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Analysis on temperature swing adsorption for carbon capture integrated with heat pump technologies

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ABSTRACT

Carbon capture is gathering the momentum to achieve the target of carbon neutrality. However, common carbon capture technology e.g. absorption technology has a very high regeneration energy which leads to the loss of thermal efficiency when retrofitting for the plant. This paper initially proposes a general concept of sorption carbon capture technology with heat pump and explore the performance of adsorption carbon capture integrated with compression heat pump as a case study. Activated carbon is selected as the adsorbent for temperature swing adsorption (TSA). Results indicates that theoretical exergy efficiency of 4-step TSA cycle ranges from 0.05 to 0.16 at different adsorption and desorption temperatures. Net efficiencies of coal-fired plant using adsorption capture technologies range from 35.1% to 35.4% when desorption temperature rises from 50°C to 70°C. Also levelized cost of electricity of coal-fired plant using activated carbon ranges from 50.5 USD·MWh^{-1} to 50.9 USD·MWh^{-1} which has a marginal increase at different desorption temperatures. The result is about 6% lower than that using Monoethanolamine. It is demonstrated that adsorption capture for coal-fired plant may be a promising solution to reduce the energy consumption in the near future.

Keywords: carbon capture, adsorption, regeneration energy, heat pump

NONMENCLATURE

Abbreviations	
APEN	Applied Energy
AC	Activated carbon
COP	Coefficient of Performance
ESA	Electric swing adsorption
LCOE	Levelized cost of electricity, USD·MWh^{-1}
MEA	Monoethanolamine
PSA	Pressure swing adsorption
PTSA	Pressure-temperature swing adsorption
Q_H	Heat input of high temperature heat source (kW)
Q_L	Heat output of low temperature heat source (kW)
T_H	Desorption temperature, K
T_L	Adsorption temperature, K
T_{in}	Heat input temperature, K
VPSA	Vacuum-pressure swing adsorption
W_{min}	Minimum separation work (kW)
W_s	Input work (kW)
W_r	Actual work (kW)
Symbols	
t	Year

1. INTRODUCTION

To achieve its carbon peak and neutrality targets, China will release implementation plans for peaking CO_2 emissions in key areas and sectors as well as a series of supporting measures [1]. As a key solution to carbon mitigation for climate change, carbon capture technology has drawn burgeoning attentions since it could maintain the utilization of fossil fuels while minimise the amount of CO_2 released into the atmosphere [2-4]. Common carbon capture technologies mainly include three methods: pre-combustion capture, oxyfuel combustion and post-combustion capture [5, 6]. Compared with first two methods, post-combustion capture requires less modification of existing power plants which is gathering the momentum [7].

Post-combustion capture can be implemented through absorption, adsorption, gas separation, cryogenic separation, membrane process [8, 9]. Among them, absorption e.g. using amine is the first to reach a commercial scale and is currently the most advanced technology for capturing CO_2 from power plants [10]. As one of the main solvents used for post-combustion CO_2 capture, monoethanolamine (MEA) is very reactive and can effectively remove a high volume of acid gas from flue gas [10]. However, during solvent regeneration, MEA is very corrosive, energy consuming, and forms components such as formaldehyde, acetic acid which cannot be regenerated by thermal heat [11]. Also the regeneration temperature of absorption technologies is relatively high i.e. higher than 100°C which indicates that the technology can hardly use low or ultralow heat sources [12, 13]. Comparably, adsorption technology is quite attractive due to its low energy consumption with low regeneration temperature, which is suitable for small and medium-sized CO_2 source [14]. The basic classification of adsorption carbon capture technology could be pressure swing adsorption (PSA) and temperature swing adsorption (TSA). The derived type e.g. pressure-temperature swing adsorption (PTSA), vacuum-pressure swing adsorption (VPSA) and electric swing adsorption (ESA) are considered to meet various demands [15]. Since vacuum process of PSA causes excessive energy input, TSA is usually regarded as a desirable technology use low grade heat sources to provide effective thermal integration opportunities [16].

For thermal integration, it could have an influence on the on-site plant e.g. heat to power efficiency of the power plant due to extracting the steam from the turbine for the retrofitting [17]. For other large CO_2 source from iron and steel mills or cement plant, the retrofit for collecting waste heat is also necessary for regeneration process. Under this scenario, it tends to consider other heat supply methods while not greatly original structure [18]. Heat pump play crucial roles in industrial heat recovery of low-grade energy resources, which could upgrade the temperature of low-grade heat to a higher temperature level [19]. However, vapour compression heat pump using common hydrofluorocarbons cannot obtain output temperature higher than 100°C [20]. It is demonstrated that MEA can hardly be regenerated through common compression type. Thus it brings about more advantages to adsorption carbon capture when considering the match between regeneration and heat output temperature of heat pump.

This paper aims to bridge the knowledge gap by presenting adsorption carbon capture integrated with heat pump technologies. Also it could further explore the potential of both parts to bring a new perspective. Activated carbon (AC) is used for TSA cycle. The framework of this paper is illustrated as follows: The general concept of the integrated technology is proposed and then various thermal cycles are introduced and compared. A case study is then conducted to present the performance of TSA cycle in terms of working capacity, CO_2 recovery rate, minimum separation work and exergy efficiency.

2. GENERAL CONCEPT

Fig. 1 indicates a general concept of sorption carbon capture integrated with heat pump which aims to combine these two technologies. It aims to initially propose a very broaden sense of the integrated technology. Sorption carbon capture includes absorption and adsorption type while heat pump comprises compression, sorption and hybrid type. Regeneration heat and adsorption cooling power are the main correlation to match two technologies. For example, Fig. 2 indicates a typical case of adsorption carbon capture integrated with vapor-compression heat pump. TSA is adopted for carbon capture where a basic compression heat pump is used for regeneration heat for desorption and cooling power of adsorption. Fig. 3 indicates thermal working processes for the integrated system which are composed of two separated cycles i.e. TSA cycle and heat pump cycle. Heat pump cycle is composed of compression, condensation, expansion and evaporation i.e. 1-2-3-4-1 while TSA cycle could be divided into: adsorption, preheating, desorption and precooling. i.e. a-b-c-d-a. Adsorption heat from process a-b is practically compensated from cooling power which is obtained from process 4-1 in heat pump cycle. Also, condensation heat in process 2-3' from heat pump cycle could be used for desorption process c-d of TSA cycle.

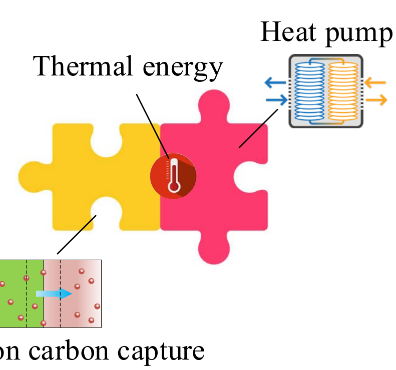


Fig. 1. General concept of sorption carbon capture integrated with heat pump.

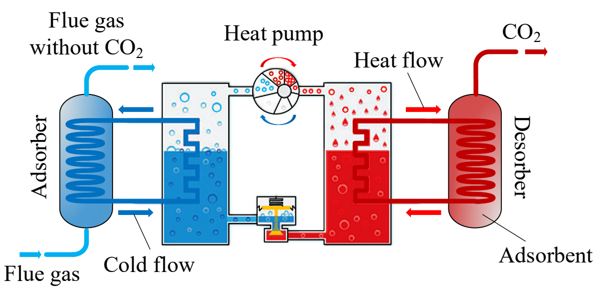


Fig. 2. A typical case of adsorption carbon capture integrated with vapor-compression heat pump.

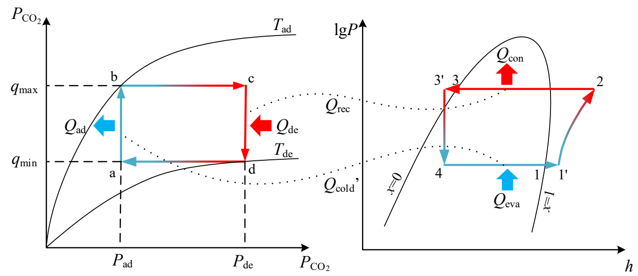


Fig. 3. Schematic diagram of TSA cycle integrated with heat pump cycle.

3. METHODOLOGY

3.1 Adsorption isotherm

AC is selected as a potential candidate to evaluate the performance of adsorption carbon capture integrated with vapour-compression heat pump due to its high stability and low cost for CO_2 adsorption. Adsorption isotherm data of carbon dioxide on ACs are obtained from the reference [21], which has detailed physical property parameters. The nonlinear expression of the D-A model is given by equation 1 and parameters of AC are given in Table 1. Adsorption isotherm model is conducive to estimation of different parameters of TSA.

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

Table 1. Parameters for isotherm of activated carbon.

E	n	q_0	$C_{p,AC}$
4957.91 J·mol^{-1}	1.24	1.09×10^{-6} m^3·g^{-1}	825 J·kg^{1}·K^{-1}

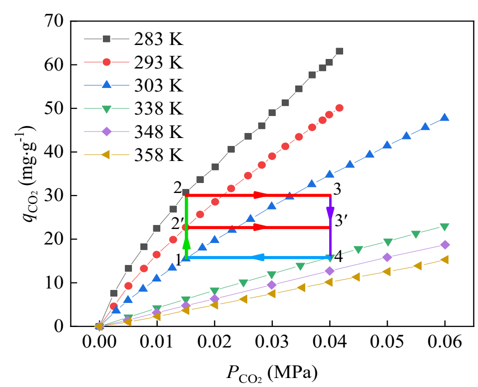
Fig. 4 indicates cycle characteristics of 4-step TSA cycle at various adsorption and desorption temperatures. Fig.4b demonstrates cycle characteristic of 4-step TSA cycle in terms of different adsorption temperatures. When adsorption temperature increases from 293 K to 303 K, 4-step TSA cycle will change from 1-2-3-4-1 to 1-2’-3’-4-1. Adsorption capacity decreases sharply with the increase of adsorption temperature, which is not conducive to CO_2 capture. Fig. 4a demonstrates cycle characteristic of 4-step TSA cycle at different adsorption temperatures. When adsorption temperature increases from 283 K to 293 K, 4-step TSA cycle will change from 1-2-3-4-1 to 1-2’-3’-4-1. Adsorption capacity decreases with the increase of adsorption temperature, which is not conducive to CO_2 capture. Fig. 4b reveals cycle characteristic of 4-step TSA cycle at different desorption temperatures. Original 4-step TSA cycle is plotted as 1-2-3-4-1. When desorption temperature decreases from 348 K to 358 K, TSA cycle will become 1’-2-3-4’-1’. It is difficult to make a preliminary assessment of cycle efficiency since both desorption capacity and desorption temperature increase.

3.2 Performance evaluation

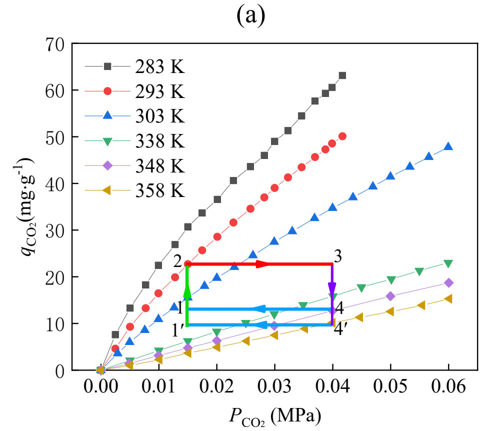
The minimum separation work (W_{min}) of carbon capture technologies is the lowest energy consumption could be given by equation 2.

$$\begin{aligned}W_{min}=RT[&n_2(y_{2,CO_2}\ln y_{2,CO_2}+y_{2,N_2}\ln y_{2,N_2})\\&+n_3(y_{3,CO_2}\ln y_{3,CO_2}+y_{3,N_2}\ln y_{3,N_2})\\&-n_1(y_{1,CO_2}\ln y_{1,CO_2}+y_{1,N_2}\ln y_{1,N_2})]\end{aligned} \tag{2}$$

where n_1, n_2, n_3 are mole numbers of the supplied gas, product gas and waste gas; y_1, y_2, y_3 are mole fractions of the mixture gas; R is universal gas constant, and T is temperature.



(a)



(b)

Fig. 4. Schematic diagram of TSA cycle integrated with heat pump cycle.

The minimum separation work (W_{min}) for CO_2 adsorption system could be calculated by Gibbs free energy equation as a state function which is independent of thermal process. According to carbon pump theory, W_{min} is only relevant with three parameters i.e. heat input temperature T_{in}, CO_2 fraction in the gas mixture y_{CO2} and CO_2 recovery Re_{CO2}, which could be defined as equation 3.

$$W_{\min} = G(T_{\text{in}}, y_{\text{CO}_2}, Re_{\text{CO}_2}) \tag{3}$$

Exergy efficiency is the ratio of the minimum separation work to the consumption of the actual work (W_r), which is defined as equation 4, referring to the reference [35].

$$\eta_{\text{ex}} = \frac{W_{\min}}{W_{\text{r}}} = \frac{W_{\min}}{W_{\min} + W_{\text{loss}}} = \frac{W_{\min}}{W_{\text{s}} + Q_{\text{H}}(1-\frac{T_0}{T_{\text{H}}}) - Q_{\text{L}}(1-\frac{T_0}{T_{\text{L}}})} \tag{4}$$

where W_s is input work, which is not considered in TSA process due to no extra power apparatus in this study. Q_H is heat input of high temperature heat source; Q_L is heat output of low temperature heat source; T_L is temperature of low temperature heat source, namely adsorption temperature. Similarly, T_H is the desorption temperature.

Refrigerant R410A is used for heat pump system since it is widely applied in large commercial buildings e.g. shopping mall, hospital, museum etc. Evaporating temperature is used from 10^oC to 15^oC, and condensation temperature is in the range of 50^oC to 70 ^oC. Isentropic efficiency in compression process of 0.85 is taken into consideration. Coefficient of Performance (COP) is given by equation 5.

$$COP = \frac{W}{Q} = \frac{h_2 - h_{1'}}{h_{1'} - h_4} \tag{5}$$

where h_2, $h_{1'}$ and h_4, $kJ \cdot kg^{-1}$, are enthalpy of point 2, 1' and 4, respectively in Fig. 3.

For carbon capture in coal-fired power plant, the propose integrated system using AC is evaluated and compared with that using MEA and polyethyleneimine (PEI) /Silica. Levelized cost of electricity (LCOE) is used to assess different system designs, which is widely used tool when comparing costs of different technologies during economic life as shown in equation 6.

$$LCOE = \frac{\sum(Investment_{\text{t}} + O\&M_{\text{t}} + Coal_{\text{t}} + Sorbent_{\text{t}} + D_{\text{t}}) \times (1+r)^{-\text{t}}}{\sum(Electricity_{\text{t}} \times (1+r)^{-\text{t}})} \tag{6}$$

where *Investment*$_t$ is the investment costs in year "t", *O&M*$_t$ is the operation and maintenance costs in year "t", *Coal*$_t$ is the coal cost in the year "t", *Sorbent*$_t$ is the costs of sorbent in year "t", D_t is the decommissioning cost in year "t" and is assumed to be 0, *Electricity* is the amount of electricity produced in year "t", $(1+r)^{-t}$ is considered as the discount factor for year "t".

To simplify techno-economic analysis of an 800MWe coal-fired power plant integrated with TSA process, several assumptions are taken into consideration referring to the references [2, 22]. On the basis of the equations mentioned above, technical analysis and comparison of three solar-assisted coal-fired power plant (SACFPPs) with different sorbents can be conducted, according to the relevant power plant information given in Table 2 [23].

Table 2. Parameters of basic coal-fired power plant.

Parameters	Value
Power plant capacity (MWe)	800
Auxiliary work (MWe)	42.13
Coal consumption ($kg \cdot s^{-1}$)	60.66
CO_2 emission ($kg \cdot s^{-1}$)	164.41
CO_2 concentration of flue gas (%mol)	14.98
Compression power (MWe)	49.87

4. RESULTS AND DISCUSSION

Theoretical performance of heat pump cycle and TSA cycle are first evaluated to present a general understanding for the potential integration. Fig. 5 shows COPs of heat pump cycle at different evaporation and condensation temperatures i.e. 10-20^oC and 50-70^oC, respectively. It is demonstrated that COPs of heat pump decreases with the increase of condensation temperature, which decrease thermal performances of refrigerants and economic effects. It is indicated that the highest COP of heat pump could reach 5.4 at 50^oC condensation temperature and 20^oC evaporation temperature which reveals more potential of this technology integrated with adsorption carbon capture. For different evaporation and condensation temperatures, *COP* of heat pump is in the range from 2.1 to 5.4 which indicates that performance of capture technologies is beneficial by using heat pump in most cases. Fig. 6 indicates exergy efficiency of 4-step TSA cycle under the condition of adsorption and desorption temperatures which is according to evaporation and condensation temperature based on thermodynamic perspective. Results show that when desorption temperature increases, exergy efficiency increases first then keep almost constant due to the increase of energy consumption. The highest exergy efficiency of 4-step TSA cycle is able to reach 0.16 which could be obtained at 70^oC desorption temperature and 10^oC adsorption temperature. For different adsorption and desorption temperatures, exergy efficiency of 4-step TSA cycle ranges from 0.05 to 0.16.

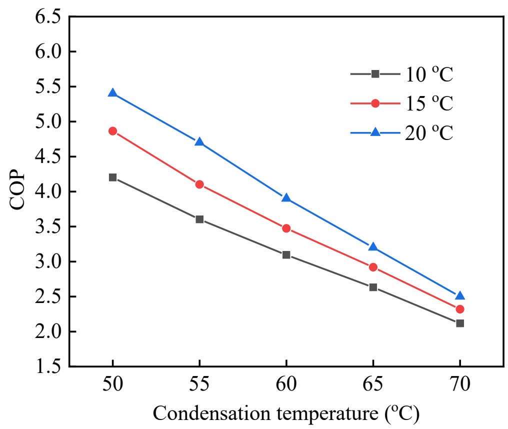


Fig. 5. COPs of heat pump cycle at different evaporation and condensation temperatures.

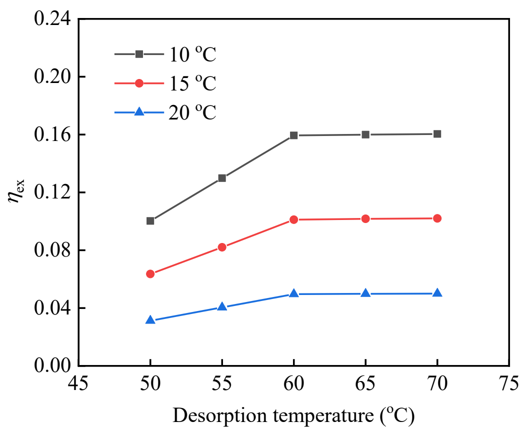


Fig. 6. Exergy efficiencies of 4-step TSA cycle in terms of desorption and adsorption temperatures.

The net efficiencies of coal-fired power plant with carbon capture technologies are presented in Fig. 7. Results indicates that the net efficiency of coal-fired power plant with carbon capture system using AC is 40.8% without considering electricity consumed by heat pump. If taking the electricity account, net efficiencies range from 35.1% to 35.4% when desorption temperature rises from 50°C to 70°C. Meanwhile, the result for carbon capture system using PEI/silica is 30.9% at 130°C. The improvement of the net efficiency of carbon capture system using AC can reach up to 12.2% when compared with that using commercial MEA. Fig. 8 illustrates LCOE at different desorption temperatures in the range of 50-70°C. It is clear that the LCOE increases with the increase of desorption temperatures. LCOE of coal-fired power plant using AC ranges from 50.5 USD·MWh^{-1} to 50.9 USD·MWh^{-1} which has a marginal increase at different desorption temperatures which is about 6% lower than that using MEA.

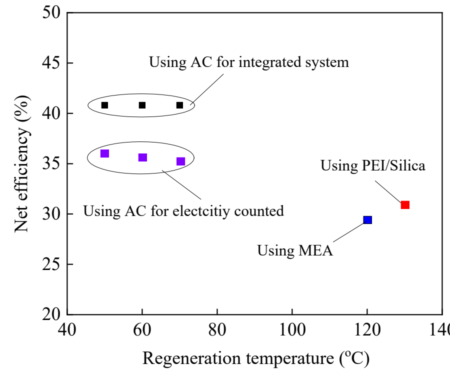


Fig. 7. Net efficiencies of coal-fired power plant by using various carbon capture technologies.

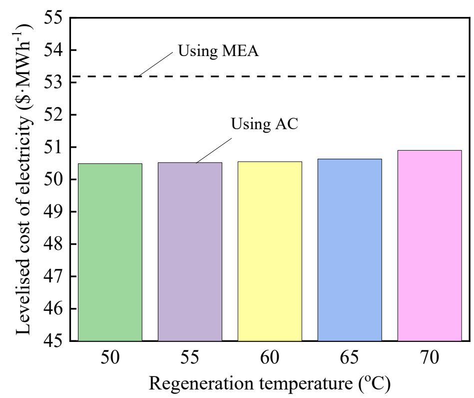


Fig. 8. LCOE of coal-fired power plant by using various carbon capture technologies.

5. CONCLUSION

An adsorption-based post-combustion CO_2 capture system using activated carbon is evaluated based on energy and economic analysis. Performance is compared with a commercial absorption-based system using monoethanolamine and an adsorption-based system using PEI/silica. Conclusions are drawn as follows:

[1] The highest COP of heat pump could reach 5.4 at 50°C condensation temperature and 20°C evaporation temperature which reveals potential of this technology integrated with adsorption carbon capture. For different evaporation and condensation temperatures, COP of heat pump ranges from 2.1 to 5.4 which indicates that performance of capture technologies is beneficial using heat pump in most cases. For different adsorption and desorption temperatures, exergy efficiency of TSA cycle ranges from 0.05 to 0.16.

[2] The net efficiency of coal-fired power plant with CCS system using AC is 40.8% without considering electricity consumed by heat pump. If taking the electricity account, net efficiencies range from 35.1%

to 35.4% when desorption temperature rises from 50 °C to 70 °C. The improvement of the net efficiency of the CCS system using AC can reach up to 12.2% when compared with that using commercial MEA. LCOE of coal-fired plant using AC ranges from 50.5 USD·MWh^{-1} to 50.9 USD·MWh^{-1} which has a marginal increase at different desorption temperatures which is about 6% lower than that using MEA.

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