

# Post-combustion CO<sub>2</sub> capture from a natural gas combined cycle power plant using activated carbon adsorption



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## HIGHLIGHTS

- Compared with monoethanolamine, net efficiency using activated carbon is improved.
- Heat regeneration of activated carbon is lower at higher CO<sub>2</sub> concentration.
- Activated carbon is cost-competitive for CO<sub>2</sub> capture in natural gas combined cycle.
- Adsorption carbon capture can be further improved using enhanced heat/mass recovery.

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## ABSTRACT

As fossil fuel power plants have emitted significant quantity of carbon dioxide (CO<sub>2</sub>) into the atmosphere which aggravates climate change, capturing and storing such emissions is key to mitigate the issue. An adsorption system based on a physical adsorbent i.e. activated carbon is first assessed to capture CO<sub>2</sub> emissions from a natural gas combined cycle. Then a subcritical sequential supplementary firing combined cycle with CO<sub>2</sub> capture is used to analyse the effect of CO<sub>2</sub> concentration. Analyses are carried out in terms of power loss and thermal efficiency. To evaluate the advantages of post-combustion CO<sub>2</sub> capture using activated carbon, results are compared with systems using a commercial absorbent, i.e. monoethanolamine and a chemical adsorbent i.e. polyethyleneimine/silica. The net efficiency of natural gas combined cycle using activated carbon increases slightly from 50.8% to 51.1% due to the lower regeneration temperature at 358 K. The performance of the system using PEI/silica is almost the same as that using activated carbon at 368 K. Although the thermal energy required to regenerate the activated carbon is relatively high, a significant improvement of net efficiency is observed with increased partial pressure. Economic analysis indicates that the systems using activated carbon is a competitive alternative for CO<sub>2</sub> capture. It is concluded activated carbon is relatively more advantageous than monoethanolamine in terms of efficiency and cost, which could be further improved with enhanced heat and mass recovery.

## 1. Introduction

In 2014, approximately 23% of carbon dioxide (CO<sub>2</sub>) emissions emitted into the atmosphere was from fossil fuel power plants [1]. Electricity production from fossil fuels is predicted to increase by about 30% before 2035 [2]. Although renewable energy is increasingly utilised, electricity generation from natural gas is expected to remain a significant global power source until at least 2030 [3], primarily due to the lower capital cost and carbon intensity of the natural gas combined cycle (NGCC) [4]. Carbon capture and storage (CCS) has the potential and is recognised for the cost effective for reducing energy-related emissions in the power sector [5] where some operators of NGCC power

plants have started to consider CCS, although the current number of applications is still limited [3]. In addition, the potential of using CO<sub>2</sub> for enhanced oil recovery (EOR) has been demonstrated due to its cheaper price and miscibility with crude oil compared to other miscible fluids [6]. It is estimated that the CO<sub>2</sub> captured from the Petra Nova project located in Texas has increased the daily oil production from 300 barrels in 2017 to about 4000 barrels to date [7].

Exhaust gas from combustion processes contains CO<sub>2</sub>, which can be captured using a range of solvents. The technology is referred to as post-combustion CO<sub>2</sub> capture. As applied in coal power plants for both the Boundary Dam and Petra Nova projects, post-combustion CO<sub>2</sub> capture using amine is the first to reach a commercial scale and is currently the

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**Nomenclature**

A	adsorption potential ( $\text{J mol}^{-1}$ )
AC	activated carbon
C	specific heat capacity ( $\text{kJ kg}^{-1} \text{K}$ )
CCS	carbon capture and storage
CEPCI	chemical engineering plant cost index
CF	capacity factor
D-A	Dubinin-Astakhov
$E$	characteristic energy ( $\text{J mol}^{-1}$ )
EGR	exhaust gas recirculation
EOR	enhanced oil recovery
ESA	electric temperature swing adsorption
$Ex$	exergy (MW)
FC	fuel cost
FCF	fixed charge factor
FOM	fixed operation and maintenance cost
$H$	reaction heat ( $\text{kJ}^{-1} \text{kg}^{-1}$ )
HP	high pressure
HR	heat rate
HRSG	heat recovery steam generator
LCOE	levelised cost of electricity
LHV	low heat value
LP	low pressure
$m$	mass (kg)
MEA	monoethanolamine
MOF	metal organic framework
MP	medium pressure
$n$	surface-structural heterogeneity factor
NGCC	natural gas combined cycle
$P$	pressure (Pa)
PEI	polyethyleneimine
PSA	pressure swing adsorption
$q$	$\text{CO}_2$ adsorption capacity ( $\text{mg}^{-1} \text{g}^{-1}$ )
$Q$	heat (kJ)
$r$	interest rate
$R$	universal gas constant ( $8.314 \text{ J mol}^{-1} \text{ K}^{-1}$ )
RC	reference cost (M\$)
RP	reference case
SC	scaled cost (M\$)

SEGR	selective exhaust gas recirculation
SP	scaled reference
SSFCC	sequential supplementary firing combined cycle
$T$	temperature ( $^{\circ}\text{C}$ )
$t$	time (s)
$\text{TCO}_2$	$\text{CO}_2$ transport cost
TIC	total investment cost
$TL$	economic life of the plant
TSA	temperature swing adsorption
VOM	variable operation and maintenance cost
VSA	vacuum swing adsorption
$W$	power output (kW)

*Greek letter*

$\eta$	efficiency
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*Superscript*

$R$	scaling exponent of the capture plant
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*Subscripts*

ad	adsorption
au	auxiliary
cap	capture
$\text{CO}_2$	carbon dioxide
com	compressor
de	desorption
e	partial
h	regeneration
hr	heat recovered
in	input
L	latent heat
LP	low pressure
p	power
re	reactor
S	sensible heat
sat	saturation

most advanced technology for capturing  $\text{CO}_2$  from power plants. This is mainly because of complementary industrial experience established from similar processes in, e.g. natural gas sweetening plants [8]. As one of the main solvents used for post-combustion  $\text{CO}_2$  capture [9], monoethanolamine (MEA) is very reactive and can effectively remove a high volume of acid gas from flue gas. However, during solvent regeneration, MEA is very corrosive, requires a large quantity of energy, and forms components e.g. formaldehyde, acetic acid, hydroxyacetaldehyde, glycolic acid, formic acid, oxalic acid etc. that cannot be regenerated by thermal heat [10]. In a NGCC, excess air is necessary for the operation of the gas turbine, which results in a high concentration of  $\text{O}_2$  in the gas turbine exhaust gas, i.e. around 15% v v<sup>-1</sup>. That consequently stimulates oxidative degradation of MEA and increases operational costs [11,12]. Another problem using MEA lies in the low  $\text{CO}_2$  concentration. Some research studies have demonstrated that the low  $\text{CO}_2$  concentration in the exhaust gas will increase the energy required for regenerating the MEA solvent for a MEA-based post-combustion  $\text{CO}_2$  capture plant [13,14]. In a NGCC,  $\text{CO}_2$  is diluted with nitrogen ( $\text{N}_2$ ) which is supplied by 200–300% of excessive air [15,16]. Thus, several approaches, e.g. exhaust gas recirculation (EGR), selective exhaust gas recirculation (SEGR), subcritical sequential supplementary firing combined cycle (SSFCC) have been proposed for increased  $\text{CO}_2$  and reduced oxygen ( $\text{O}_2$ ) concentrations in a NGCC with

absorption-based post-combustion  $\text{CO}_2$  capture using MEA [17,18]. Although EGR can increase  $\text{CO}_2$  concentration up to 6.7 mol% and improve the net efficiency of the cycle by 0.5%, the concentration of  $\text{O}_2$  will decrease from 12 mol% to 8.3 mol% [19]. As a result, the problem with amine degradation remains unsolved. Whilst SEGR presents the highest increment of  $\text{CO}_2$  in the exhaust gas from 4 mol% to 18.6 mol% and the efficiency is increased by 0.5%, the concentration of  $\text{O}_2$  remains high [19]. Subcritical SSFCC increases  $\text{CO}_2$  concentration from 4.0 mol% to 8.94 mol% [19]. The volumetric flow is reduced by 50% approximately, leading to the highest reduction in  $\text{O}_2$  concentration from 12 mol% to 1 mol% [19]. It is worth noting that the quantities of  $\text{CO}_2$  and  $\text{O}_2$  mentioned previously are dependent on the assumptions made in Ref. [19], and therefore they are subject to change in line with the assumptions defined in a study. In other words, the performance of these absorption-based post-combustion  $\text{CO}_2$  capture approaches is affected by  $\text{CO}_2$  [20], which is usual around 3–4 mol% [21].

Compared with absorption-based post-combustion  $\text{CO}_2$  capture, adsorption is a promising and versatile technique, and its performance is not influenced by  $\text{O}_2$  concentration [22]. The advantages of adsorption-based post-combustion  $\text{CO}_2$  capture technology include reduced costs in  $\text{CO}_2$  separation, lower regeneration energy requirements, and minimised pressure losses, which ensure a relatively good performance in the process of capturing  $\text{CO}_2$  [23,24]. Operating methods (which

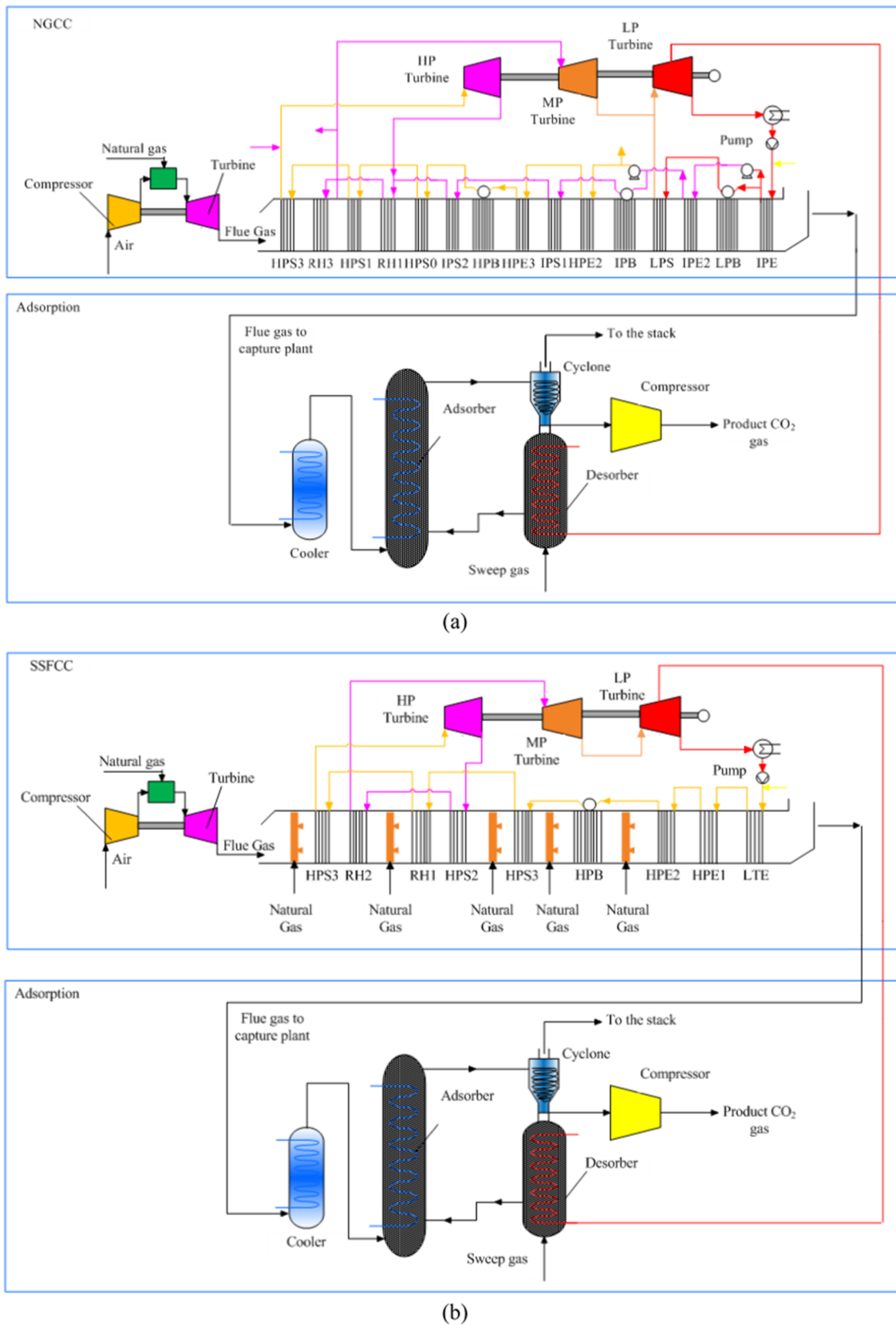


Fig. 1. The schematic diagram of combined cycle power plants integrated with an adsorption system in (a) a conventional NGCC power plant; and (b) a subcritical SSFCC power plant [42].

correspond to different carbon capture cycles) and adsorbent materials are two research hotspots affecting the performance of CO<sub>2</sub> capture. Adsorption-based post-combustion CO<sub>2</sub> capture can be classified into pressure swing adsorption (PSA) [25], vacuum swing adsorption (VSA) [26], temperature swing adsorption (TSA) [27] and electric temperature swing adsorption (ESA) [28]. PSA operates above atmospheric pressure, VSA happens at atmospheric pressure whilst desorption takes place under low pressure. During TSA, a desorber is heated by an external heat source e.g. hot water whilst an adsorber is cooled by a cooling medium e.g. cooling water. ESA is a type of TSA where electricity is used for fast desorption. In the operating process, adsorption and desorption happen alternatively to acquire high purity CO<sub>2</sub>. This cycle is intermittent, and therefore a second set of the adsorber and the desorber is required to achieve continuous operation. Moving beds have been proposed as a regenerator but their heat transfer is poor, leading to an undesirable overall performance [29]. Recently, fluidized beds which can continuously capture CO<sub>2</sub> have been conceptually designed but the performance of their amine-based adsorbent is yet to be explored [30]. A novel carbon pump theory used for evaluating CO<sub>2</sub> capture processes has been successfully applied to TSA, PSA, VSA and ESA [28], which provides insights into the thermal performance of CCS technologies [31,32]. Also, various solid adsorbents, which are classified into physical and chemical adsorbents, can be selected for capturing CO<sub>2</sub> in different applications [33]. Physical sorbents e.g. zeolite 5A, zeolite 13X, activated carbon (AC) and silica gel have been widely investigated for adsorption-based CO<sub>2</sub> capture which are inexpensive, insensitive to moisture and with a large surface area [34,35]. Several novel physical adsorbents e.g. metal organic framework (MOF) have attracted attention due to their large adsorption capacity and high gas selectivity [36]. Nevertheless, their costs are relatively high compared to those of conventional adsorbents. As for chemical sorbents, amine-based materials are more advantageous due to their lower generation heat [37]. However, these materials have a similar degradation issue with high O<sub>2</sub> concentration [37]. It is worth noting that adsorption investigations on CCS have been mainly focused on the characteristics of materials. However, there is no research study on adsorption technology using AC in a NGCC and a subcritical SSFCC. In this study, simulation for AC covering a range of desorption temperatures, have

been carried out. Thus, the novelty of this work relates in its application to work in the context and detail of a real-world application.

This paper is original as it aims to evaluate the performance of TSA technology using AC for post-combustion CO<sub>2</sub> capture in NGCC and subcritical SSFCC power plants, which has neither been investigated previously nor covered in literature. AC is selected as the adsorbent for capturing CO<sub>2</sub> from flue gas, which is most commonly used for CO<sub>2</sub> capture when adsorption characteristics, cost, sensitivity to moisture, thermal and mechanical stability are taken into consideration [38,39]. Experimental results of previous research have demonstrated its feasibility for CO<sub>2</sub> capture by using fluidized bed on top of reporting the effect of CO<sub>2</sub> partial pressure and superficial gas velocity [40]. Adsorption isotherms and reaction heat (*H*) of AC have been investigated by various researchers, for instance [22,41] where the established thermal properties can be used for system design and optimisation of CO<sub>2</sub> capture. Desorption heat is calculated based on carbon pump theory [31]. The overall performance of the NGCC integrated with TSA system using AC is compared with the systems using MEA and another amine-based adsorbent i.e. polyethyleneimine (PEI)/silica respectively. How CO<sub>2</sub> concentration of the flue gas affects regeneration heat is also evaluated by using the SSFCC as a case study to show the advantages of AC in dealing with flue gas which has high CO<sub>2</sub> concentration. The framework of this paper is as follows. The novel system is introduced in Section 2 where both power generation and CO<sub>2</sub> capture cycles are illustrated. Then methodology applied in the study is presented in Section 3. Section 4 shows simulation results and analysis, followed by conclusions in Section 5.

## 2. Power plants with carbon capture

### 2.1. System description

A schematic diagram of the NGCC integrated with TSA is shown in Fig. 1(a). The power generation system is composed of a 9FB General Electric gas turbine with a heat recovery steam generator (HRSG), and a steam turbine. The steam produced in the HRSG flows into the steam turbine to generate power. Three pressure levels of steam are generated in the HRSG, i.e. high, medium and low steam pressure which

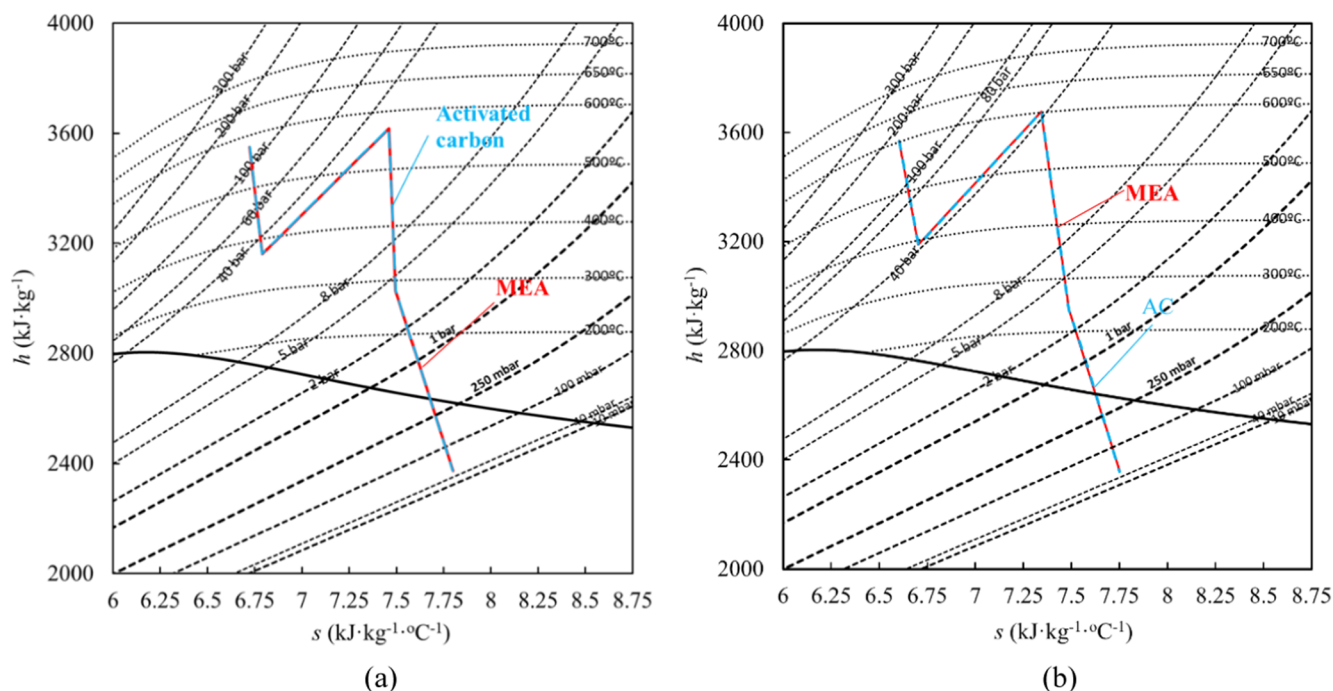


Fig. 2. Steam turbine diagrams showing thermal processes of (a) the NGCC; and (b) the SSFCC.

corresponds to the high pressure (HP), medium pressure (MP) and low pressure (LP) turbines respectively. Unlike the NGCC using MEA where thermal energy for regeneration is extracted from the crossover pipe, steam required for desorption of AC is extracted from the LP steam turbine. As desorption temperature is lower than 105 °C, low-grade steam or hot water can be used as the heat source.

Similarly, a schematic diagram of the SSFCC is presented in Fig. 1(b). The power generation system is composed of a 9FB General Electric gas turbine with HRSG, and a steam turbine. Only high pressure steam is generated in the HRSG. A detailed SSFCC process could refer to Reference [42]. It is indicated that the main difference between the SSFCC and the NGCC lies in the HRSG. Sequential combustion reduces O<sub>2</sub> concentration and generates additional CO<sub>2</sub> in flue gas. Supplementary firing in each step is limited by keeping the flue gas temperature after each duct burner to approximately 820 °C. Fuel is burned in five steps through the HRSG, resulting in an improved power output but reduced efficiency. The last stage brings O<sub>2</sub> around to the stoichiometric limit i.e. approximately 1% v v<sup>-1</sup>. Although the efficiency is lower than that of the conventional NGCC, the increment in the power output of the combined steam cycle leads a reduction of gas turbines, at a similar power output generated for a conventional NGCC. This leads to a lower investment cost of the post-combustion CO<sub>2</sub> capture plant. For countries with cheap natural gas i.e. \$ 2–4 per million British Thermal Unit (MMBTU), the SSFCC presents a marginal reduction on the levelised cost of electricity (LCOE) as reported by Reference [42].

The concept design and feasibility of this adsorption-based CO<sub>2</sub> capture system is detailed in Reference [30]. The system mainly consists of a cooler, an adsorber, a desorber, a cyclone and a compressor, as shown in Fig. 1(a) and (b). A circulating fluidized bed is adopted as the adsorber whilst a bubbling fluidized bed is chosen as the desorber. This integrated compact system enables the adsorbent to be continuously circulated in a closed loop. Flue gas is first cooled by cooling water. Then CO<sub>2</sub> in the flue gas is adsorbed by solid adsorbents. The cyclone is used to capture the adsorbent entrained by the adsorber while the CO<sub>2</sub> free flue gas is released into the atmosphere through the stack. The adsorbent is regenerated in the desorber by using thermal heat from the power plant. The high purity CO<sub>2</sub> is collected at the exit, compressed, transported and stored away. Similar to MEA, the solid adsorbent used in the system is also recirculated in a closed loop. During desorption, energy required by AC is determined based on its basic properties. The fluidized reactor is used for the adsorber and the desorber. A centrifugal compressor, with a pressure ratio of 80, is used to compress CO<sub>2</sub> to approximately 150 bar for EOR application. The compression system consists of seven stages; each involves inter-cooling and water removal

equipment. The compressor is simulated in Aspen plus.

## 2.2. Thermal cycles

Steam from an extraction of the LP steam turbine instead of the crossover pipe of the steam cycle is used to regenerate AC. Fig. 2(a) and (b) show thermal processes of the NGCC and the SSFCC respectively (as indicated by the underlying blue lines) and steam extraction to regenerate the amine solvent (i.e. the red dotted lines). As the temperature/heat diagram for heat recovery steam generator (HRSG) is typical and common, see [42,43], detailed illustration is not further presented here.

Based on the carbon pump theory, the Clapeyron schematic of a TSA cycle for the NGCC power plant is shown in Fig. 3(a). Desorption temperatures of AC ranging between 293 K and 358 K are evaluated to observe the working processes. In real application, two processes happen simultaneously, i.e. desorption (3–4) proceeds with heating (2–3) whereas adsorption (1–2) proceeds with cooling (4–1). The partial pressure of adsorption is 0.0372 bar according to the CO<sub>2</sub> proportion of flue gas. Desorption starts at a temperature of 322 K at Point 3. Thus, the 4-step TSA cycle is plotted as 1–2–3–4–1. When desorption temperature varies from 348 K to 358 K, the TSA cycle will become 1'–2'–3'–4'–1', which indicates a slight increase in the cycle sorption capacity. Similarly, Fig. 3(b) illustrates the Clapeyron schematic of a TSA cycle for the subcritical SSFCC power plant, which is used to indicate the effect of CO<sub>2</sub> partial pressure i.e. molar concentration of CO<sub>2</sub> in flue gas. The TSA cycle for the conventional NGCC power plant is plotted as 1–2–3–4–1 where the desorption temperature is 358 K and adsorption pressure is 0.0372 bar. Comparably, the TSA cycle for the SSFCC power plant becomes 1'–2'–3'–4'–1' when adsorption pressure increases to 0.0894 bar. It is worth noting that sorption capacity increases remarkably with CO<sub>2</sub> concentration, which reveals the vase potential for improving the performance of CO<sub>2</sub> capture.

## 3. Methodology

### 3.1. Chemical process flowsheet model

The power plant is simulated in Aspen plus using information available in Refs. [44,45]. The information revealed in Refs. [44,45] presents realistic market conditions, and the power plant simulation is validated with information generated by ThermoFlow, which is based on the performance map provided by the manufacturer. A flow diagram of the steps applied in developing the models for the case studies is

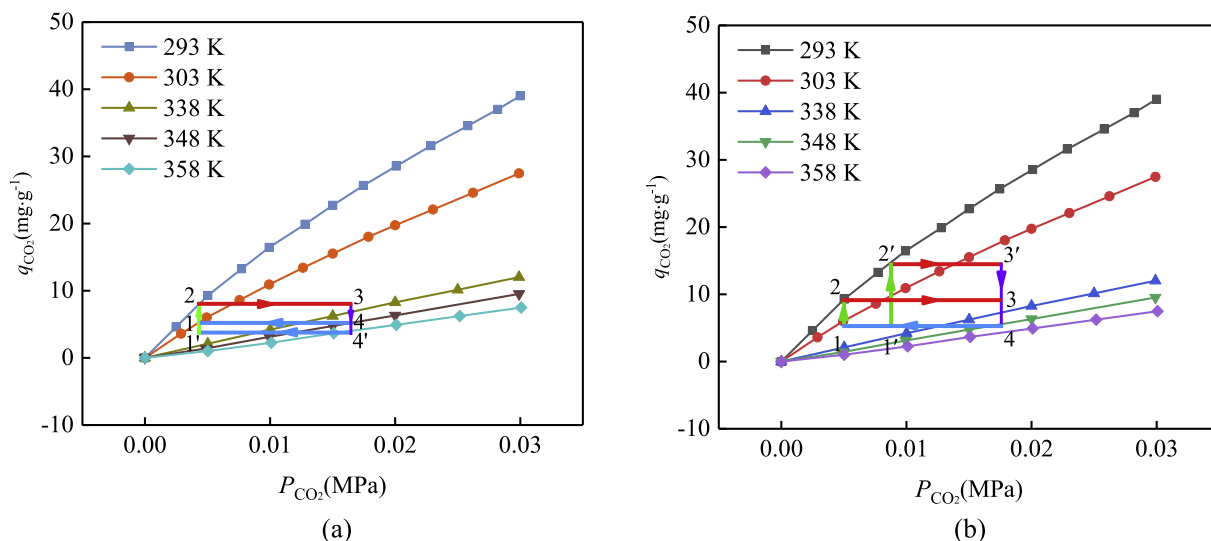


Fig. 3. The 4-step TSA cycles at various desorption temperatures for (a) the conventional NGCC power plant; and (b) the subcritical SSFCC power plant.

shown in Fig. 4. The base methods used in the simulation are Peng-Robinson for gaseous phase parameters [46] and Aspen Plus libraries (stmnbs2) which can be applied to calculate thermodynamic properties of water and steam. Steam required for regenerating AC is extracted from the LP steam turbine at 150 °C and 1.2 bar. Schematic diagrams of Aspen plus simulation are shown in Fig. 5(a) and (b) for the NGCC and the subcritical SSFCC respectively. Due to confidentiality, it is impossible to disclose commercial data of CO<sub>2</sub> capture plants (amines and activated carbon at industrial site). Therefore, the validation of this study, like many others in literature, is carried out based on a comparison in modelling presented in literature. In the case of the power plant without CO<sub>2</sub> capture, comparison is carried out using information available in Thermoflow™, which is a software suite that mainly consists of GT PRO, GT MASTER and Thermoflex software. GT PRO is the leading gas turbine and combined cycle modelling software used by electricity generation industry. It represents realistic market conditions as it offers gas turbine databases with mapped performance curves. The main reason of simulating the NGCC in Thermoflow is to ensure all case studies could be performed using the same platform where all models can be easily developed and modified in Aspen Plus. The same power plant, flue gas and CO<sub>2</sub> concentration are used in the NGCC with CO<sub>2</sub> capture using MEA and AC. Similarly, all the key boundary conditions applied for the SSFCC with CO<sub>2</sub> capture using MEA and AC including the capture level of 90%, as well as water and environmental conditions have been kept the same. With this, the comparison is conducted on a fair platform and boundary conditions are equal. The schematic diagrams of the NGCC and SSFCC simulated in Aspen Plus are shown in Fig. 5.

### 3.2. Performance evaluation

The results of MEA system are obtained from Aspen Plus software (version 9) where the capture plant has been modelled using 30 wt% MEA solvent. The methodology to optimise the design of the CO<sub>2</sub> capture plant is summarised as follows [42]:

- (1) The lean solvent loading of the MEA solution is manipulated to find the minimum energy required in the reboiler to regenerate the solvent.
- (2) To study the effect of different lean loadings, the pressure of the stripper section of the reboiler is manipulated whilst temperature is kept constant at 120 °C [47].

- (3) Finally, to achieve 90% of CO<sub>2</sub> capture, the circulation rate of the MEA solvent is varied.

The capacity of one train is defined as 331 kg s<sup>-1</sup>. To cover the total flue gas of the NGCC, two trains are required.

The performance evaluation of this study focuses on the adsorption process as the performance of the NGCC has been widely assessed in previous researches. For adsorption and desorption processes, equilibrium reactions are considered for AC as the total system efficiency is the main subject of investigation in this study. For post-combustion CO<sub>2</sub> capture using AC, the nonlinear expression of a Dubinin-Astakhov (D-A) model is applied to evaluate sorption capacity ( $q$ ), as shown in Eq. (1). Relevant important parameters i.e. the limiting volumetric adsorption capacity ( $q_0$ ), characteristic energy ( $E$ ), and the surface-structural heterogeneity factor of adsorbents ( $n$ ) are evaluated using adsorption isotherms data. The above parameters used for the D-A model in this paper can refer to Refs. [22,48]. The CO<sub>2</sub> capture rate is defined as 90%.

$$q = \left( \frac{q_0}{v_a} \right) e^{-\left( \frac{A}{E} \right)^n} \quad (1)$$

where  $v_a$  and  $A$  are the specific volume of CO<sub>2</sub> during the adsorbed phase and the adsorption potential, which are defined by Eqs. (2) [49] and (3) respectively:

$$v_a = v_t e^{\alpha(T-T_t)} \quad (2)$$

where  $v_t$  and  $T_t$  are the specific volume and the temperature of liquid CO<sub>2</sub>,  $T$  is the working temperature (K), and  $\alpha$  is the thermal expansion coefficient [50]; and

$$A = RT \ln \left( \frac{P_{sat}}{P_e} \right) \quad (3)$$

where  $R$  is the universal gas constant (8.314 J mol<sup>-1</sup> K<sup>-1</sup>),  $P_{sat}$  and  $P_e$  are saturation and partial pressure of CO<sub>2</sub> (MPa).

The adsorption isotherm data of AC are adopted from Ref. [51] detailing physical properties such as  $E$ ,  $n$ ,  $q_0$  and specific heat capacity  $C_{p, AC}$ , i.e. 4957.9 J mol<sup>-1</sup>, 1.24,  $1.1 \times 10^{-6}$  m<sup>3</sup> g<sup>-1</sup> and 825 J kg<sup>-1</sup> K<sup>-1</sup> respectively.

The adsorption isotherm model is conducive to the TSA performance evaluation. The following description is based on the TSA cycles shown in Fig. 3(a) and (b). The regeneration heat,  $Q_h$  (per kg of

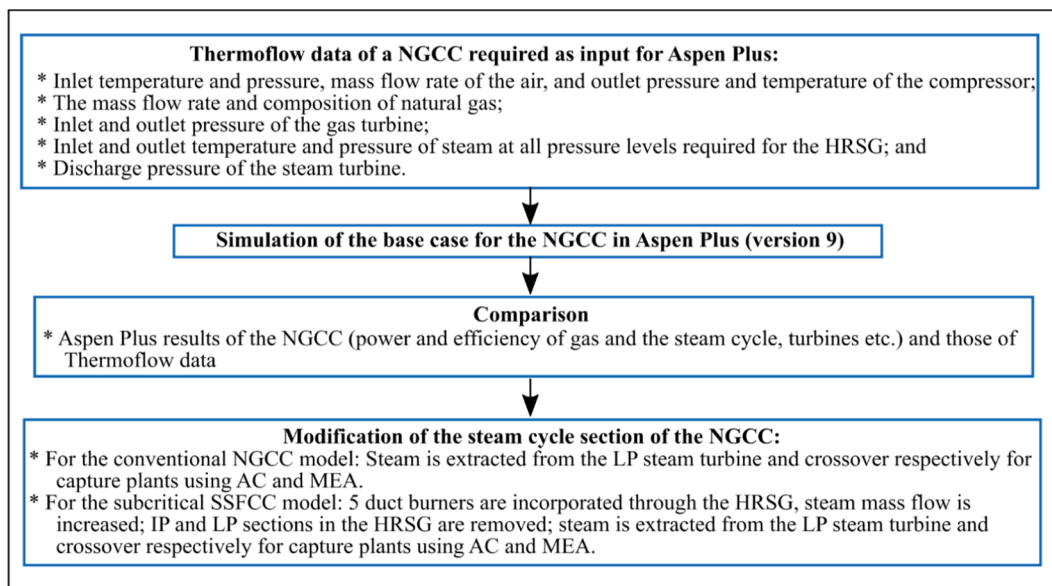


Fig. 4. A flow diagram of the steps to develop the models of the case studies.

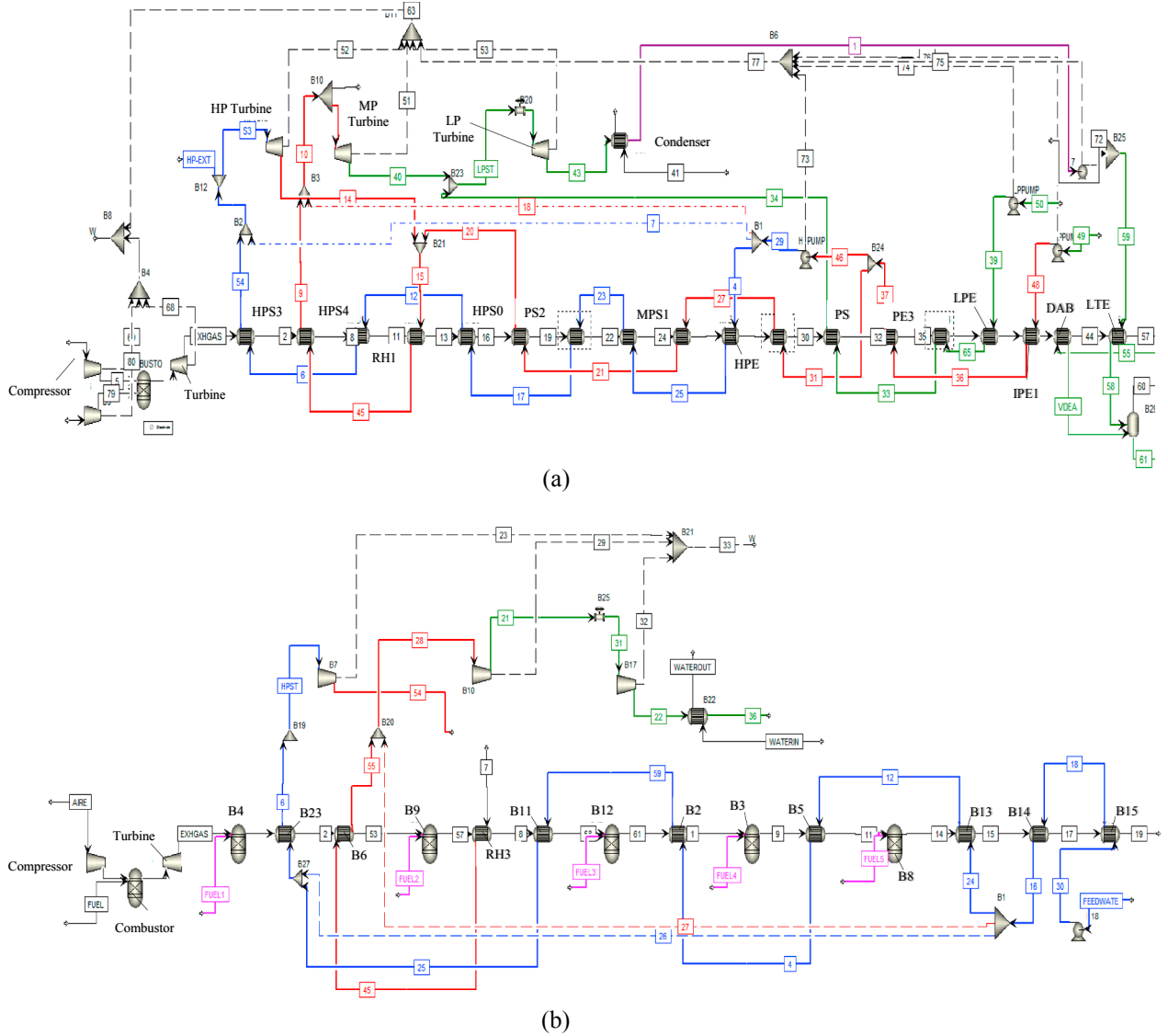


Fig. 5. The Aspen plus models of (a) the conventional NGCC; and (b) the subcritical SSFCC power plants; both are integrated with an adsorption-based CO<sub>2</sub> capture system.

captured CO<sub>2</sub>) is estimated using Eq. (4) which is composed of both sensible ( $Q_s$ ) and latent heat ( $Q_L$ ).

$$Q_h = \frac{(Q_s + Q_L)}{(q_3 - q_4)} \quad (4)$$

where  $q_3$  and  $q_4$  are sorption capacities according to Points 3 and 4 in Fig. 3(a) and (b), respectively.  $Q_s$  can be expressed as Eq. (5):

$$Q_s = \int_{T_2}^{T_4} C_{p,AC} dT + q_3 \int_{T_2}^{T_3} C_{p,a} dT + \int_{T_3}^{T_4} q C_{p,a} dT \quad (5)$$

where  $C_{p,AC}$  and  $C_{p,a}$  are the specific heat capacity of AC and the adsorbed CO<sub>2</sub>, respectively.  $Q_L$  can be determined using Eq. (6), as follows:

$$Q_L = H_{ad} \int_{T_3}^{T_4} dq = H_{ad}(q_3 - q_4) \quad (6)$$

where  $H_{ad}$  is the reaction heat of the adsorbent.  $Q_s$  includes the sensible heat of the adsorbent ( $Q_{s, ad}$ ) and the sensible heat of the CO<sub>2</sub> adsorbed gas phase ( $Q_{s, CO_2}$ ) during preheating and desorption respectively. Thus, to determine  $Q_h$ , Eq. (4) can be transformed into Eq. (7), as follows:

$$Q_h = (Q_{s, CO_2} + Q_{s, ad} + Q_{L, ad}) / (q_3 - q_4) = (Q_{s, CO_2} + Q_{s, ad}) / (q_3 - q_4) + H_{ad} \quad (7)$$

where  $Q_{L, ad}$  is the latent heat of the adsorbent. The exergy of  $Q_h$  ( $Ex_h$ ) can be presented as Eq. (8):

$$Ex_h = Q_h \left( 1 - \frac{T_0}{T_h} \right) \quad (8)$$

where  $T_0$  and  $T_h$  are ambient and heating temperatures, respectively.

The net power plant efficiency ( $\eta$ ) is a key factor to assess the economic performance of a power plant with and without a CO<sub>2</sub> capture system. For a power plant without CO<sub>2</sub> capture, it is usually defined as the percentage of the total thermal energy input of natural gas which is converted into electricity, as shown in Eq. (9):

$$\eta = \frac{W_{net} t}{Q_{in}} \times 100\% = \frac{(W_p - W_{au}) t}{Q_{in}} \times 100\% \quad (9)$$

where  $W_{net}$  is the net power output of the NGCC;  $Q_{in}$  is the total thermal energy input;  $W_p$  is the gross power output from turbines;  $W_{au}$  is the total auxiliary loads including plant operation, energy consumption and the losses of transformers; and  $t$  is the length of period. For the NGCC

integrated with CO<sub>2</sub> capture,  $\eta$  can be expressed as Eq. (10).

$$\eta = \frac{W_{net}t}{Q_{in}} = \frac{(W_p - W_{au} - W_{cap} - W_{com})t}{Q_{in}} \quad (10)$$

where  $W_{cap}$  is the loss in power output due to steam extraction and electricity consumption required for the CO<sub>2</sub> capture system; and  $W_{com}$  is the electricity required to compress the captured CO<sub>2</sub> to the desired pressure for transportation and storage.

## 4. Results and discussion

### 4.1. Energy and exergy analysis of the NGCC with TSA

Fig. 6 shows the trends of  $Q_h$  for CO<sub>2</sub> capture systems using AC when desorption temperature increases from 348 K to 378 K, MEA at 393 K and PEI/silica at 403 K respectively. The regeneration heat of PEI/silica could refer to Ref. [30] which mainly depends on the CO<sub>2</sub> concentration in the flue gas. In spite of the difference of CO<sub>2</sub> concentration between this study and Reference [30], it has marginal influence on the comparative results e.g. power loss and net efficiency. It is found that  $Q_h$  for the CO<sub>2</sub> capture system using AC decreases with desorption temperature. The reasons are explained as follows. For physical adsorbents, e.g. AC and zeolite,  $Q_s$  constitutes a major proportion of  $Q_h$  when compared with  $Q_L$ . Since adsorption capacity increases with temperature, the ratio of  $Q_s$  to  $Q_h$  decreases. The results reveal that  $Q_h$  of the CO<sub>2</sub> capture system using AC ranges from 4.91 GJ tonne CO<sub>2</sub><sup>-1</sup> to 5.81 GJ tonne CO<sub>2</sub><sup>-1</sup>, which is in agreement with the range of 4.65–13.96 GJ tonne CO<sub>2</sub><sup>-1</sup> presented by Refs. [52,53] for carbon-based sorbents. Compared with MEA and PEI/silica, the difference in  $Q_h$  can reach up to 3.3 GJ tonne CO<sub>2</sub><sup>-1</sup>. Similarly, hot fluid e.g. stream extracted from the LP steam turbine is indicated for different desorption temperatures as shown in Fig. 7. When temperature increases from 348 K to 378 K, the quantity of hot fluid extracted from the NGCC using AC decreases at a rate ranging 259–307 tonne h<sup>-1</sup>. The stream from PEI/silica shows a minimum use which is lower than the CO<sub>2</sub> capture system using MEA and much lower than that using AC.

$Q_h$  and desorption temperature vary with the choice of sorbents. AC offers much higher  $Q_h$  because of its lower adsorption capacity compared with MEA and PEI/silica which involve higher adsorption capacities. The advantage of using AC is that steam/hot water at lower temperatures and pressure can be used due to its low regeneration temperature, leading to reduced losses in power and energy efficiency. Power losses of the NGCC with CO<sub>2</sub> capture system using AC are compared with the conventional power plant with CO<sub>2</sub> capture systems using MEA and PEI/silica respectively, as shown in Fig. 8. The losses are due to CO<sub>2</sub> compression, LP power output loss during steam extraction and auxiliaries for the capture plant, and power plant auxiliaries. Although  $Q_h$  of AC is higher than that of MEA and PEI/silica, as mentioned previously, AC used steam at lower temperatures and pressure. As a result, AC presents power losses for steam extraction which are almost similar with PEI/silica but less than those of MEA. Based on the power losses shown in Fig. 8, the efficiency of the NGCC with CO<sub>2</sub> capture system is presented in Fig. 9. The maximum capacity that can be extracted from the LP steam turbine is limited by the mass flow of the steam that is supplied to the LP steam turbine i.e. 375.6 tonne h<sup>-1</sup>. The results also show that the net efficiency of the NGCC with CO<sub>2</sub> capture system using AC increases from 50.5% to 50.9% when the adsorption temperature rises from 348 K to 378 K. Meanwhile, the result for the CO<sub>2</sub> capture system using PEI/silica is almost the same as that using AC at 368 K. The improvement of the net efficiency of the CO<sub>2</sub> capture system using AC can reach up to 3% when compared with that using commercial MEA.

To further illustrate the advantage and disadvantage of CO<sub>2</sub> capture using AC, an exergy analysis is conducted and the results are shown in Fig. 10, which reflects the quality of heat extracted from the LP turbine

of the NGCC. The heat extracted from the NGCC with CO<sub>2</sub> capture system using AC has much lower exergy than that from the NGCC with CO<sub>2</sub> capture systems using MEA and PEI/silica, resulting in higher net efficiency of the NGCC with CO<sub>2</sub> capture system using AC, though  $Q_h$  of the NGCC with CO<sub>2</sub> capture system using AC is also much higher than the systems using MEA and PEI/silica. Results show that the largest exergy of the system using AC can be reduced by approximately 23 MW at 378 K and 11 MW at 348 K respectively when compared with the alternatives of using MEA and PEI/silica, which reveals the potential of the NGCC with adsorption-based CO<sub>2</sub> capture system using AC.

To understand different post-combustion CO<sub>2</sub> capture systems for the NGCC, some key parameters are presented in Table 1. The net power output of the NGCC with absorption-based post-combustion CO<sub>2</sub> capture using MEA is 368.85 MW. Because of a lower desorption temperature i.e. 85 °C, the net power output of the CO<sub>2</sub> capture system using AC increases by 2.76% and reaches 377.6 MW, which offers the highest efficiency i.e. 51.09% compared to 49.67% and 50.82% for the alternatives of using MEA and PEI/silica, respectively. Detailed parameters of the HRSG of the NGCC are presented in Appendix, Table A1.

### 4.2. Energy analysis of the SSFCC with TSA

Fig. 11 presents the effect of CO<sub>2</sub> concentration on the adsorption systems using AC, MEA and PEI/silica respectively. The results indicate that higher partial pressure of CO<sub>2</sub> in the flue gas would have a positive effect on the  $Q_h$  of AC. Comparably, the generation heat of MEA is decreased by 8.3% from 3.75 GJ tonne CO<sub>2</sub><sup>-1</sup> at 3.72% of CO<sub>2</sub> concentration to 3.44 GJ tonne CO<sub>2</sub><sup>-1</sup> at 8.94%. When AC is used to substitute for MEA,  $Q_h$  is reduced by 33.3% from 4.92 GJ tonne CO<sub>2</sub><sup>-1</sup> to 3.28 GJ tonne CO<sub>2</sub><sup>-1</sup> when CO<sub>2</sub> concentration varies from 3.72% to 8.94%. The  $Q_h$  of PEI/silica decreases by 2% from 2.54 GJ tonne CO<sub>2</sub><sup>-1</sup> at 4% of CO<sub>2</sub> concentration to 2.49 GJ tonne CO<sub>2</sub><sup>-1</sup> at 14% [30]. It can be noted that AC is more sensitive to CO<sub>2</sub> concentration.

It is recognised that the SSFCC is an alternative to increase the CO<sub>2</sub> concentration in flue gas. In this study, CO<sub>2</sub> concentration rises from 3.72% (NGCC) to 8.94% (SSFCC) when supplementary firing is incorporated. Fig. 12 shows the net efficiency of the SSFCCs using different adsorbents. It is found that the net efficiencies of the SSFCCs using AC and PEI/silica are quite close, which are higher than that using MEA. Although the net efficiency of the SSFCC using AC is slightly lower in comparison with that of the NGCC, it could be improved by 8.2% when compared to that using MEA i.e. 43.32%. The key parameters and the performance of the SSFCCs are also presented in Table 2. It is possible to increase the total power output from 771 MW to

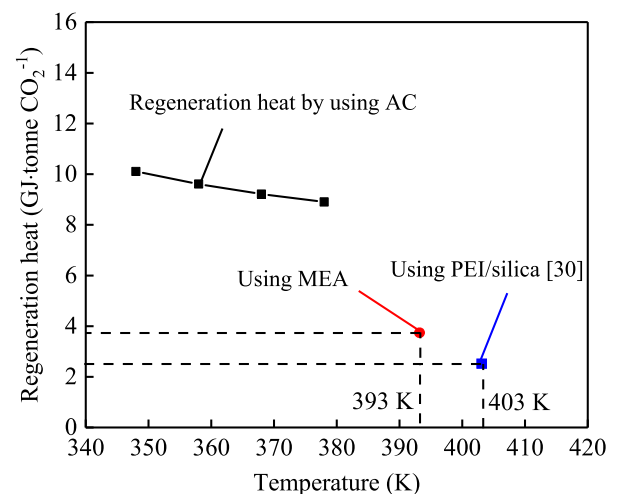


Fig. 6. Regeneration heat ( $Q_h$ ) of the CO<sub>2</sub> capture system using AC vs. desorption temperatures.



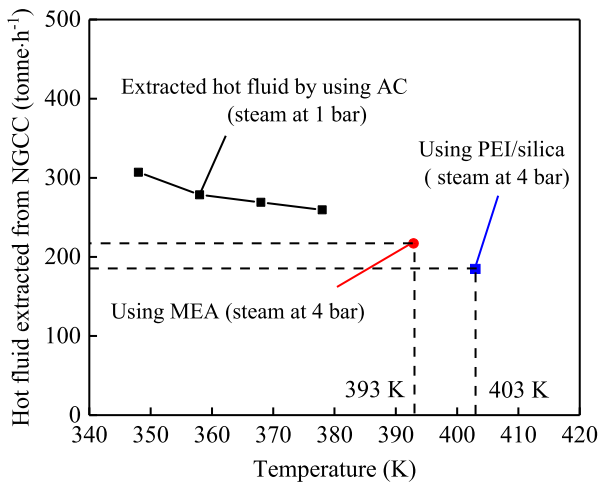


Fig. 7. Hot fluid extracted from the LP steam turbine vs. desorption temperatures.

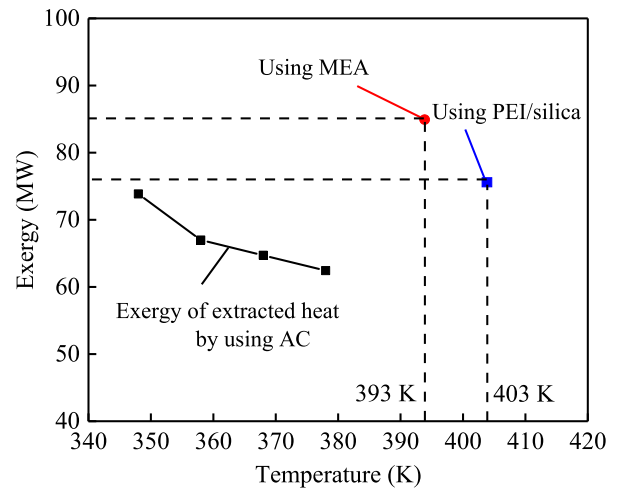


Fig. 10. Exergy of the steam used for regeneration at different desorption temperatures.

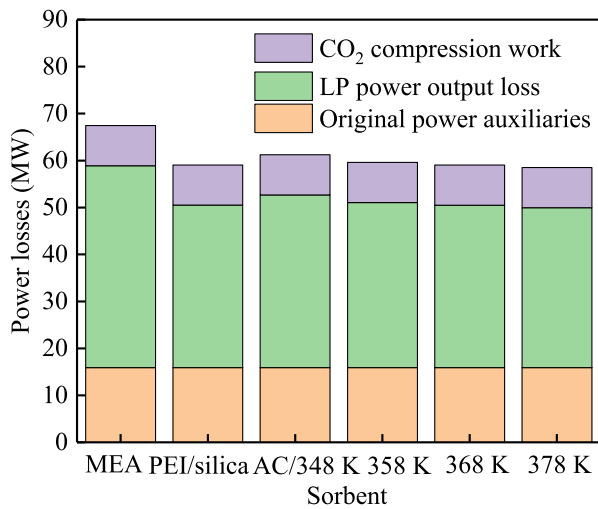


Fig. 8. Power losses of the NGCC with CO<sub>2</sub> capture systems using AC, MEA and PEI/silica at different desorption temperatures.

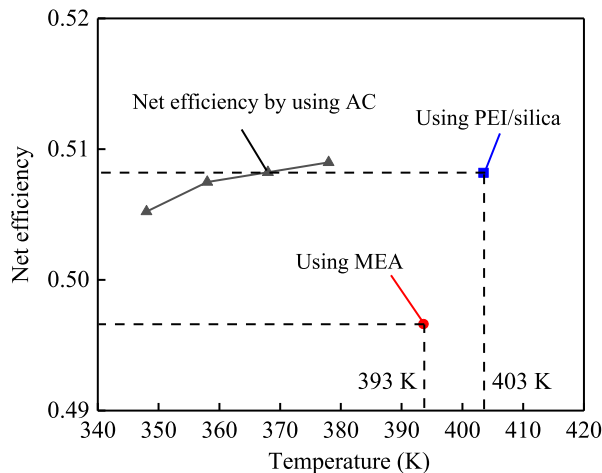


Fig. 9. The net efficiency of the NGCC vs. desorption temperatures.

815.9 MW using AC, and the main advantage is the possibility to employ low-grade steam in the application. Detailed parameters of the HRSG of the SSFCC are presented in Appendix, Table A2.

Table 1

Key parameters of post-combustion CO<sub>2</sub> capture using adsorption technology and MEA in NGCC.

Technology	MEA	AC	PEI/silica
Net power output without CO <sub>2</sub> capture (MW)	411.62	411.62	411.62
Net power output with CO <sub>2</sub> capture (MW)	368.85	377.61	377.00
Net efficiency without CO <sub>2</sub> capture (%)	56.34	56.34	56.34
Net efficiency with CO <sub>2</sub> capture (%)	49.67	51.09	50.82
Mass flow rate of natural gas to gas turbine (kg s <sup>-1</sup> )	13.99	13.99	13.99
Total steam in the crossover pipe (kg s <sup>-1</sup> )	104.4	104.4	104.4
Power consumption by the CO <sub>2</sub> compressor (MW)	10.67	10.67	10.67
Gas composition (mol fraction)			
– H <sub>2</sub> O	0.0841	0.0841	0.0841
– N <sub>2</sub>	0.7529	0.7529	0.7529
– O <sub>2</sub>	0.1257	0.1257	0.1257
– CO <sub>2</sub>	0.0372	0.0372	0.0372
Flow of flue gas (kg s <sup>-1</sup> )	662.3	662.3	662.3
Temperature of flue gas (°C)	110.69	110.69	110.69
Steam extracted from the crossover pipe (kg s <sup>-1</sup> )	59.8	N/A	53
Steam extracted from the LP steam turbine (kg s <sup>-1</sup> )	N/A	72.1	N/A
Temperature of the reboiler (°C)	120	N/A	N/A
Desorption regeneration temperature (°C)	N/A	85	130
Steam pressure of the reboiler (bar)	3	N/A	N/A
Desorption regeneration pressure (bar)	1.898	1.013	
Mass flow of CO <sub>2</sub> to pipeline (kg s <sup>-1</sup> )	35.15	35.15	35.15
Total auxiliary power consumption of the NGCC (MW)	8.57	8.57	8.57

#### 4.3. Economic assessment

As the main difference of the NGCC with CO<sub>2</sub> capture systems using MEA or AC lies in the capital cost of CO<sub>2</sub> capture process, the costs of post-combustion CO<sub>2</sub> capture using MEA and AC are analysed. The total plant cost of the CO<sub>2</sub> capture system using MEA for the NGCC is calculated by scaling up the cost indicated in Refs. [54,55], as expressed in Eq. (11):

$$SC = RC \left( \frac{SP}{RP} \right)^R \quad (11)$$

where SC represents a scaled cost; RC denotes a reference cost for the CO<sub>2</sub> capture plant i.e. \$181 million in 2011 as reported by Ref. [56]; SP and RP are parameters chosen for the scaled and the reference cases (e.g. flows, volume etc.). In this case, the flow of flue gas to the CO<sub>2</sub> capture plant is 662.33 kg s<sup>-1</sup>, see Table 1. R is a scaling exponent of the capture plant i.e. 0.61.

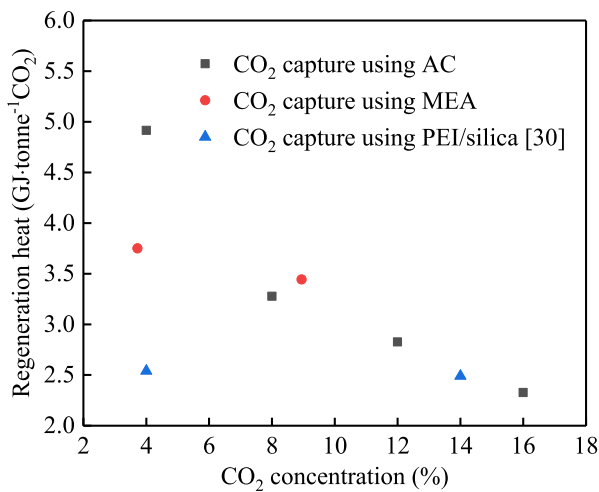


Fig. 11. Regeneration heat ( $Q_h$ ) of the CO<sub>2</sub> capture systems using AC, MEA and PEI/silica respectively at different CO<sub>2</sub> concentrations.

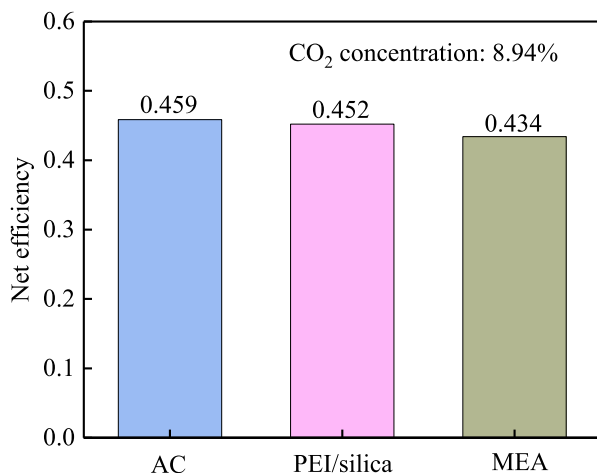


Fig. 12. The net efficiency of the SSFCC using different solvents.

Similarly, for the adsorption process,  $SC$  is the scaled cost,  $RC$  is the reference cost of the adsorption plant \$ 3.713 million in 2017 as reported in Reference [57].  $SP$  is the scaled parameter (e.g. volume capacity, which is the size of equipment, e.g. adsorber, in volume, m<sup>3</sup>) and  $RP$  is the scaled reference (where volume capacity of the adsorbent plant is 6.57 m<sup>3</sup> as reported in Reference [57]).  $R$  is the scaling exponent of the capture plant i.e. 0.57 [46]. The cross section of commercial fluidized reactors ranges 36–110 m<sup>2</sup> [58]. The diameter of the adsorber is calculated by using Aspen Plus. In total, eight separated adsorbers are required, which is estimated based on the flue gas flow rate and maximum size of commercially available fluidised bed i.e. 110 m<sup>2</sup>. The volume of the reactor (adsorber using AC) and the volumetric flow rate reported in Ref. [59] are first adopted to calculate the resident time, which is then used to calculate the volume according to the flue gas volumetric flow of this paper. The volume of adsorber is evaluated as 5000 m<sup>3</sup>. Similar situation applies to desorber and SSFCC. The calculation takes advantages of existing literature to estimate the performance of AC for carbon capture of flue gas. To get more accurate results, more details e.g. experimental sorption kinetic of adsorbent in fluidised bed will be required, which is planned for future work.

The calculated scaled costs are evaluated by using the Chemical Engineering Plant Cost Index (CEPCI) (2017) [60], which is dimensionless and is used to adjust process plant construction costs from one period to another. An updated cost, for instance in 2017, can be accessed by using Eq. (12) based on indices, as follows:

Table 2

Key parameters of post-combustion CO<sub>2</sub> capture using MEA, AC and PEI/silica in the SSFCC.

Technology	MEA	AC	PEI/silica
Net power output (MW)	771.0	815.6	803.9
Net efficiency with CO <sub>2</sub> capture (%)	43.32	45.85	45.19
Mass flow rate of natural gas to gas turbine (kg s <sup>-1</sup> )	13.99	13.99	13.99
Mass flow rate of natural gas to duct burners (kg s <sup>-1</sup> )	17.8	17.8	17.8
Total steam in the crossover pipe (kg s <sup>-1</sup> )	375.3	375.3	375.3
Power consumption by the CO <sub>2</sub> compressor (MW)	31.57	31.57	31.57
Gas composition (mol fraction)			
– H <sub>2</sub> O	0.18798	0.18798	0.18798
– N <sub>2</sub>	0.71215	0.71215	0.71215
– O <sub>2</sub>	0.01043	0.01043	0.01043
– CO <sub>2</sub>	0.08944	0.08944	0.08944
Flow of flue gas (kg s <sup>-1</sup> )	683.88	683.88	683.88
Steam extracted from the crossover pipe (kg s <sup>-1</sup> )	138.08	N/A	87
Steam extracted from the LP steam turbine (kg s <sup>-1</sup> )	N/A	132	N/A
Temperature of the reboiler (°C)	120	N/A	N/A
Desorption regeneration temperature (°C)	N/A	122	130
Steam pressure of the reboiler (bar)	3	N/A	N/A
Desorption regeneration pressure (bar)	1.875	1.013	
Mass flow of CO <sub>2</sub> to pipeline (kg s <sup>-1</sup> )	87.75	87.75	87.75
Total auxiliary power consumption of the SSFCC (MW)	8.7	8.7	8.7

$$\text{Cost}_2 = \text{Cost}_1 \left( \frac{\text{Index}_2}{\text{Index}_1} \right) \quad (12)$$

where  $\text{Cost}_2$  is the scaled cost in 2017;  $\text{Cost}_1$  is the cost in a base year chosen for the analysis i.e. 2011 in this analysis;  $\text{Index}_2$  and  $\text{Index}_1$  are the indices reported for both corresponding years i.e. 535.3 and 585.7 in 2017 and 2011 respectively.

It is assumed that the capital cost of the NGCC can be broken down following the ratios applied in [54,55] i.e. 65% for absorber column, contact cooler and blower whilst 35% is due to stripper column, circulation pumps, heat exchanger and reboiler. As the flue gas in both NGCC and SSFCC is similar (i.e. 662.3 kg s<sup>-1</sup> and 683.9 kg s<sup>-1</sup> respectively), the cost of the absorption section is assumed to be the same in both cases. In connection to the desorption section, the cost of the SSFCC is increased by 2.5 times in line with the quantity of CO<sub>2</sub> required by NGCC and SSFCC, following a ratio of 2:5. The operation and maintenance costs of the CO<sub>2</sub> capture plant using MEA and AC are based on Reference [56] and Refs. [61,62] respectively. Tables 3–6 present the investment and the operation and maintenance cost of the NGCC and SSFCC with post-combustion CO<sub>2</sub> capture using MEA and AC respectively. It is found that the total investment cost of the NGCC with CO<sub>2</sub> capture plant using MEA and compression, i.e. \$ 509 million, is

Table 3

Investments estimated for the NGCC with post-combustion CO<sub>2</sub> capture using MEA and AC.

		MEA [56]	AC [57]
Power plant	Investment cost (\$ million) <sup>1</sup>	302.7	302.7
CO <sub>2</sub> capture	Plant cost (\$ million)	186	–
	Owner's costs (\$ million)	17	–
Compressor unit	Investment cost (\$ million)	203	163
	Investment cost (\$ million) <sup>2</sup>	3.5	3.5
Total investment cost (TIC) (\$ million)		509.2	469.2

<sup>1,2</sup> Information is available in Ref. [42] where half of the price is considered as only one GT train is involved in this study compared with Ref. [42] where two GTs are used. The data in Ref. [42] is updated following CEPCI in 2013 to that in 2017 i.e. 567.3 and 562.1 respectively using Eq. (12).

**Table 4**

The operation and maintenance costs of NGCC with post-combustion CO<sub>2</sub> capture using MEA and AC.

		MEA	AC
Power plant	Operation and maintenance (\$ million) <sup>a</sup>	15.45	15.45
CO <sub>2</sub> capture plant	Fixed operation and maintenance cost (\$ million) <sup>b</sup>	4.13	3.26
	Variable cost (\$ million) <sup>c</sup>	5.5	13.16
Total operation and maintenance (\$ million)		25.1	31.9

<sup>a</sup> Operation and maintenance cost based on Ref. [42].

<sup>b</sup> 2% of the total investment cost of the CO<sub>2</sub> capture plant including CO<sub>2</sub> compression [64].

<sup>c</sup> The variable cost is related to the makeup of MEA i.e. 2.6 kg tonne CO<sub>2</sub><sup>-1</sup> [65]. Cost of MEA is \$2.09 kg<sup>-1</sup>. Makeup of AC is \$13 tonne CO<sub>2</sub><sup>-1</sup> captured [61,62].

**Table 5**

Investments estimated for the subcritical SSFCC with CO<sub>2</sub> capture using MEA and AC.

		MEA [56]	AC [57]
Power plant	Investment cost (\$ million) <sup>1</sup>	539	539
CO <sub>2</sub> capture	Investment cost (\$ million)	310	163 <sup>2</sup>
Compressor unit	Investment cost (\$ million) <sup>3</sup>	8.1	8.1
Total investment cost (\$ million)		857	710

<sup>1,3</sup>Based on Ref. [42], updated from 2013 to 2017 using CEPCI i.e. 567.3 and 562.1 respectively.

<sup>2</sup>The cost of the adsorption plant is considered as the same in both NGCC and SSFCC. Flue gas varies marginally for the supplementary firing burned in the HRSG but the quantity of CO<sub>2</sub> increases by 2.5 times.

**Table 6**

The operation and maintenance cost of subcritical SSFCC with post-combustion CO<sub>2</sub> capture using MEA and AC.

		MEA	AC
Power plant	Operation and maintenance (\$ million) <sup>a</sup>	45.5	45.5
CO <sub>2</sub> capture plant	Fixed operation and maintenance costs (\$ million) <sup>b</sup>	6.2	3.26
	Variable cost (\$ million) <sup>c</sup>	4.6	32.9
Total operation and maintenance (\$ million)		56.3	81.6

<sup>a</sup> Based on Ref. [42].

<sup>b</sup> 2% of the total investment cost of the CO<sub>2</sub> capture plant [64].

<sup>c</sup> The variable cost is related to the makeup of MEA i.e. 1.7 kg tonne CO<sub>2</sub><sup>-1</sup> [66]. Cost of MEA is \$2.09 kg<sup>-1</sup>. Makeup of AC is \$13 tonne CO<sub>2</sub><sup>-1</sup> captured [61,62].

8.53% higher than that using AC. For SSFCC with CO<sub>2</sub> capture using AC and compressor,  $r$  the total investment is \$ 509 million, i.e. 17.15% higher than that using AC. The operation and maintenance cost of the power plants with CO<sub>2</sub> capture process using AC is higher than that of using MEA for both NGCC and SSFCC. As a result, the total costs (including investment, operation and maintenance) of the NGCC with CO<sub>2</sub> capture using MEA and AC are \$ 534.3 million and \$ 501.1 million; and \$ 913.3 million and \$ 791.6 million for the SSFCC, respectively. Both costs are in agreement with the estimate presented in Ref. [63]. It can be concluded that CO<sub>2</sub> capture using AC is more competitive from an economic perspective.

The following conditions apply in this study in estimating the LCOE of the power plant (including compression units):

- The gas price is fixed as \$5 MMBTU<sup>-1</sup>.
- CO<sub>2</sub> is used for EOR whilst no storage cost is considered.
- CO<sub>2</sub> is sold at a price of \$20 tonne CO<sub>2</sub><sup>-1</sup> (in reality, the price will be fluctuated with oil prices but this is not taken into consideration in this study).

- Carbon price associated with the residual carbon emissions is unavailable.
- A total 8000 operating hours per year.
- An annual factor of 10.6%.
- A low heat value (LHV) is 51.8 MJ kg<sup>-1</sup>.

The formulas used to estimate LCOE in this work are simplified as presented by Eqs. (13) and (14) [67].

$$LCOE = \frac{TIC \times FCF + FOM}{Poweroutput \times CF \times 8000} + VOM + HR \times FC + TCO_2 \quad (13)$$

$$FCF = \frac{r \times (1 + r)^{TL}}{(1 + r)^{TL} - 1} \quad (14)$$

where TIC is the total investment cost; FCF is the fixed charge factor; FOM is the fixed operation and maintenance cost; MW is the net power output; CF is the capacity factor; VOM is the variable operation and maintenance cost; HR is the net power heat rate; FC is the fuel cost per unit of energy; and TCO<sub>2</sub> is the transportation cost of CO<sub>2</sub>; where all are in \$ MWh<sup>-1</sup>. Meanwhile,  $r$  is the interest rate; and  $TL$  is the economic life of the plant which is considered as 30 years in this work.

The information presented in Tables 4–6 is used in Eqs. (13) and (14) to estimate the LCOE, and the results are shown in Fig. 13. The LCOE of the NGCC with CO<sub>2</sub> capture using AC is marginally lower than that using MEA, i.e. \$54.26 MWh<sup>-1</sup> compared with \$54.84 MWh<sup>-1</sup>. The slight reduction is the result of improved efficiency and reduced investment cost. The LCOE of the SSFCC for both MEA and AC is even lower compared with that of the NGCC using MEA and AC due to the impact of CO<sub>2</sub> concentration in flue gas.

#### 4.4. Potential improved performance

Table 7 compares post-combustion CO<sub>2</sub> capture using AC, PEI/silica and MEA for the NGCC in terms of material type, sorption capacity, regeneration heat, O<sub>2</sub> concentration, net efficiency, cost and current development stage. It is demonstrated that chemical adsorbents (e.g. PEI/silica) and absorbents (e.g. MEA) have higher sorption capacities than physical adsorbents (e.g. AC). PEI/silica and MEA show much lower Q<sub>h</sub> than AC; however, AC can be regenerated by low-grade heat (e.g. hot water). It is also worth noting that for PEI/silica and MEA high O<sub>2</sub> concentration may cause degradation whereas AC does not have such a problem. The net efficiency of CO<sub>2</sub> capture using adsorption technology (e.g. AC and PEI/silica) is higher than that of using absorption technology (e.g. MEA), which also results in a lower initial cost. Currently CO<sub>2</sub> capture using MEA is mature whilst adsorption-

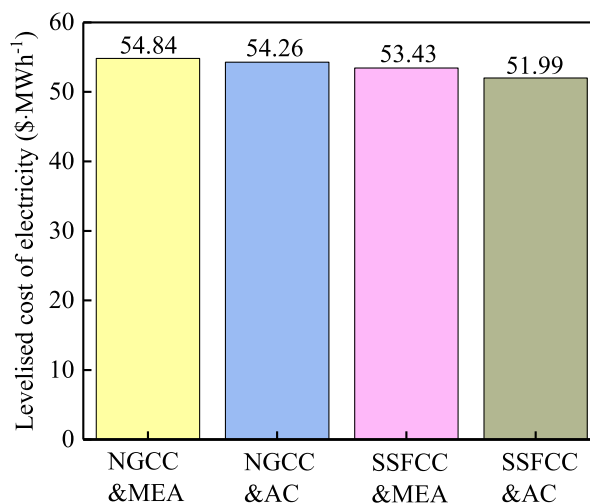


Fig. 13. LCOEs of the NGCC and the SSFCC; both with post-combustion CO<sub>2</sub> using MEA and AC.

**Table 7**  
Comparison of CO<sub>2</sub> capture using AC, PEI/silica and MEA.

Sorbent	Type	Sorption capacity	Regeneration heat	O <sub>2</sub> concentration	Net efficiency	Cost	Development stage
AC	Physical adsorption	Low	High	None	High	Low	Theoretical
PEI/silica	Chemical adsorption	High	Low	Low	High	Low	Lab-scale prototype
MEA	Absorption	High	Medium	High	Low	High	Commercial

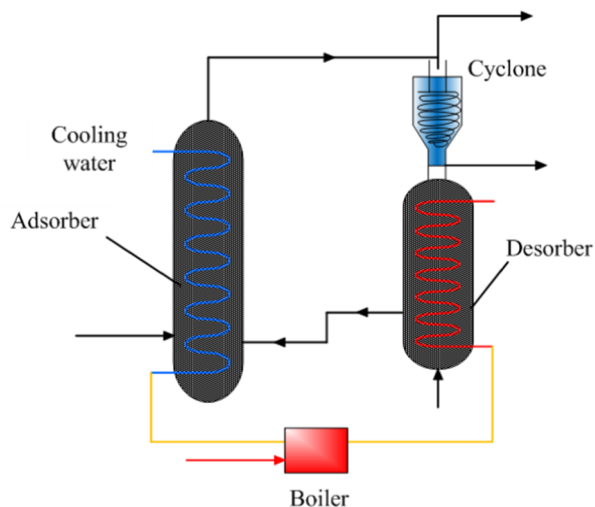


Fig. 14. Heat recovery design for the NGCC with adsorption [30].

based post-combustion CO<sub>2</sub> capture is undergoing commercialisation. One striking fact is that both absorption and adsorption technologies using MEA and PEI/silica respectively for post-combustion CO<sub>2</sub> capture from the NGCC show improved thermal performance i.e. low  $Q_h$  via heat recovery. For example, Fig. 14 presents a heat recovery design for the post-combustion CO<sub>2</sub> capture system using PEI/silica, as reported in Ref. [30]. To increase the temperature of the heat transfer medium to a specific desorption temperature, cooling water is pre-heated by recovering adsorption heat, and then heated by a boiler. This method is advantageous as no extra heat will be extracted from the LP turbine and therefore will have little to no influence on the NGCC. The regeneration heat of this system ( $Q_h'$ ) can be calculated using Eq. (15):

$$Q_h' = (Q_{s, CO_2} + Q_{s, ad} + Q_{L, ad} - Q_{hr}) / (q_3 - q_4) \quad (15)$$

where  $Q_{hr}$  is the heat recovered during the process. Due to  $Q_{hr}$ ,  $Q_h'$  of PEI/silica can be reduced from 5.15 GJ tonne CO<sub>2</sub><sup>-1</sup> to 2.54 GJ tonne CO<sub>2</sub><sup>-1</sup>, this recovery method is more effective when the adsorption heat of material is relatively high, which is more efficient for most of chemical adsorbents. Comparably, physical adsorbents (e.g. AC) usually have low adsorption heat and small sorption capacity. When the total capacity of  $Q_h$  is considered,  $Q_{s, ad}$  is several times higher than that of  $Q_{L, ad}$ . Under this scenario, performance improvement is limited. Thus, recovering  $Q_{s, ad}$  and  $Q_{L, ad}$  between the adsorbent and the desorbent is a better alternative. Different from MEA, heat transfer efficiency of the solids inside the heat exchanger may be low, which may limit heat recovery options to transporting heat between hot and cold solid streams. Thus, a new conceptual design is proposed in Fig. 15 which aims to achieve heat and mass recovery in the process. Cold and hot materials from the adsorber and the desorber can flow into a tank in respective pipes. As mass transfer channels are provided around the pipes, only gas can pass through. Thus, both temperature and pressure potential could be utilised (different from the current research on adsorption CO<sub>2</sub> capture, for instance [68], which considers heat transfer only). Due to differences in the chemical potential, regenerated adsorbents can further desorb adsorbates in the heat and mass recovery tank. Fig. 16 indicates a P-T

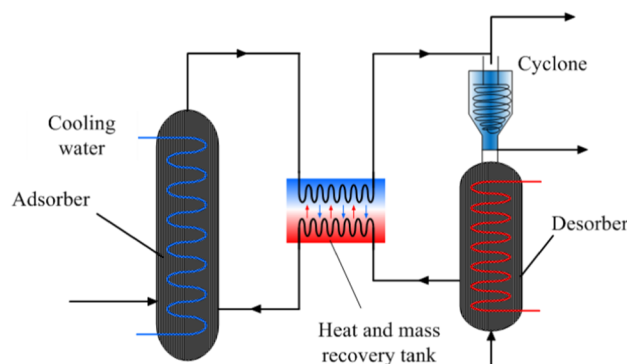


Fig. 15. A new conceptual design for heat and mass recovery of the NGCC.

diagram of the adsorbent by using heat and mass recovery. It is demonstrated that the new cycle 1–6–7–3–8–9–1 becomes wider when compared with the original cycle 1–2–3–4–1. Thus, an extra sorption capacity ( $\Delta q$ ) i.e. between Points 7 and 2 or Points 9 and 4 could be obtained (which could have a substantial effect on the regeneration heat in some cases) while  $Q_{s, ad}$  remains to be recovered. The regeneration heat of the new system using heat and mass recovery ( $Q_h''$ ) can be calculated using Eq. (16):

$$Q_h'' = (Q_{s, CO_2} + Q_{s, ad} + Q_{L, ad} - Q_{hr}) / (q_3 - q_4 + \Delta q) \quad (16)$$

This allows for simultaneous heat and mass recovery in one process, which may lead to lower regeneration heat  $Q_h'$  and higher net efficiency of systems using both chemical and physical adsorbents.

### 5. Conclusions

An adsorption-based post-combustion CO<sub>2</sub> capture system using activated carbon for the natural gas combined cycle is evaluated based on energy, exergy and economic analysis. The performance is compared

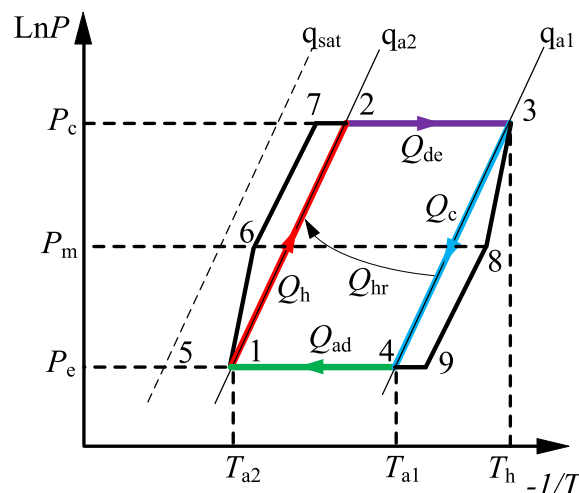


Fig. 16. The P-T diagram of adsorption-based post-combustion CO<sub>2</sub> capture using heat and mass recovery.

with a commercial absorption-based system using monoethanolamine and an adsorption-based system using polyethyleneimine/silica, which is also a novel chemical adsorbent. Conclusions are drawn as follows:

- (1) The regeneration heat of the system using activated carbon is much higher than those using monoethanolamine and polyethyleneimine/silica, which is in the range of 8.9–10.11 GJ tonne CO<sub>2</sub><sup>-1</sup>. However, low-grade steam can be extracted from the low pressure turbine for activated carbon to desorb CO<sub>2</sub>, which results in higher net efficiency than that of the systems using monoethanolamine and polyethyleneimine/silica. For instance, net efficiency of the system will increase from 49.67% to 51.09% if activated carbon is used as a substitution for monoethanolamine.
- (2) The regeneration heat of activated carbon will reduce at a higher CO<sub>2</sub> concentration in the flue gas, which is validated in the case study of a sequential supplementary firing combined cycle system. Although the net efficiency using activated carbon for a sequential supplementary firing combined cycle is slightly decreased in comparison with that of a natural gas combined cycle, it could be improved by 8.2% when compared to that using monoethanolamine i.e. 43.32%.

- (3) The levelised cost of electricity of a natural gas combined cycle using monoethanolamine is \$58.84 MWh<sup>-1</sup>, which is 7.78% higher than that using activated carbon. In addition, the levelised cost of electricity for a sequential supplementary firing combined cycle is \$53.43 MWh<sup>-1</sup>, which is 2.7% higher than that using activated carbon. From an economic perspective, post-combustion capture plant activated carbon based is a competitive and promising alternative for CO<sub>2</sub> capture in a natural gas combined cycle.
- (4) Physical adsorbents e.g. activated carbon are as competitive as absorbents (e.g. monoethanolamine) and chemical adsorbents (polyethyleneimine/silica) for post-combustion CO<sub>2</sub> capture technology. The novel heat and mass recovery method is expected to improve its performance, which may further reduce the regeneration heat of the system using physical adsorbents.

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### Appendix A

See Tables A1 and A2.

**Table A1**

Temperature and pressure (in and out) of each heat exchanger of the conventional NGCC. Pressure gas side is assumed to be 1.013 bar and pressure drop zero.

Heat exchanger ID	Steam side				Gas side	
	Temperature in °C	Temperature out °C	Pressure in bar	Pressure out bar	Temperature in °C	Temperature out °C
HPS3	528	566	127.66	123.96	601	590
RH3	479	566	31.0	28.44	590	567
HPS1	488	528	128.66	127.66	567	558
RH1	399	479	31.6	31.0	558	529
HPS0	331	488	130.9	128.66	529	468
IPS2	308	399	31.84	31.6	468	463
HPB1	331	331	130.9	130.9	463	349
HPE3	331	331	132.6	130.89	349	327
IPS1	236	308	32.22	31.9	327	322
HPE2	237	297	133.8	132.6	322	292
IPB	236	236	32.22	32.22	292	252
LPS	142	182	4.365	3.999	252	251
IPE2	140	233	32.22	32.22	251	197
LPB	143	147	4.365	4.365	197	159
LPE	105	143	4.70	4.365	159	156
IPE1	104	139	32.22	32.22	156	137
DAB	104	106	172.0	172	137	131
LTE	91	104	172.0	172	131	114

**Table A2**

Temperature and pressure (in and out) of each heat exchanger of the subcritical SSFCC. Pressure gas side is assumed to be 1.013 bar and pressure drop zero.

Heat exchanger ID	ID Aspen simulation ID	Steam side				Gas side	
		Temperature in °C	Temperature out °C	Pressure in bar	Pressure out bar	Temperature in °C	Temperature out °C
HPS3	B23	572	601	174.5	172.48	820	785
RH2	B6	530	601	42.38	41.77	785	710
RH1	RH3	390	530	43	42.38	820	672
HPS2	B11	527	572	176.6	174.5	672	613
HPS3	B2	356.6	527	178.6	176.6	818	440.6
HPB	B5	356.6	356.6	178.6	178.6	792	443
HPE2	B13	199	356.6	180.9	178.6	783	407
HPE1	B14	100	199	182.2	180.9	407	211
LTE	B15	33.6	100	183	182.2	211	80

## References

- [1] International Energy Agency I. World energy outlook; 2015 [cited 2018 18 October]; Available from < <https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings> > .
- [2] World Economic Outlook Update; 2019. [cited 2018 18 October]; Available from: < <https://www.imf.org/en/Publications/WEO/Issues/2019/01/11/weo-update-january-2019> > .
- [3] Perspectives for the Energy Transition. Investment needs for a low-carbon energy system; 2017 [cited 2018 18 October]; Available from: < <https://www.irena.org/publications/2017/Mar/Perspectives-for-the-energy-transition-Investment-needs-for-a-low-carbon-energy-system> > .
- [4] Adams T, Mac Dowell N. Off-design point modelling of a 420 MW CCGT power plant integrated with an amine-based post-combustion CO<sub>2</sub> capture and compression process. *Appl Energy* 2016;178:681–702.
- [5] Cabral RP, Mac Dowell N. A novel methodological approach for achieving £/MWh cost reduction of CO<sub>2</sub> capture and storage (CCS) processes. *Appl Energy* 2017;205:529–39.
- [6] NETL. Carbon dioxide enhanced oil recovery: untapped domestic energy supply and long term carbon storage solution; 2010. [cited 2018 18 October]; Available from: < <https://www.netl.doe.gov/oil-gas/oil-recovery> > .
- [7] DOE. DOE-Supported Petra Nova Captures More Than 1 Million Tons of CO<sub>2</sub>; 2018. [cited 2018 18 October] < <https://www.energy.gov/fe/articles/doe-supported-petra-nova-captures-more-1-million-tons-co2> > .
- [8] Herzog H, Meldon J, Hatton A. Advanced post-combustion CO<sub>2</sub> capture 2009 [cited 2018 18 October]; Available from: < <http://www.canadiancleanpowercoalition.com/pdf/AS19%20-%20herzog-meldon-hatton> > .
- [9] Luis P. Use of monoethanolamine (MEA) for CO<sub>2</sub> capture in a global scenario: consequences and alternatives. *Desalination* 2016;380:93–9.
- [10] Programme IGGRD. CO<sub>2</sub> capture in the cement industry; 2008 [cited 2018 18 October]; Available from: < [https://ieaghg.org/docs/General\\_Docs/Reports/2008-3](https://ieaghg.org/docs/General_Docs/Reports/2008-3) > .
- [11] Goff GS, Rochelle GT. Monoethanolamine degradation: O<sub>2</sub> mass transfer effects under CO<sub>2</sub> capture conditions. *Ind Eng Chem Res* 2004;43:6400–8.
- [12] Chaffee AL, Knowles GP, Liang Z, Zhang J, Xiao P, Webley PA. CO<sub>2</sub> capture by adsorption: materials and process development. *Int J Greenhouse Gas Control* 2007;1:11–8.
- [13] Li H, Ditaranto M, Berstad D. Technologies for increasing CO<sub>2</sub> concentration in exhaust gas from natural gas-fired power production with post-combustion, amine-based CO<sub>2</sub> capture. *Energy* 2011;36:1124–33.
- [14] Merkel TC, Wei X, He Z, White LS, Wijmans JG, Baker RW. Selective exhaust gas recycle with membranes for CO<sub>2</sub> capture from natural gas combined cycle power plants. *Ind Eng Chem Res* 2013;52:1150–9.
- [15] Laboratory NET. Current and Future Technologies for Natural Gas Combined Cycle (NGCC) Power Plants. US Department of Energy, Office of Fossil Energy; 2013. [cited 2018 18 October]; Available from: < <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.819.2479&rep=rep1&type=pdf> > .
- [16] IEAGHG. CO<sub>2</sub> capture at gas fired power plants. International Energy Agency Greenhouse Gas. 2012 [cited 2018 18 October]; Available from: < [https://ieaghg.org/docs/General\\_Docs/Reports/2012-08.pdf](https://ieaghg.org/docs/General_Docs/Reports/2012-08.pdf) > .
- [17] Diego ME, Akram M, Bellas J-M, Finney KN, Pourkashanian M. Making gas-CCS a commercial reality: the challenges of scaling up. *Greenhouse Gases Sci Technol* 2017;7:778–801.
- [18] Aboudheir A, ElMoudir W. Performance of formulated solvent in handling of enriched CO<sub>2</sub> flue gas stream. *Energy Procedia* 2009;1:195–204.
- [19] González Díaz A. PhD Thesis dissertation “Sequential supplementary firing in natural gas combined cycle plants with carbon capture for enhanced oil recovery”. School of Engineering University of Edinburgh. 2016. [cited 2018 18 October]; Available from: < <https://www.era.lib.ed.ac.uk/handle/1842/22935> > .
- [20] Li H, Ditaranto M, Yan J. Carbon capture with low energy penalty: Supplementary fired natural gas combined cycles. *Appl Energy* 2012;97:164–9.
- [21] Pan M, Aziz F, Li B, Perry S, Zhang N, Bulatov I, et al. Application of optimal design methodologies in retrofitting natural gas combined cycle power plants with CO<sub>2</sub> capture. *Appl Energy* 2016;161:695–706.
- [22] Singh VK, Anil Kumar E. Measurement and analysis of adsorption isotherms of CO<sub>2</sub> on activated carbon. *Appl Therm Eng* 2016;97:77–86.
- [23] Lee S-Y, Park S-J. A review on solid adsorbents for carbon dioxide capture. *J Ind Eng Chem* 2015;23:1–11.
- [24] Li S, Deng S, Zhao L, Zhao R, Lin M, Du Y, et al. Mathematical modeling and numerical investigation of carbon capture by adsorption: literature review and case study. *Appl Energy* 2018;221:437–49.
- [25] Qasem NAA, Ben-Mansour R. Energy and productivity efficient vacuum pressure swing adsorption process to separate CO<sub>2</sub> from CO<sub>2</sub>/N<sub>2</sub> mixture using Mg-MOF-74: a CFD simulation. *Appl Energy* 2018;209:190–202.
- [26] Hedin N, Andersson L, Bergström L, Yan J. Adsorbents for the post-combustion capture of CO<sub>2</sub> using rapid temperature swing or vacuum swing adsorption. *Appl Energy* 2013;104:418–33.
- [27] Jiang L, Roskilly AP, Wang RZ. Performance exploration of temperature swing adsorption technology for carbon dioxide capture. *Energy Convers Manage* 2018;165:396–404.
- [28] Zhao R, Liu L, Zhao L, Deng S, Li H. Thermodynamic analysis on carbon dioxide capture by Electric Swing Adsorption (ESA) technology. *J CO<sub>2</sub> Util* 2018;26:388–96.
- [29] Yang W-C, Hoffman J. Exploratory design study on reactor configurations for carbon dioxide capture from conventional power plants employing regenerable solid sorbents. *Ind Eng Chem Res* 2009;48:341–51.
- [30] Zhang W, Sun C, Snape CE, Irons R, Stebbing S, Alderson T, et al. Process simulations of post-combustion CO<sub>2</sub> capture for coal and natural gas-fired power plants using a polyethyleneimine/silica adsorbent. *Int J Greenhouse Gas Control* 2017;58:276–89.
- [31] Zhao R, Deng S, Liu Y, Zhao Q, He J, Zhao L. Carbon pump: fundamental theory and applications. *Energy* 2017;119:1131–43.
- [32] Zhao R, Zhao L, Deng S, Song C, He J, Shao Y, et al. A comparative study on CO<sub>2</sub> capture performance of vacuum-pressure swing adsorption and pressure-temperature swing adsorption based on carbon pump cycle. *Energy* 2017;137:495–509.
- [33] Ben-Mansour R, Habib MA, Bamidele OE, Basha M, Qasem NAA, Peedikakkal A, et al. Carbon capture by physical adsorption: materials, experimental investigations and numerical modeling and simulations – a review. *Appl Energy* 2016;161:225–55.
- [34] Saha BB, Jribi S, Koyama S, El-Sharkawy II. Carbon dioxide adsorption isotherms on activated carbons. *J Chem Eng Data* 2011;56:1974–81.
- [35] Zhao YJ, Wang LW, Wang RZ, Ma KQ, Jiang L. Study on consolidated activated carbon: choice of optimal adsorbent for refrigeration application. *Int J Heat Mass Transf* 2013;67:867–76.
- [36] Lestari WW, Wibowo AH, Astuti S, Irwingsyah, Pamungkas AZ, Krisnandi YK. Fabrication of hybrid coating material of polypropylene itaconate containing MOF-5 for CO<sub>2</sub> capture. *Prog Org Coat* 2018;115:49–55.
- [37] Zhang W, Liu H, Sun Y, Cakstins J, Sun C, Snape CE. Parametric study on the regeneration heat requirement of an amine-based solid adsorbent process for post-combustion carbon capture. *Appl Energy* 2016;168:394–405.
- [38] Rashidi NA, Yusup S, Borhan A. Development of novel low-cost activated carbon for carbon dioxide capture. *Int J Chem Eng Appl* 2014;5:1–5.
- [39] Himeno S, Komatsu T, Fujita S. High-pressure adsorption equilibria of methane and carbon dioxide on several activated carbons. *J Chem Eng Data* 2005;50:369–76.
- [40] Raganati F, Ammendola P, Chirone R. CO<sub>2</sub> adsorption on fine activated carbon in a sound assisted fluidized bed: effect of sound intensity and frequency, CO<sub>2</sub> partial pressure and fluidization velocity. *Appl Energy* 2014;113:1269–82.
- [41] Tiwari D, Bhunia H, Bajpai PK. Adsorption of CO<sub>2</sub> on KOH activated, N-enriched carbon derived from urea formaldehyde resin: kinetics, isotherm and thermodynamic studies. *Appl Surf Sci* 2018;439:760–71.
- [42] González Díaz A, Sánchez Fernández E, Gibbins J, Lucquiaud M. Sequential supplementary firing in natural gas combined cycle with carbon capture: a technology option for Mexico for low-carbon electricity generation and CO<sub>2</sub> enhanced oil recovery. *Int J Greenhouse Gas Control* 2016;51:330–45.
- [43] Kehlhofer P, Hannemann F, Stirnimann F, Rukes B. Combined-cycle gas and steam turbine power plant. 3rd edition PennWell corporation; 2009 [cited 2018 18 October]; Available from: < <https://www.pennwellbooks.com/power-generation-distribution/power-generation/combined-cycle-gas-steam-turbine-power-plants-3rd-edition/> > .
- [44] Rostami A, Anbaz MA, Erfani Gahrooei HR, Arabloo M, Bahadori A. Accurate estimation of CO<sub>2</sub> adsorption on activated carbon with multi-layer feed-forward neural network (MLFNN) algorithm. *Egypt J Pet* 2018;27:65–73.
- [45] González-Díaz A, Alcaráz-Calderón AM, González-Díaz MO, Méndez-Aranda Á, Lucquiaud M, González-Santaló JM. Effect of the ambient conditions on gas turbine combined cycle power plants with post-combustion CO<sub>2</sub> capture. *Energy* 2017;134:221–33.
- [46] Perry RH, Green DW, Maloney JO. Perry’s chemical engineers’ handbook. 7th edition. New York: McGraw-Hill. 1999 [cited 2018 18 October]; Available from: < <https://chembugs.files.wordpress.com/2015/12/perrys-chemical-engineering-handbook1.pdf> > .
- [47] Knudsen JN. Results from test campaigns at the 1 t/h CO<sub>2</sub> post-combustion capture pilot-plant in Esbjerg under the EU FP7 CESAR Project. PCCC1 Abu Dhabi 2011 [cited 2018 18 October]; Available from: < [https://ieaghg.org/docs/General\\_Docs/PCCC1/Abstracts\\_Final/pccc1Abstract00010.pdf](https://ieaghg.org/docs/General_Docs/PCCC1/Abstracts_Final/pccc1Abstract00010.pdf) > .
- [48] Singh VK, Kumar EA. Experimental investigation and thermodynamic analysis of CO<sub>2</sub> adsorption on activated carbons for cooling system. *J CO<sub>2</sub> Util* 2017;17:290–304.
- [49] Ozawa S, Kusumi S, Ogino Y. Physical adsorption of gases at high pressure. IV. An improvement of the Dubinin—Astakhov adsorption equation. *J Colloid Interface Sci* 1976;56:83–91.
- [50] Rahman KA, Chakraborty A, Saha BB, Ng KC. On thermodynamics of methane + carbonaceous materials adsorption. *Int J Heat Mass Transf* 2012;55:565–73.
- [51] Xiao J, Peng R, Cossement D, Bénard P, Chahine R. CFD model for charge and discharge cycle of adsorptive hydrogen storage on activated carbon. *Int J Hydrogen Energy* 2013;38:1450–9.
- [52] Sjöström S, Krutka H, Starns T, Campbell T. Pilot test results of post-combustion CO<sub>2</sub> capture using solid sorbents. *Energy Procedia* 2011;4:1584–92.
- [53] Hills TP, Sceats M, Rennie D, Fennell P. LEILAC: low cost CO<sub>2</sub> capture for the cement and lime industries. *Energy Procedia* 2017;114:6166–70.
- [54] Diego ME, Bellas J-M, Pourkashanian M. Techno-economic analysis of a hybrid CO<sub>2</sub> capture system for natural gas combined cycles with selective exhaust gas recirculation. *Appl Energy* 2018;215:778–91.
- [55] Franco F, Anantharaman R, Bolland O, Booth N, Van Dorst E, Ekstrom C, et al. European best practice guidelines for assessment of CO<sub>2</sub> capture technologies. 2012. [cited 2018 18 October]; Available from: < [https://www.sintef.no/globalassets/project/decarbit/d-1-4-3\\_euro\\_bp\\_guid\\_for\\_ass\\_co2\\_cap\\_tech\\_280211.pdf](https://www.sintef.no/globalassets/project/decarbit/d-1-4-3_euro_bp_guid_for_ass_co2_cap_tech_280211.pdf) > .
- [56] DOE/NETL. Capital Cost Scaling Methodology Quality Guidelines for Energy System Studies: Capital Cost Scaling Methodology. 2013 [cited 2018 18 October]; Available from: < <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.278.4351&rep=rep1&type=pdf> > .
- [57] Chen E, Rolin K, Stillman Z. Activated carbon-based carbon dioxide adsorption

- process. *Senior Design Reports (CBE)* 2017;89:63.
- [58] Basu P. Combustion and gasification in fluidized beds. In: Chapter 8: Circulating Fluidized Bed Boiler. 2006 [cited 2018 18 October]; Available from: < <https://cdn.dal.ca/content/dam/dalhousie/pdf/faculty/engineering/mechanical/Prabir%20Basu%20Book%207> > .
- [59] Chen E, Rolin K, Stillman Z. Activated carbon-based carbon dioxide adsorption process. *Senior Design Reports (CBE)*, University of Pennsylvania. 2017 [cited 2018 18 October]; Available from: < [https://repository.upenn.edu/cgi/viewcontent.cgi?article=1098&context=cbe\\_sdr&fbclid=IwAR1B9VSR6BOL2v9bCjGtvbxRy5LX4OPhyi7IbEu6OFfk2ZhyQ\\_aGcRmFyY](https://repository.upenn.edu/cgi/viewcontent.cgi?article=1098&context=cbe_sdr&fbclid=IwAR1B9VSR6BOL2v9bCjGtvbxRy5LX4OPhyi7IbEu6OFfk2ZhyQ_aGcRmFyY) > .
- [60] Chemical engineering plant cost index (CEPCI); 2017. [cited 2018 18 October]; Available from: < <https://www.chemengonline.com/site/plant-cost-index/> > .
- [61] Krutka H, Sjostrom S. Valuation of Solid Sorbents as a Retrofit Technology for CO<sub>2</sub> Capture from Coal-fired Power Plants. E – Final Technical Report ADA-Environmental Solutions. 2011. [cited 2018 18 October]; Available from: < <https://www.osti.gov/servlets/purl/1261627> > .
- [62] Meghani B. Moving bed temperature swing adsorption processes for post-combustion CO<sub>2</sub> capture. University of Nottingham; 2015 [cited 2018 18 October]; Available from: < <http://eprints.nottingham.ac.uk/29140/> > .
- [63] Glier JC, Rubin ES. Assessment of solid sorbents as a competitive post-combustion CO<sub>2</sub> capture technology. *Energy Procedia* 2013;37:65–72.
- [64] IEAGHG. Retrofitting CO<sub>2</sub> capture to existing power plants. 2011 [cited 2018 18 October]; Available from: < [https://ieaghg.org/docs/General\\_Docs/Reports/2011-02.pdf](https://ieaghg.org/docs/General_Docs/Reports/2011-02.pdf) > .
- [65] Gorset O, Knudsen JN, Bade OM, Askestad I. Results from testing of Aker Solutions advanced amine solvents at CO<sub>2</sub> Technology Centre Mongstad. *Energy Procedia* 2014;63:6267–80.
- [66] Ramezan M, Skone TJ, Nsakala NY, Liljedahl GN, Gearhart LE, Hestermann R, et al. Carbon dioxide capture from existing coal-fired power plants. National Energy Technology Laboratory, DOE/NETL Report; 2007.
- [67] Rubin ES, Short C, Booras G, Davison J, Ekstrom C, Matuszewski M, McCoy S. A proposed methodology for CO<sub>2</sub> capture and storage cost estimates. *Int J Greenhouse Gas Control* 2013;17:488–503.
- [68] Pröll T, Schöny G, Sprachmann G, Hofbauer H. Introduction and evaluation of a double loop staged fluidized bed system for post-combustion CO<sub>2</sub> capture using solid sorbents in a continuous temperature swing adsorption process. *Chem Eng Sci* 2016;141:166–74.