop of turbine efficiency will occur due to variable working conditions. Thus, it can be adjusted according to the correction method adopted in the commercial software Epsilon 11. The correction equation can be found in ref. [22].

4. *INFLUENCE OF SEPARATION EFFICIENCY ON SYSTEM CAPTURE PENALTY*

From the perspective of the effects on capture penalty, the role of improving separation efficiency will be investigated and compared in this section.

A paper published in Science [20] recorded that the existing chemical absorption process already provides about 50% separation efficiency (η_s), and is generally accepted as the ceiling of further improvement for current technical route, indicating that the further efforts in energy saving may be limited for chemical absorption under low CO_2 concentration. Thus, the η_s of 50% is set as the boundary for optimizing the separation process in this section.

Fig.2 shows the impact of separation efficiency on separation energy consumption, and the corresponding role in the system energy supply. R_{ex} indicates the proportion of the exergy of extracted steam to main steam from boiler. As shown in Fig.2, separation energy consumption decreases with the increase of separation efficiency. The energy consumed under 20% separation efficiency 90% recovery ratio conditions is about 86.1 MW, and 52 MW can be saved when the separation efficiency is increased to 50%. Due to that the separation process achieves CO_2 separation by extracting steam from turbine, the proportion of energy consumed by extracting steam (R_{ex}) is worth studying. As indicated by Fig.2, the exergy of extracted steam for separation accounts for about 27.8% of the total power steam under 20% separation efficiency, and declines to 11.1% for 50% separation efficiency. Thus, it is necessary to pay attention to the large extraction energy needed for separation, and the optimization of separation efficiency can greatly reduce the extraction energy consumption

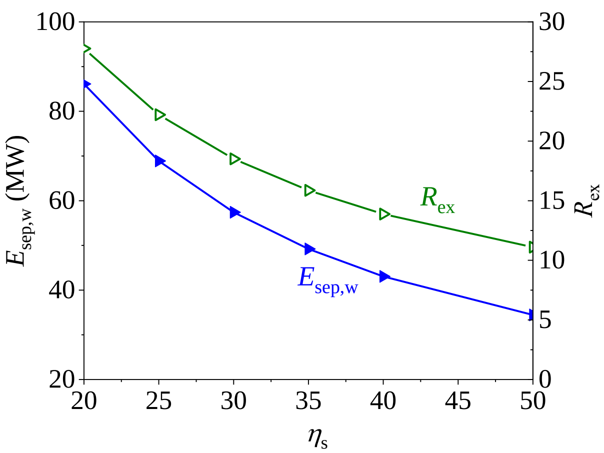

Fig. 2. The effect of η_s on separation energy consumption

Although the majority capture energy consumption is caused by E_{sep} in post-combustion capture, the amount and mechanism of E_{int} are worthy of further discussion. E_{int} in CFPP-PCC system mainly includes three parts: the decline in turbine efficiency due to steam extraction deteriorating the heat to work performance, throttle and depressurize to the saturated vapor parameters required by the reboiler, loss of residual velocity due to extraction. For example, under 20% separation efficiency, the energy consumption caused by the decline of turbine efficiency is about 20% of E_{int}. And more seriously, the extracted steam is required to throttle and depressurize from (299.0℃, 5.47 MPa) to (135.7℃, 3.12 MPa) with about 19 MW work consumption (~80% of E_{int}). Finally, only a small amount of energy (less than 1% of E_{int}) is consumed by the residual velocity loss due to the lower velocity of steam flow at the outlet of rotor blade and less amount of extracted steam. Therefore, the integration energy consumption is undoubtedly mainly caused by the throttle and depressurize process.

The green curve in Fig.3 shows the trend of integration efficiency of separation process with the change of separation efficiency. The integration

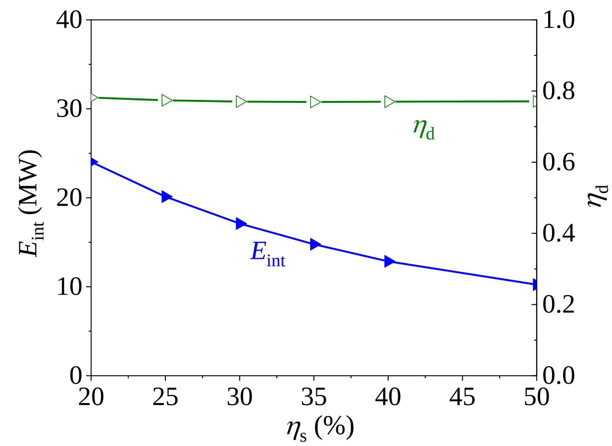

Fig. 3. The effect of separation efficiency on supply

efficiency indicates that E_{sep} accounts for nearly 80% proportion of capture energy consumption. With the increase of separation efficiency, the integration efficiency of separation process remains almost unchanged. It indicates that although the effect of separation efficiency on separation energy consumption is direct and significant, the variation of integration energy consumption does not deviate. Reasons may come from the simple or relative weak, connections between separation process and thermal cycle in PCC case. The decline of E_{int} along with separation efficiency mainly due to the impact of E_{sep} on E_{int}, and this influence is not affected by the separation efficiency. For PCC, E_{int} is produced in proportion to E_{sep}, which is directly related to the parameters of the extracted steam. Thus, E_{sep} shows a directly drop due to the increase of separation efficiency, while E_{int} show a similar trend with E_{sep}, leading to a constant integration efficiency for separation process with the change of separation efficiency. However, although separation efficiency has small effect on integration efficiency of separation in PCC case, for other technical capture routes, where the capture process is closely integrated with the energy conversion process, the results may be quite different.

At the same time, the energy saving potential of capture process can be evaluated from the perspective of separation process. The results are shown in Fig.4. As indicated by Fig.4, with the increase of separation efficiency, the thermal efficiency shows a dramatically increase from 35.8% to 40.5% (without CO_2 compression), and the corresponding efficiency penalty drops from 7.9 to 3.2 percent point. When CO_2 compression work is considered, an additional 2.7 percent points efficiency penalty will be paid. In other words, the efficiency penalty can be reduced by 4.7 percent point when the separation efficiency reaches

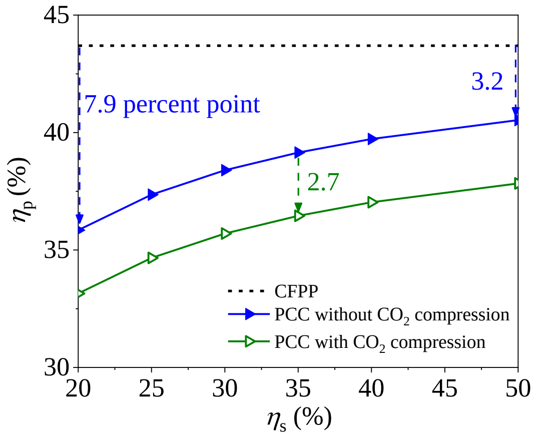

Fig. 4. The effect of η_s on system penalty

50% through absorbent innovation and process upgrading of separation technology compared with the current state of demonstration power plants (20%). In addition, the economic analysis results indicate that, the cost of CO_2 capture declines obviously from around 34 \$/t CO_2 to 24 \$/t CO_2 with separation efficiency increasing from 20% to 50% (with CO_2 compression), and an additional reduction of 8 \$/t CO_2 can be achieved when compression is not considered. Thus, the capture cost of 24 \$/t CO_2 (with CO_2 compression) can be expected by improving separation technology in PCC case, when the ceiling of 50% separation efficiency is reached.

5. *CONCLUSIONS*

This paper introduced a thermodynamic analysis method with new criterion to reveal the mechanism of energy consumption in power system integrating CO_2 capture from a new angle. CO_2 capture energy consumption is composed of energy directly consumed in separation process and integration penalty due to energy utilization deterioration in system, where the former is the dominant part and the later is highly related to the former in CFPP-PCC case. For separation efficiency improvement, the ceiling of 50% separation efficiency indicates as low as 5.9 percent points penalty (with CO_2 compression), and the CO_2 capture cost of around 24 \$/t CO_2 can be anticipated for 50% separation efficiency. Separation efficiency has small effect on integration efficiency of separation, whose reason is the simple, or can be say the relative weak, connections between separation process and thermal cycle in PCC case.

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