Energy Proceedings
Vol 36, 2023
ISSN 2004-2965

Challenges for Power Plant Adopting CO_2 Capture in a Carbon Neutral Power System

Xueqing Wang[1,2], Yuanxue Zhang[3], Lin Gao[4*]

1 School of Energy, Power, and Mechanical Engineering, North China Electric Power University, Beijing 102206, China

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

3 Huaneng Clean Energy Research Institute, Changping District, Beijing 102209, China

4 University of Chinese Academy of Sciences, Beijing 100049, China

(*Corresponding Author: gaolin@iet.cn)

ABSTRACT

The coal fired power plants has to frequently work in partial load conditions to contribute flexibility to the grid. The partial load operation of power generation system will undoubtedly influence the CO_2 capture unit, which may lead to the variation of CO_2 capture ratio (CCR). The aim of this paper is to evaluate the potential of CO_2 emission reduction of a variable load power plant. The model of a coal-fired power plants with post-combustion CO_2 capture had been setup via EBSILON and Aspen. The performance of a typical coal fired power plants and the operating characteristics of the CO_2 capture unit in partial load operation are explored. The results indicate several factors including the CO_2 concentration in the flue gas and the flow rate of flue gas, will impose the possible impact on CO_2 capture unit. The two factors together reduced the CCR for treated gas from 90% at 100% load to 50.42% at 30% load. The all operating conditions CCR for a power generation unit in a period of real operation conditions is lower than design CCR for treated gas, which is 90% at 100% load. Conclusively, the factors influencing capture ratio on the power generation side, such as flue gas and steam parameters, are important factors in CCR changing.

Keywords: carbon capture ratio, coal-fired power plant, partial load, carbon neutrality

1. INTRODUCTION

China proposed a target to reach maximum CO_2 emissions before 2030 and attain carbon neutrality by 2060 in 2020. As a system highly relying on fossil fuel, and at the same time, with the rapid growth of renewable energy, the power system in China has to face the challenges both from carbon emission reduction and stability of electric grid.

In the first half of 2023, China's installed capacity of renewable energy reached 1.322 billion kW, accounting for approximately 48.8% of the total installed capacity, surpassing the proportion of coal-fired power installations for the first time in history [1]. The renewable energy has experienced significant expansion over the past decade and this growth trend is projected to continue in the foreseeable future [2]. As the proportion of renewable energy with strong randomness and volatility increases, it increases the burden of grid system regulation. China's power structure is dominated by thermal power, and the flexibility of the power grid system some extents depends on the peak regulation ability of coal-fired power plants [3]. Thermal power plants not only need to adapt to fluctuations on the demand side but also to the variations in renewable energy generation [4]. As a result, more and more thermal power plants are operating under varying load conditions. The average annual utilization hours of coal-fired power plants from over 5,500 hours in 2003 to less than 4,500 hours at present. It can be predicted that the future coal fired power plants has to frequently work in partial load conditions to contribute flexibility to the grid, and moreover, to recover its carbon emission through adopting CO_2 capture technology. However, the partial load operation of power generation system will undoubtedly influence the CO_2 capture unit, which may lead to the variation of CO_2 capture ratio (CCR).

The CO_2 capture unit integrated with power

This is a paper for the 9th Applied Energy Symposium: Low Carbon Cities and Urban Energy Systems (CUE2023), Sep. 2-7, 2023, Matsue & Tokyo, Japan.

generation system usually uses chemical absorption, and research mainly focuses on the study of the mechanism of the chemical absorption process [5], the improvement and development of absorbents [6], and the optimization of the capture process [7]. However, capture units, as chemical processes, are usually operated at steady state and do not involve variable load operation. Capture unit has to be operated flexibility because of the frequent load variation of coal-fired power plant [8]. Various studies on the flexibility characteristics of capture unit have been conducted. Wu et al. developed a multi-model system to approximate the dynamics of CO_2 capture process in a wide range [9] and proposed a control strategy for coordinative operation of the coal-fired power plant with post combustion CO_2 capture [10]. The nonlinear dynamics of key parameters include CO_2 capture rate, reboiler temperature and lean solvent temperature are analyzed [11]. Fu et al. conducted the thermodynamic performance of the coal-fired power plant integrated with CO_2 capture unit under partial load operation conditions. The study showed that the efficiency penalty rates of the system is 9.7% mainly caused by the reboiler duty [12].

However, most of the existing studies focus on the optimization of design conditions and benchmark conditions, and the integration of coal-fired power system and capture units under variable loads is still relatively less. Therefore, this study aims to investigate the operational characteristics and behavior of a typical chemical absorption carbon capture process, under partial load conditions in a representative power plant. The focus is primarily on analyzing the variations in CCR and identifying the underlying reasons for these changes. The findings will serve as a technical basis for achieving the coordinated objectives of load flexibility and decarbonization in future carbon capture power plants.

2. SYSTEM DESCRIPTION

2.1 System description

This study focuses on a 1000MW ultra-supercritical power generation unit, as illustrated in Fig. 1. A 30%wt solution of monoethanolamine (MEA) which widely recognized for its high reactivity and CO_2 selectivity [13] was chosen for CO_2 capture. Before entering the capture unit, the flue gas usually removes NO_x and SO_x before, as they can lead to the degradation of the absorbing solvent MEA [14]. The EBSILON software was employed to simulate the coal-fired power system in this study. The key parameters are presented in Table 1. The performance adjustments were made to pumps, turbines, and heat exchangers based on mass flow rates [15]. The accuracy and reliability of the simulation has been previously validated, showing an output power deviation of only -0.27% compared to the design value at full load, thus verifying its accuracy [15].

Table 1 Main equipment parameters of a 1000MW coal-fired thermal power system with post combustion CO_2 capture

Parameters	Value
Main steam temperature °C	605
Main steam pressure MPa	28
Reheated steam temperature °C	623
Reheated steam pressure MPa	5.434
Feedwater temperature °C	315
Lower steam turbine exhaust pressure kPa	9

The CO_2 capture unit is integrated to power generation system through connection of flue gas and steam extraction in a post-combustion system. The process flow diagram, as shown in Fig. 1, was modeled and simulated in Aspen Plus using rate-based calculation. The absorption column has a height of the packed section of 25m, diameter of 27m, and pressure drop of 1kPa. The desorption column has a height of the packed section of 8m, diameter of 14.4m, and pressure drop of 19kPa. The heat required for MEA solvent regeneration is provided by extracting steam from the power generation side, utilizing the commonly used intermediate pressure–low pressure (IP-LP) crossover extraction [16] as depicted in Fig. 1, section 6#.

2.2 Operation strategy

Based on a reference load condition of 100%, the opening of the steam extraction valves is adjusted to meet the heat load requirements of the regeneration reboiler, ensuring a capture ratio of 90%. Under load variation conditions, the opening of the steam extraction valves remains unchanged, and the operating parameters of the capture unit are not adjusted.

2.3 Performance indicators

For a power generation unit adopting CO_2 capture, the extent of CO_2 recovery is another important parameter other than power generation efficiency.

CO_2 capture ratio (CCR) for treated gas usually refers to the ratio of the outlet mass flow rate $m_{CO2,product}$ of desorption column to the mass flow rate $m_{CO2,capture}$ of the flue gas entering the capture unit.

$$CCR_{T} = \frac{m_{CO_2,\text{product}}}{m_{CO_2,\text{capture}}} \tag{1}$$

When only a portion of the flue gas from the power generation system is captured, the capture ratio for a

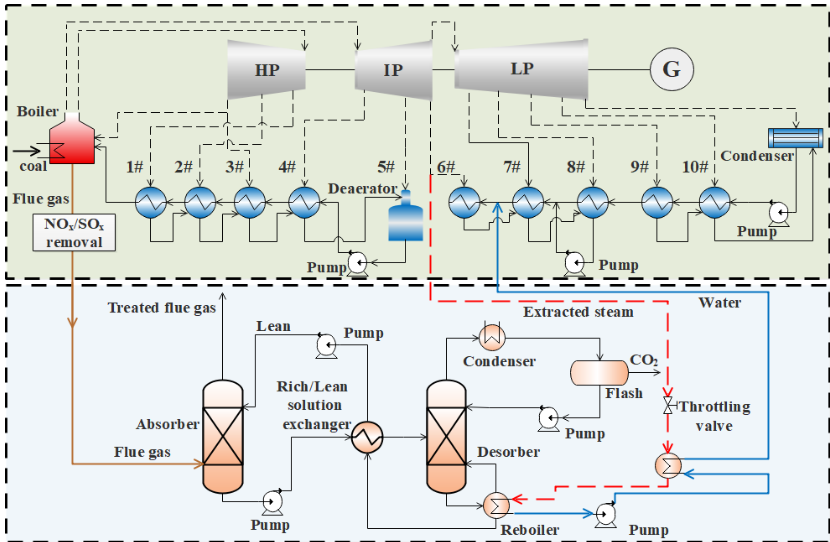

Fig. 1. Flow diagram of a 1000MW coal-fired thermal power system equipped with post combustion CO_2 capture

coal-fired power system equipped with post-combustion capture is defined as CCR for one power generation unit.

$$CCR_G = CCR_T \times r \tag{2}$$

where, r is the flue gas treatment ratio, r = $m_{CO2,capture}/m_{CO2,fluegas}$, kg/s; $m_{CO2,fluegas}$ is the total amount of flue gas in the generation unit, kg/s. For full-flow capture, r=1. The flue gas in this paper is captured at full flow, CCR_G=CCR_T, for simplicity it is all denoted CCR below.

CCR for treated gas and CCR for one generation unit are designed parameters for full load conditions. However, the all operating conditions CCR for a power generation unit in a period of real operation conditions, obviously has more engineering instructive value.

$$CCR_A = \frac{\int_{t_1}^{t_2} m_{CO_2,\text{product}}(Load)dt}{\int_{t_1}^{t_2} m_{CO_2,\text{fluegas}}(Load)dt} = \frac{\int_{t_1}^{t_2} m_{CO_2,\text{fluegas}}(Load)\cdot CCR_G(Load)dt}{\int_{t_1}^{t_2} m_{CO_2,\text{fluegas}}(Load)dt} \tag{3}$$

3. RESULTS AND DISCUSSIONS

3.1 *The performance of representative coal-fired power plants in partial load operation*

In general, sliding pressure operation is typically employed to vary output power by adjusting the main steam pressure and temperature. Under varying load conditions, the coal feed rate and excess air coefficient changes, directly impacting the concentration of CO_2 in the flue gas. As the load decreases from 100% to 30%, the excess air coefficient increases from 1.33 to around 1.73, while the mass fraction of CO_2 in the flue gas decreases from 17.8% to 13.9%, as shown in Fig. 2.

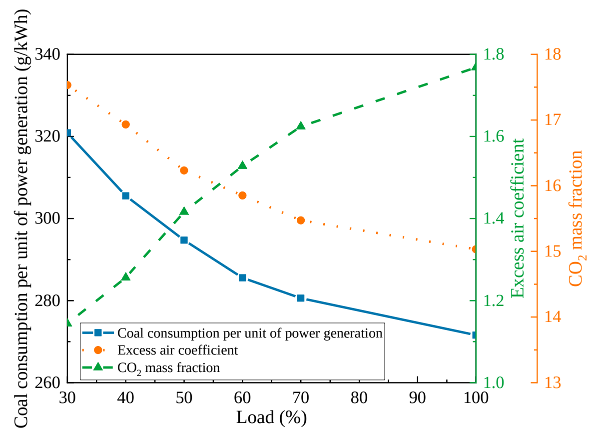

Fig. 2. Coal consumption per unit of power generation, excess air coefficient, and CO_2 mass fraction under different loads

Since the desorption temperature during CO_2 desorption process is around 123°C, a saturated steam temperature of approximately 130°C is required to ensure effective heat transfer. Correspondingly, the extraction steam pressure is usually maintained at around 3 bar. However, when the load rate decreases to 50%, the extraction steam pressure drops to 2.832 bar (as shown in Fig. 3), which is insufficient to meet the operational demands of the capture unit. Consequently, a pressure maintaining valve (PMV) needs to be installed to fulfill the requirements of the capture unit [17].

3.2 *Operation characteristics of CO_2 capture unit in partial load*

Under variable load conditions, there is no active control or adjustment of the opening of the steam extraction valves. The heat load provided by the steam extraction to the regeneration reboiler decreases approximately linearly, as illustrated in Fig. 4.

As the load rate decreases, the CCR exhibits a decreasing trend. The CCR decreases from 90% at 100%

load to 50.42% at 30% load, with a more obvious decrease observed at lower loads.

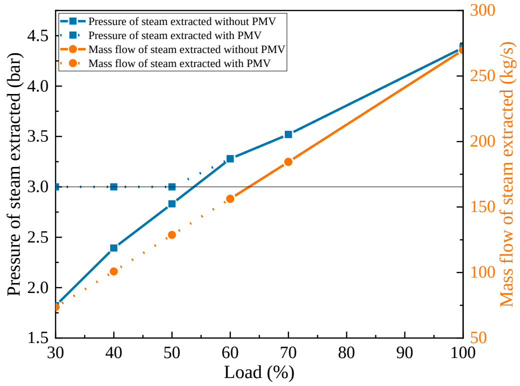

Fig. 3. Impact of steam extraction on power generation system under different loads

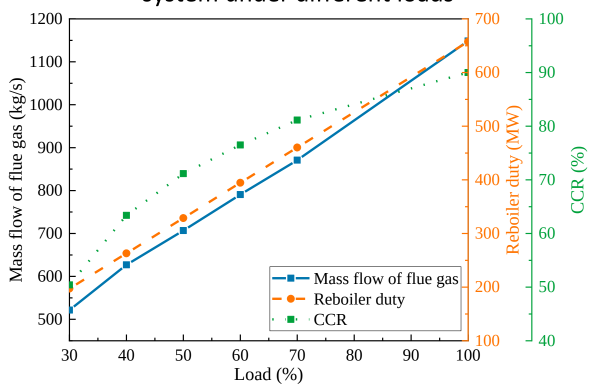

Fig. 4. The influence of changes in flue gas mass flow rate on CCR under different loads

Equations (1) and (2) can be further derived:

$$CCR_{\mathrm{T}} = \frac{m_{\mathrm{CO_2,product}}}{m_{\mathrm{CO_2,fluegas}}} = \frac{\Delta\alpha \times L \times M_{\mathrm{CO_2}} \times 10^{-3}}{m_{\mathrm{CO_2,fluegas}}} \quad (4)$$

$$\Delta\alpha = \alpha_{\mathrm{CO_2-rich}} - \alpha_{\mathrm{CO_2-lean}} \quad (5)$$

Here, $\Delta\alpha$ represents the difference in CO_2 loading of lean and rich solvents, in terms of molCO$_2$/molMEA. *L* denotes the solvent flow rate in mol/s, M_{CO2} corresponds to the molar mass of CO_2, which is 44g/mol.

As illustrated in Fig. 5, with the decrease in power load, $\Delta\alpha$ exhibits a decreasing trend. The value of $\alpha_{CO2\text{-lean}}$ is primarily determined by the steam side of the desorber column. With a constant solvent mass flow rate, the energy consumption per ton of CO_2 desorbed increases as the power load decreases [12].

However, due to the proportional reduction in reboiler load, the total amount of CO_2 desorbed decreases (as shown in Fig. 6). Consequently, the CO_2 loading in the lean solvent at the outlet of the desorber column increases. The value of $\alpha_{CO2\text{-rich}}$ is mainly influenced by the absorption column. As the flue gas is directly connected to the absorption column, changes in flue gas composition and flow rate directly impact the absorption process, thereby influencing the value of $\alpha_{CO2\text{-rich}}$. Considering the varying operating conditions under partial load, including flue gas mass flow, flue gas composition, and steam mass flow, multiple parameters are affected. Therefore, the individual effects of different factors on $\alpha_{CO2\text{-lean}}$ and $\Delta\alpha$ are studied as follow.

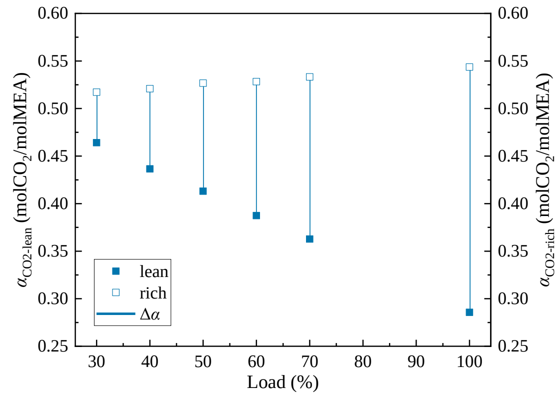

Fig. 5. Variation of lean-rich liquid loading under different power loads

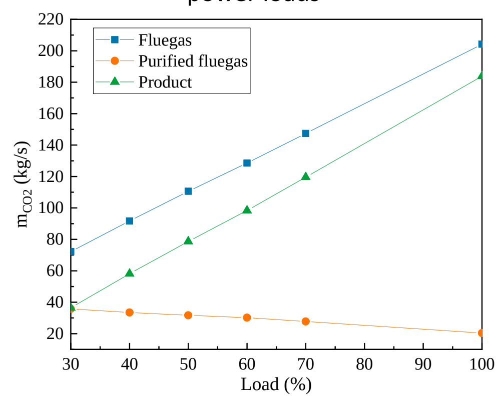

Fig. 6. Variation of CO_2 mass flow rate under different loads

The influence of flue gas composition is studied using the practical proportions under different load ratios, with the flue gas flow rate and lean solvent CO_2 loading held constant at 100% load conditions. The results are presented in Fig. 7. The practical effect of the change in flue gas components is a change in the partial pressure of CO_2. It can be observed that as the CO_2 partial pressure decreases, the solubility of CO_2 in the MEA solution decreases, resulting in a decrease in $\Delta\alpha$.

Then, the influence of flue gas mass flow is studied using the practical mass flow under different power load, maintaining the flue gas composition and lean solvent CO_2 loading at 100% load conditions. The results are shown in Fig. 8. When the mass flow of flue gas decreases, which is equivalent to an increase in the liquid-to-gas ratio. As a result, mass transfer fails to reach equilibrium, leading to a reduction in $\alpha_{CO2\text{-rich}}$ at the outlet. Compared to flue gas composition, flue gas flow rate has a greater impact on $\Delta\alpha$.

Under partial load conditions, the capture unit is collectively affected by these factors, all of which have a negative impact on $\Delta\alpha$. As a result, with a decrease in power load, $\Delta\alpha$ decreases substantially, leading to a significant decrease in CCR.

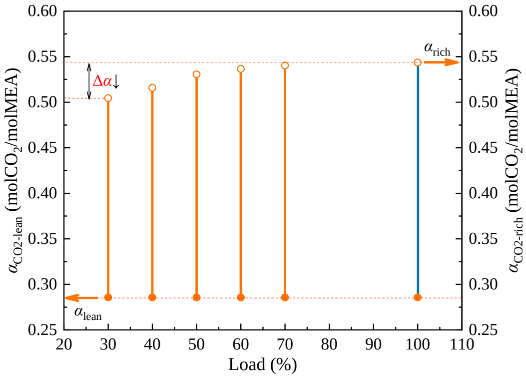

Fig. 7. Influence of flue gas composition on $\Delta\alpha$

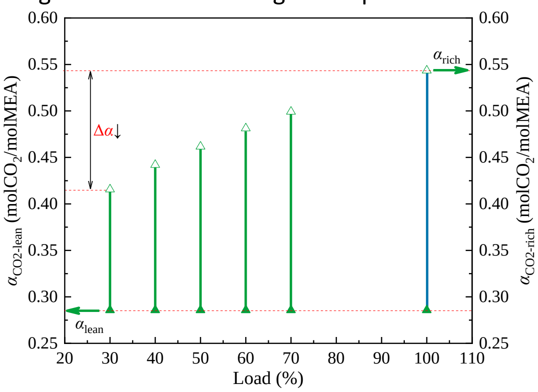

Fig. 8. Influence of flue gas mass flow on $\Delta\alpha$

4. REQUIREMENTS FOR CCR OF NEUTRAL POWER SYSTEM

CCS technology plays an indispensable role during the transitional phase of China's energy structure transformation as the sole means of achieving low carbon emissions from high carbon energy sources. The carbon neutrality formula for the power system is established based on the balance between carbon sources and sinks, as shown in Eq. (6).

$$NE = \text{Source} + \text{Sink} = \sum_{i=\mathrm{C,CN,CF}} NE_i = \frac{44}{12} F_{\mathrm{C}} C_{\mathrm{C}} + \sum_{i=\mathrm{C,CN}} \left(-\frac{44}{12} F_i C_i K_i \right) \quad (6)$$

where, *F* represents the total energy consumption of the fuel, *C* denotes the carbon content per unit of fuel energy, and *K* stands for the CCR. The subscript C represents fossil energy sources; CN represents carbon-neutral energy sources; CF represents zero-carbon energy sources. If the *R* is defined as the proportion of carbon content from fossil energy sources in the entire power system, then equation (6) can be expressed as follows:

$$R = \frac{F_{\mathrm{C}} C_{\mathrm{C}}}{F_{\mathrm{C}} C_{\mathrm{C}} + F_{\mathrm{CN}} C_{\mathrm{CN}}} \quad (7)$$

$$NE = \frac{44}{12} \left[R(1 - K_{\mathrm{C}}) - (1 - R) K_{\mathrm{CN}} \right] \sum_{i=\mathrm{C,CN}} F_i C_i \quad (8)$$

Obviously, when the power system achieves carbon neutrality, equation (8) equals to zero. The relationship between the CCR and the proportion of fossil energy in the power system can be observed from Fig. 9 [18]. Carbon neutrality can be achieved without CCS technology when the proportion of fossil energy is 0. However, considering that China's energy structure is primarily coal-based and may not undergo significant changes in the short term, CCS is an essential technology for carbon emission reduction. As illustrated in Fig. 9, it is evident that the larger the proportion of fossil energy, the more demanding the CCR becomes.

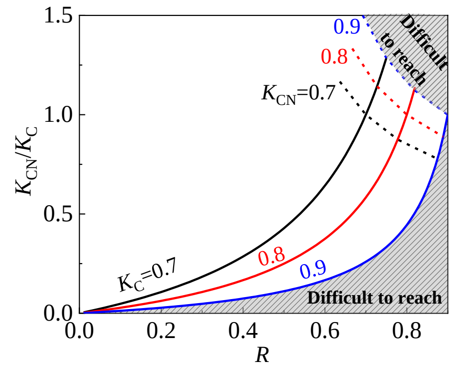

Fig. 9. Relationship between different energy structure compositions and capture ratios under carbon neutrality [18]

It is worth noting that the CCR represented by K_c and K_{cn} should be referred to as the CCR_A for a power generation unit in a period of real operation conditions. The following section presents a calculation of a simplified case study. Only the steady state conditions are considered. Assuming the duration of each operating condition as shown in Table 2, and using the computational results from Section 3.2 as an example, the calculation of CCR_A of the power system is as follows.

Table 2 Example of calculating CCR_A of a power generation system equipped with capture units

Load	100%	70%	60%	50%	40%	30%
Steady-state CCR	90%	81.1%	76.5%	71.2%	63.4%	50.4%
Duration / h	2000	1400	1300	800	100	100
$m_{\mathrm{CO2,fluegas}}$ / kg·s^{-1}	204.2	147.4	128.6	110.6	91.7	72.2
CCR_A	82.92%					

It can be observed that even when the CCR is set at 90% under design conditions, the CCR_A may not reach 90%. This discrepancy could potentially impact the carbon neutrality goals.

5. CONCLUSIONS

According to the carbon neutrality equation, both the installed capacity and the CCR_A for a power generation unit in a period of real operation conditions can affect the carbon neutrality goals within a power system. In this study, a 1000MW coal-fired power system equipped with a post-combustion capture unit was selected as the research subject to investigate the relationship between the power generation system and the capture unit under partial load conditions. The main conclusions are as follows:

The flue gas mass flow rate and CO_2 concentration in flue gas all have a negative impact on $\Delta\alpha$, collectively contributing to its decrease, which subsequently leads to a reduction in CCR. The CCR decreases from 90% at 100% load to 50.42% at 30% load.

The CCR in the carbon neutrality equation refers to the designed CCR under design conditions. However, calculations show that the CCR_A of a system designed with a CCR of 90% is only 82.92%. The CCR_A differs significantly from the designed CCR, and this should be taken into consideration in the overall energy system configuration.

ACKNOWLEDGEMENT

This work is funded by the Beijing Municipal Science & Technology Commission (Grant No. Z211100004521006), the National Science and Technology Major Project of China (J2019-I-0009-0009).

Xueqing Wang and Yuanxue Zhang contributed equally to this work.

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.

REFERENCE

[1] National Energy Administration. Transcript of the National Energy Administration's online press conference in the third quarter of 2023 2023. http://www.nea.gov.cn/2023-07/31/c_1310734825.htm (accessed August 8, 2023).

[2] National Bureau of Statistics. National data 2023. https://data.stats.gov.cn/easyquery.htm?cn=C01 (accessed August 8, 2023).

[3] Shu Y, Zhang Z, Guo J, Zhang Z. Study on key factors and solution of renewable energy accommodation. Proc Chin Soc Electr Eng 2017;37:1–9.

[4] Yu H, Yan W, Wen G, Gao Y, Zhang M, Li X. Characteristics analysis, promotion path and multi-market mechanism design of high permeability new energy power system under double carbon constraint. Power Syst Big Data 2023;26:77–88.

[5] Wang J, Sun T, Zhao J, Deng S, Li K, Xu Y, et al. Thermodynamic considerations on MEA absorption: Whether thermodynamic cycle could be used as a tool for energy efficiency analysis. Energy 2019;168:380–92.

[6] Rochelle G, Chen E, Freeman S, Van Wagener D, Xu Q, Voice A. Aqueous piperazine as the new standard for CO2 capture technology. Chem Eng J 2011;171:725–33.

[7] Le Moullec Y, Neveux T, Al Azki A, Chikukwa A, Hoff KA. Process modifications for solvent-based post-combustion CO2 capture. Int J Greenh Gas Control 2014;31:96–112.

[8] Wu X, Shen J, Li Y, Wang M, Lawal A. Flexible operation of post-combustion solvent-based carbon capture for coal-fired power plants using multi-model predictive control: A simulation study. Fuel 2018;220:931–41.

[9] Jia D, Liang X, Wu X, Shen J. Nonlinearity analysis and multi-model modeling of CO2 capture system. 2017 Chin. Autom. Congr. CAC, Jinan: IEEE; 2017, p. 7129–34.

[10] Tang Z, Wu X. Distributed predictive control guided by intelligent reboiler steam feedforward for the coordinated operation of power plant-carbon capture system. Energy 2023;267:126568.

[11] Liao P, Wu X, Li Y, Wang M, Shen J, Lawal A, et al. Application of piece-wise linear system identification to solvent-based post-combustion carbon capture. Fuel 2018;234:526–37.

[12] Fu Y, Wang L, Liu M, Wang J, Yan J. Performance analysis of coal-fired power plants integrated with carbon capture system under load-cycling operation conditions. Energy 2023;276:127532.

[13] Wang M, Lawal A, Stephenson P, Sidders J, Ramshaw C. Post-combustion CO2 capture with chemical absorption: A state-of-the-art review. Chem Eng Res Des 2011;89:1609–24.

[14] Fostås B. Effects of NOx in the flue gas degradation of MEA. Energy Procedia 2011;4:1566–73.

[15] Wang C, He S, Liu L, Li X, Gao L. Tradeoff between the efficiency penalty and load depth in a coal-fired power plant with CO2 capture under partial load conditions. Energy Convers Manag 2023;278:116608.

[16] Ma J. A new integration scheme for CO2 capture in low-rank coal fired power plants with energy savings. Appl Therm Eng 2023;228.

[17] Kather A, Liebenthal U, Ehlers S. 23 - Power plant integration methods for liquid absorbent-based post-combustion CO2 capture. In: Feron PHM, editor. Absorpt.-Based Post-Combust. Capture Carbon Dioxide, Woodhead Publishing; 2016, p. 555–88.

[18] Zheng Y, Gao L, Dong R, He S. Role of CCUS in carbon neutral power system. Carbon Neutrality 2022;1:19.