1 Conceptual design of a novel pressure swing CO₂
2 adsorption process based on self-heat recuperation
3 technology

4

5 Chunfeng Song, Yasuki Kansha, Masanori Ishizuka, Qian Fu, Atsushi Tsutsumi*

6

7 Collaborative Research Center for Energy Engineering, Institute of Industrial Science,

8 The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan

9

10

11

12

13

14

15

16 *Corresponding author. Tel: +81-3-5452-6727. Fax: +81-3-5452-6728.

17 E-mail: a-tsu2mi@iis.u-tokyo.ac.jp.

18

19

20

21 Abstract

22 CO₂ capture and storage (CCS) technology has attracted attention for the mitigation
23 of CO₂ emissions. Among the dominant CO₂ capture technologies, pressure swing
24 adsorption (PSA) is a promising alternative to amine-based absorption. However, its
25 capture cost should be further decreased to facilitate its commercial implementation in
26 industry. In this study, a novel low-cost PSA CO₂ capture process based on self-heat
27 recuperation technology is discussed. An energy balance of the conventional process
28 and the proposed process is simulated and compared using a commercial process
29 simulator (PRO/II ver. 9.1, Invensys). In the proposed PSA process, the exothermic heat
30 of adsorption is recuperated using a reaction heat transformer (RHT) and is recirculated
31 for adsorbent regeneration. The waste residual gas pressure can also be recovered by an
32 expander at the top of an adsorption tower. The simulation results indicate that the
33 energy consumption of the proposed PSA process is 40% that of the conventional
34 process.

35

36 *Keywords:* CO₂ capture, pressure swing adsorption, self-heat recuperation, reaction heat
37 transformer

38

39

40

41

42

Nomenclature

H	Enthalpy, J
T	Temperature, °C
ΔT	Temperature difference, K
Q	Heat, J
W	Work, J
c_p	Heat capacity, J/K

Greek letters

v	Flow rate, kmol/hr
-----	--------------------

Abbreviations

CCS	CO ₂ capture and storage
GHG	Greenhouse gas
PSA	Pressure swing adsorption
SHR	Self-heat recuperation
RHT	Reaction heat transformer
$NGCC$	Natural gas combined cycle
PCC	Post-combustion capture

43

44 1. Introduction

45 Fossil fuels are a primary energy source worldwide. Upon their combustion, large
46 amounts of greenhouse gases (GHGs) are generated and emitted into the atmosphere
47 [1,2]. Climate change has become a critical issue and is of great concern. It is caused by
48 GHG emissions. A report from the Intergovernmental Panel on Climate Change (IPCC)
49 indicated that CO₂ makes up a high proportion of these gases because of its presence in
50 the atmosphere. It contributes to 70% of global warming effects among the GHGs [3].
51 Therefore, CO₂ capture and storage (CCS) from large point sources (i.e., fossil fuel fired
52 power plant, steel or iron factory, cement plant and petrochemicals industry) is
53 considered to be the most significant strategy to control the GHG effect and mitigate
54 climate change [4,5].

55 Three main CO₂ capture strategies are applicable to the combustion of fossil fuels,
56 namely post-combustion, pre-combustion and oxy-fuel combustion [6,7]. Among these,
57 post-combustion capture (PCC) is considered the most effective strategy because
58 retrofitting existing fossil fuel-based power plants can be done without much
59 modification [8,9]. To date, absorption, adsorption, membrane and cryogenic methods
60 are the dominant CO₂ capture technologies [10,11]. They have been widely investigated

61 for the capture of GHGs from industrial post-combustion stations [12-14]. Absorption is
62 the most mature technology and it is used commercially for scrubbing industrial
63 emissions [15,16]. However, the integration of CCS units (such as MEA absorption)
64 into a retrofitted coal-fired power plant for 90% CO₂ capture can reduce the thermal
65 efficiency from an approximate 35% HHV (high heating value) basis to 24% at a cost of
66 \$80 to capture a ton of CO₂ [17]. Meanwhile, regeneration of rich solvents requires
67 additional thermal (from 2.5 to 3.5 MJ/kg CO₂) of the solvent regeneration which 80%
68 of the total energy consumption [18-20].

69 Pressure swing adsorption (PSA) technology is a promising alternative to the
70 amine-based absorption process [21-23]. Compared to other CO₂ capture techniques,
71 adsorption process shows many potential advantages, such as reduced energy for
72 regeneration, greater capacity, selectivity and ease of handling [24,25]. The regeneration
73 energy requirement for CO₂ capture using solid sorbent is significantly reduced more
74 than that of the aqueous amine-based process, because of the absence of large amounts
75 of water. Moreover, the heat capacity of solid sorbent is comparatively lower than that
76 of an aqueous amine solvent [24]. However, the sorption or absorption reaction is an
77 exothermic reaction. Therefore there is heat release from the system. The generated heat
78 can adversely affect adsorption performance because of the increase in temperature [26].
79 Therefore, it is necessary to add a cooling unit to manage the temperature of the
80 adsorption column. Typically, exothermic heat is removed by cooling water [27]. On the
81 other hand, the regeneration of adsorbents (in a desorption column) is an endothermic

82 process, which requires the addition of heat. For the PSA process, this heat is usually
83 supplied by decompressing the pressure of the bed [28]. As a result, the net electrical
84 efficiency of a power plant would decrease by about 10% because of CO₂ capture unit
85 retrofitting [29].

86 To overcome the issue of high energy consumption and improve the net efficiency of
87 power plants, much effort has been put into optimizing the configuration of the CO₂
88 capture process. These include an inter-heated column, a split-stream, a bi-pressure
89 stripper, a multi-pressure stripper, a stripper with vapor recompression and an absorber
90 with inter-cooling [30-33]. Recently, self-heat recuperation has been suggested as a
91 significant alternative to recover waste heat from chemical processes [34,35]. Using
92 self-heat recuperation technology, the waste heat generated in thermal processes can be
93 recovered by compression. All the latent and sensible heat is recycled in the process by
94 well heat pairing.

95 In this study, a novel low-energy consumption PSA CO₂ capture process was
96 exploited. To achieve the energy-saving aim, self-heat recuperation technology was
97 retrofitted to the PSA process to recover the adsorption heat to regenerate the adsorbent.
98 To evaluate the energy consumption, a detailed energy balance of the conventional and
99 proposed PSA process was initially investigated. The total capture performance of the
100 PSA process with and without the SHR was evaluated by simulation.

101 2. Process description

102 2.1 Conventional PSA CO₂ capture process

103 A typical pressure swing CO₂ adsorption (PSA) process is illustrated in Fig. 1, and a
104 detailed flow diagram of the conventional PSA process is shown in Fig. 2. The flue gas
105 from a typical coal-fired power plant is first compressed (S1→S2) and then sent to an
106 adsorption column (R-1). Under high-pressure conditions, the CO₂ in the gas stream is
107 captured by the adsorbent (S8) and other gases are expelled from the top of the
108 adsorption tower (S7). The energy flow in the adsorption step mainly consists of
109 compression work and exothermic heat. After sufficient adsorption, the pressure in the
110 column (R-2) is dramatically decreased (S8→S9) to separate CO₂ and regenerate the
111 adsorbent. When the captured CO₂ (S12) is thoroughly retrieved from the outlet of the
112 desorption tower (R-2), the regenerated adsorbent (S13) is reused to capture CO₂ from
113 the following feed stream. During the desorption stage, the energy input comes from the
114 evacuation process during regeneration. It should be pointed out that the reactors (R-1,
115 2) of the adsorption/desorption process are defined as fixed duty (set to 0 MJ). An
116 additional cooler and heater after R-1 and 2 was assumed in the simulation process to
117 determine the exothermic and endothermic heat, respectively. The aim of this
118 assumption is to allow a meaningful comparison between the conventional process and
119 the proposed PSA process.

120 2.2 Proposed PSA CO₂ capture process

121 The proposed PSA CO₂ capture process is based on self-heat recuperation technology
122 and is illustrated in Fig. 3. The waste heat generated in the capture process is recovered,
123 which is different to the conventional process. To circulate the adsorption heat, a
124 reaction heat transformer (RHT) was used to circulate the exothermic heat (S16→S17)
125 generated in the adsorption stage (S5→S6). Furthermore, the recovered heat was reused
126 for sorbent regeneration (S18→S19) in the desorption stage (S9→S10). Additionally,
127 the waste heat of the exhaust gas (S7) was recovered by heat exchange (HX-1). An
128 expander was then added to recover the waste pressure (S14→S15) associated with the
129 residual gas (such as N₂).

130 Detailed working principles of the RHT are illustrated in Fig. 4. A working fluid is
131 used to withdraw exothermic heat from the adsorber via heat exchange (HX-2). Pentane
132 was selected as the working fluid in this work. The working fluid is at low temperature
133 and pressure in the liquid phase (state A, S16), and has a vaporization temperature in the
134 required range when receiving heat (S5→S6) from the adsorber (R-1). A phase change
135 in the working fluid from liquid to vapor (S16→S17) thus occurs and the heat from the
136 adsorber is recovered by the working fluid. A heated, vaporized, low-pressure working
137 fluid is thus obtained after this heat exchange (HX-2) with the adsorber (state B, S17).
138 The working fluid is continually compressed (Comp.2) and is thus further heated. A
139 high exergy rate stream (state C, S18) is then introduced to heat exchanger 3 (HX-3) in
140 the desorption column (R-2). Because of the endothermic heat reaction of adsorbent
141 regeneration, the heat stored in the working fluid is released and absorbed by the rich

142 adsorbent. With sufficient heat exchange, a high-purity CO₂ product (S12) and a
 143 regenerated adsorbent (S13) are obtained at different positions in the column. The
 144 working fluid after heat exchange is still in the gas phase at low temperature and under
 145 high pressure (state D, S19). Here, a decompression valve is used to close the cycle, and
 146 a low-temperature liquefied working fluid is regenerated (state A, S16). The refreshed
 147 working fluid is sent to the adsorber again and reused to recover the exothermic heat
 148 expelled from the adsorption reaction.

149 3. Theoretical analysis

150 Fig. 5 shows the temperature-heat (T-Q) diagram of the conventional PSA CO₂
 151 capture process. The total input energy of the process mainly consists of compression
 152 and decompression (vacuum) work. It is worth noting that the heat of the exothermic
 153 adsorption is wasted without recovery in the conventional PSA process. Therefore, the
 154 total energy of consumption can be calculated by the following equation:

$$155 \quad W_{input, con} = W_{com, 1} + W_{decom} \quad (1)$$

156 where $W_{input, con}$ is the total input energy of the conventional PSA process. $W_{com, 1}$ and
 157 W_{decom} are the work of compression and decompression, respectively.

158 To achieve significant heat circulation and energy saving, self-heat recuperation
 159 technology was used to recover the reaction heat during the proposed process. Fig. 6

160 shows the T-Q diagram of the proposed PSA CO₂ capture process. As shown in the
161 figure, RHT was used to recirculate the exothermic heat from the adsorption to the
162 desorption stage. The waste pressure of the residual gas was recovered by an expander.
163 Therefore, the total input energy of the proposed process can be calculated as follows:

$$164 \quad W_{input, pro} = W_{com, 1} + W_{com, 2} - W_{ex} \quad (2)$$

165 where $W_{input, pro}$ is the total energy consumption of the proposed PSA CO₂ capture
166 process, $W_{com, 2}$ is the compression work of the RHT and W_{ex} is the energy recovered by
167 the expander.

168 A detailed description of self-heat recuperation technology and its application to
169 chemical engineering processes can be found in Kansha et al., 2009 [34]. A detailed
170 calculation of the energy requirements of a typical thermal process with and without the
171 SHR is summarized in Table 1.

172 4. Simulation

173 Several commercial software can be used in chemical engineering processes, such as,
174 Pro/II, Aspen plus and hysis. In this study, the overall capture performance of the
175 proposed PSA process was simulated using PRO/II ver. 9.1 (Invensys). PRO/II process
176 simulation software is a steady-state simulator enabling improved process design and
177 operational analysis. The advantages of PRO/II can be summarized as following: 1)

178 rigorously evaluate heat and material balance calculations for a wide range of chemical
179 engineering processes. 2) Effectively improve plant yields through the optimization of
180 existing plant processes. 3) Accurately assess and optimize capital and operational cost
181 of existing processes. 6) Offer a wide variety of thermodynamics and physical property
182 data applicable to chemical industries.

183 The feed gas composition and other conditions were simulated based on a typical
184 600-MW coal-fired power plant and the results are summarized in Table 2. To simplify
185 the calculation, the following assumptions were made: 1) the thermodynamic
186 calculation was performed based on the Soave-Redlich-Kwong (SRK) equation, 2) the
187 adiabatic efficiency of the compressor and the expander were both set to 85%, 3) the
188 heat loss over the whole capture process was neglected, 4) no mass transport resistance
189 in all phases and no pressure drop during heat exchange in each heat exchanger, 5) the
190 minimum approach temperature in all the heat exchangers was set to 10 K, and 6) the
191 type of reactors for the adsorption/desorption reaction was defined as conversion. After
192 defining the properties of units (i.e. reactor, compressor, flasher etc.) and their operating
193 conditions, the information of feed gas (as shown in Table 2) is input. Then, energy
194 consumption of each units, CO₂ purity and recovery for the total adsorption process can
195 be precisely calculated by PRO/II.

196 5. Results and discussion

197 5.1 Conventional PSA process

198 Simulation results for the conventional PSA CO₂ capture process are summarized in
199 Fig. 7. The flue gas was first compressed to 404 kPa by a compressor (S1→S2). The
200 temperature of the feed stream increased from 40 °C to 240 °C. To capture CO₂ at the
201 desired temperature, cooling water was used to decrease the temperature of the stream
202 to 40 °C (S2→S3). The high-pressure feed gas was then introduced to the adsorption
203 column (R-1). It is worth noting that the amount of heat (98.4 MW) generated
204 associated with the adsorption process and was wasted by water cooling (S5→S6). On
205 the other hand, additional heat (98.4 MW) was introduced into the desorption stage to
206 regenerate the rich adsorbent (S10→S11). After the CO₂ front breaks through the
207 packed bed, the pressure in the column decreased to 10 kPa (S8→S9) and the captured
208 CO₂ was thus separated from the adsorbent. Because the regeneration of the adsorbent is
209 an endothermic reaction, additional heat is required to retain a constant temperature
210 during the initial and end states (40 °C).

211 To accurately analyze the energy requirement, the T-Q diagram of each unit in the
212 conventional PSA process was compiled and illustrated in Fig. 8. The total energy
213 consumption units consist of: compression (96.9 MW), cooling (12.9 MJ), adsorption
214 (98.4 MW), vacuum (39.4 MW) and desorption (98.4 MW). The total input energy of
215 the process is distributed between the compression (96.9 MW) and decompression (39.4
216 MW). Therefore, the sum of the energy consumption is 136.2 MW (which equals 340.5

217 MJ) to capture CO₂ from a typical flue gas (600 kg/s).

218 It can be observed that in the conventional PSA CO₂ capture process, the utilization
219 of waste heat and is not optimal and should be further improved. First, the adsorption
220 heat (98.4 MW) is abandoned without any recovery due to lower temperature and
221 exergy rate compared with that in desorption column (which is endothermic reaction).
222 Second, the sensible heat (12.9 MW) after compression treatment is wasted by cooling
223 water. Meanwhile, the compression work is also substantial, which is wasted with the
224 residual gas stream at the top of adsorption column. As a result, the energy consumption
225 of the conventional PSA process is 2.99 MJ/kg CO₂, which is energy intensive.

226 *5.2 Proposed PSA process*

227 Fig. 9 shows simulation results for the proposed process. The flue gas was
228 compressed to 404 kPa (S1→S2) and this was the same as that of the conventional
229 process for a meaningful comparison. The compression work of the compressor (Com.1)
230 was 96.9 MW. Unlike the conventional process, the temperature of the feed stream after
231 compression decreased because of the heat exchanger (HX-1). This heat exchanger
232 consisted of a heat transformer (HT-1) and a heat receiver (HR-1). Therefore, the
233 compression heat (around 12.9 MW) is effectively reused in this process. The
234 exothermic heat generated during the adsorption stage (R-1) was recovered by HX-2
235 and transferred to HX-3 to regenerate the sorbent. To separate the captured CO₂ from

the adsorbent, the pressure of the bed was decreased to 101 kPa (S8→S9). Furthermore, the reaction heat recovered from the adsorption stage is released in the desorption column (R-2). High-purity (99.9%) CO₂ product is collected at the outlet of the column (S12) and the regenerated adsorbent (S13) is reused for the following capture cycle. From these results, the reaction heat of the adsorption stage was effectively recovered (exothermic heat of 98.4 MW) and reused in the desorption process by the reaction heat transformer (RHT). The pressure of the residual gas was recuperated by an expander at the outlet of the adsorber (51.6 MW).

Fig. 10 shows a T-Q diagram of the proposed PSA process based on self-heat recuperation technology. The total energy consumption units are as follows: compression, adsorption, decompression, RHT and desorption. The compression heat (12.9 MW) was recovered by a heat exchanger (HX-1) using the residual gas (S7→S14) in the proposed process. The waste pressure (51.6 MW) was also recovered by an expander. Therefore, the hot and cold curves were almost completely parallel and they showed good heat pairing with regard to the sensible heat. The exothermic heat along with adsorption (98.4 MW) was recuperated by the RHT and reused in the desorption stage (S9→S10). The energy consumption of the RHT was 13.1 MW.

It should be noted that in proposed PSA CO₂ capture process, the exothermic heat generated in adsorber is effectively recovered, and used as endothermic heat for sorbent regeneration. Because the temperature and exergy rate of the working fluid is increased

256 by RHT. On the other hand, the part of compression work is also recovered as gained
257 expander work at the exit of adsorption column. Hence, higher energy efficiency could
258 be achieved in the proposed PSA CO₂ capture process. As a result, the exergy loss in the
259 proposed PSA process could be minimized to 1.18 MJ/kg CO₂, leading to a significant
260 reduction in the energy penalty.

261 *5.3 Comparison*

262 To estimate the performance of the proposed process, a brief comparison with the
263 conventional approach was undertaken. Fig. 11 shows the overall required and
264 recovered energy of the conventional process and the proposed PSA CO₂ capture
265 process. The total input energy of the conventional process is 136.2 MW and this is
266 mainly composed of compression work (96.9 MW) and decompression work (39.4
267 MW). It should be noted that around 98.4 MW heat is generated because of the
268 exothermic reaction in the adsorption stage, which is wasted by the cooling water. By
269 contrast, the exothermic heat (approximately 98.4 MW) of the adsorption column is
270 effectively recovered by self-heat recuperation technology in the proposed PSA process.
271 Additionally, the waste pressure associated with the residual gas from the top of the
272 adsorption tower is recovered by an expander and around 51.6 MW electricity can
273 therefore be saved. As a result, 13.1 MW net input work is necessary for the RHT to
274 recycle the adsorption heat to the regeneration column. Therefore, the net input energy
275 of the proposed process is reduced to 58.5 MW and around 60% of the input energy can

276 be saved compared with the conventional PSA process.

277 The energy consumption of the conventional and proposed PSA processes was also
278 investigated under different CO₂ concentrations (from 5% to 40%). As shown in Fig. 12,
279 the energy consumption of the proposed process was effectively reduced compared with
280 the conventional method. For the dilute CO₂ emissions (5% CO₂), the energy
281 consumption of the proposed process decreased from 6.8 MJ/kg CO₂ to 2.8 MJ/kg CO₂.
282 With an increase in CO₂ concentration, the energy consumption gradually decreased.
283 When the CO₂ concentration was increased to 40%, the energy consumption decreased
284 from 1.9 MJ/kg CO₂ to 0.8 MJ/kg CO₂. For a typical coal-fired power plant (15% CO₂)
285 the energy requirement of the proposed PSA process is 1.18 MJ/kg CO₂, which is 40%
286 that of the conventional process.

287 6. Conclusion

288 In this study, a novel PSA CO₂ adsorption process based on self-heat recuperation
289 technology was designed. The energy and material balance of the conventional process
290 and the proposed PSA CO₂ capture process were simulated. Compared with the
291 conventional PSA CO₂ adsorption process, the adsorption heat (98.4 MW) and waste
292 pressure (51.6 MW) of the residual gas were recovered. This indicates that a significant
293 reduction in energy consumption can be achieved. From the simulation results, around
294 60% of the input energy can be saved in the proposed CO₂ capture process. The energy

295 penalty of the proposed PSA CO₂ capture process is reduced to 1.18 MJ/kg CO₂.

296 For the future work, a detail technical-economic analysis of the novel PSA CO₂
297 capture process will be carried out. In addition, the detail configuration of heat
298 recirculation between exothermic and endothermic heat is a key technical challenge. To
299 exchange the heat, the reactor may have the medium fluid flowing in a jacket at the wall.
300 However, this is not the final configuration, the extension studies on energy requirement
301 topic are still needed.

302 Acknowledgments

303 This research was supported by the Advanced Low Carbon Technology Research and
304 Development Program of the Japan Science and Technology Agency (JST).

305 References

- 306 [1] C.M. White, D.H. Smith, K.L. Jones, A.L. Goodman, S.A. Jikich, R.B. LaCount, S.B. DuBose,
307 E. Ozdemir, B.I. Morsi, K.T. Schroeder, Sequestration of Carbon Dioxide in Coal with
308 Enhanced Coalbed Methane Recovery—A Review, *Energy Fuels* 19 (3) (2005) 659–724.
- 309 [2] I. von Harbou, S. Hoch, H. P. Mangalapally, R. Notz, G. Sieder, H. Garcia, O. Spuhl, H. Hasse,
310 Removal of carbon dioxide from flue gases with aqueous MEA solution containing ethanol,
311 *Chem. Eng. Process.* 75 (2014) 81–89.
- 312 [3] B. Metz, O. Davidson, H. de Coninck, M. Loos, L. Meyer. IPCC Special Report on Carbon
313 Dioxide Capture and Storage. Intergovernmental Panel on Climate Change. Cambridge

314 University Press. 2005.

315 [4] J.D. Figueroa, T. Fout, S. Plasynski, H. McIlvried, R.D. Srivastava, Advances in CO₂ capture
 316 technology-the U.S. department of energy's carbon sequestration program, Int. J. Greenhouse
 317 Gas Control 2 (1) (2008) 9–20.

318 [5] C. Song, Y. Kitamura, S. Li, Energy analysis of the cryogenic CO₂ capture process based on
 319 Stirling coolers, Energy 65 (2014) 580–589.

320 [6] E.S. Rubin, H. Mantripragada, A. Marks, P. Versteeg, J. Kitchin, The outlook for improved
 321 carbon capture technology, Prog. Energ. Combust. Sci. 38 (2012) 630–671.

322 [7] J. Koornneef, A. Ramírez, W. Turkenburg, A. Faaij, The environmental impact and risk
 323 assessment of CO₂ capture, transport and storage – An evaluation of the knowledge base, Prog.
 324 Energ. Combust. Sci. 38 (2012) 62–86.

325 [8] Z.H. Lee, K.T. Lee, S. Bhatia, A.R. Mohamed, Post-combustion carbon dioxide capture:
 326 Evolution towards utilization of nanomaterials, Renew. Sust. Energ. Rev. 16 (2012) 2599–2609.

327 [9] K. Dietl, A. Joos, G. Schmitz, Dynamic analysis of the absorption/desorption loop of a carbon
 328 capture plant using an object-oriented approach, Chem. Eng. Process. 52 (2012) 132–139.

329 [10] H.A. Rodriguez-Flores, L.C. Mello, W.M. Salvagnini, J.L. de Paiva, Absorption of CO₂ into
 330 aqueous solutions of MEA and AMP in a wetted wall column with film promoter, Chem. Eng.
 331 Process. 73 (2013) 1–6.

332 [11] S. Yan, Q. He, S. Zhao, Y. Wang, P. Ai, Biogas upgrading by CO₂ removal with a highly
 333 selective natural amino acid salt in gas–liquid membrane contactor, Chem. Eng. Process. 85
 334 (2014) 125–135.

- 335 [12] A.A. Olajire, CO₂ capture and separation technologies for end-of-pipe applications – A review,
336 Energy 35 (2010) 2610–2628.
- 337 [13] C.F. Song, Y. Kitamura, S.H. Li, W.Z. Jiang, Parametric analysis of a novel cryogenic CO₂
338 capture system based on Stirling coolers, Environ. Sci. Technol. 46 (2012) 12735–12741.
- 339 [14] H.M. Kvamsdal, J.P. Jakobsen, K.A. Hoff, Dynamic modeling and simulation of a CO₂
340 absorber column for post-combustion CO₂ capture, Chem. Eng. Process. 48 (2009) 135–144.
- 341 [15] M. Wang, A. Lawal, P. Stephenson, J. Sidders, C. Ramshaw, Post-combustion CO₂ capture with
342 chemical absorption: A state-of-the-art review, Chem. Eng. Res. Des. 89 (2011) 1609–1624.
- 343 [16] C. Song, Y. Kitamura, S. Li, J. Lu, Deposition CO₂ Capture Process Using a Free Piston Stirling
344 Cooler, Ind. Eng. Chem. Res. 52 (42) (2013) 14936–14943.
- 345 [17] M. Ramezan, T.J. Skone, N. Nsakala, G.N. Liljedahl, Carbon dioxide capture from existing
346 coal-fired power plants. Final Report DOE/NETL-401/110907, December; 2007.
- 347 [18] C.M. White, B.R. Strazisar, E.J. Granite, J.S. Hoffman, Separation and capture of CO₂ from
348 large stationary sources and sequestration in geologic formations-coal beds and deep saline
349 aquifers, J. Air Waste Manag. Assoc. 53 (6) (2003) 45–715.
- 350 [19] A. Widodo, Y. Sujatnika, D. Awali, T. Prakoso, T.P. Adhi, T.H. Soerawidjaja, A. Indarto,
351 Thermal heat-free regeneration process using antisolvent for amine recovery, Chem. Eng.
352 Process. 89 (2015) 75–79.
- 353 [20] S. Yan, Q. He, P. Ai, Y. Wang, Y. Zhang, Regeneration performance of concentrated CO₂-rich
354 alkanolamine solvents: The first step study of a novel concept for reducing regeneration heat
355 consumption by using concentration swing absorption technology, Chem. Eng. Process. 70

356 (2013) 86– 94.

357 [21] Q. Wang, J. Luo, Z. Zhong, A. Borgna, CO₂ capture by solid adsorbents and their applications:
 358 current status and new trends, *Energy Environ. Sci.* 4 (2011) 42–55.

359 [22] N. Hedin, L. Andersson, L. Bergström, J. Yan, Adsorbents for the post-combustion capture of
 360 CO₂ using rapid temperature swing or vacuum swing adsorption, *Appl. Energy* 104 (2013)
 361 418–433.

362 [23] M.T. Ho, G.W. Allinson, D.E. Wiley, Reducing the Cost of CO₂ Capture from Flue Gases Using
 363 Pressure Swing Adsorption, *Ind. Eng. Chem. Res.* 47 (2008) 4883–4890.

364 [24] A. Samanta, A. Zhao, G.K.H. Shimizu, P. Sarkar, R. Gupta, Post-Combustion CO₂ Capture
 365 Using Solid Sorbents: A Review, *Ind. Eng. Chem. Res.* 51 (2012) 1438–1463.

366 [25] M. Yavary, H.A. Ebrahim, C. Falamaki, The effect of number of pressure equalization steps on
 367 the performance of pressure swing adsorption process, *Chem. Eng. Process.* 87 (2015) 35–44.

368 [26] B. Chalermisinsuwan, P. Piumsomboon, D. Gidaspow, A computational fluid dynamics design
 369 of a carbon dioxide sorption circulating fluidized bed, *AIChE. Journal* 56 (2010) 2805–2824.

370 [27] A. Jamal, R.P. Gupta, 2012, Heat recovery from sorbent-based CO₂ capture, US Patent US
 371 2014/0005460 A1.

372 [28] P. Chaiwang, D. Gidaspow, B. Chalermisinsuwan, P. Piumsomboon, CFD design of a sorber for
 373 CO₂ capture with 75 and 375 micron particles, *Chem. Eng. Sci.* 105 (2014) 32–45.

374 [29] C. Reddick, M. Sorin, F. Rheault, Energy savings in CO₂ (carbon dioxide) capture using
 375 ejectors for waste heat upgrading, *Energy* 65 (2014) 200–208.

376 [30] B.A. Oyekan, G.T. Rochelle, Alternative stripper configurations for CO₂ capture by aqueous

amines, *AIChE J.* 53 (2007) 3144–3154.

[31] L.M. Romeo, I. Bolea, Y. Lara, J.M. Escosa, Optimization of intercooling compression in CO₂ capture systems, *Appl. Therm. Eng.* 29 (2009) 1744–1751.

[32] H.W. Liang, Z.G. Xu, F.Q. Si, Economic analysis of amine based carbon dioxide capture system with bi-pressure stripper in supercritical coal-fired power plant, *Int. J. Greenhouse Gas Control* 5 (2011) 702–709.

[33] D.H. Van Wagener, G.T. Rochelle, Stripper configurations for CO₂ capture by aqueous monoethanolamine, *Chem. Eng. Res. Des.* 89 (2011) 1639–1646.

[34] Y. Kansha, N. Tsuru, K. Sato, C. Fushimi, A. Tsutsumi, Self-Heat Recuperation Technology for Energy Saving in Chemical Processes, *Ind. Eng. Chem. Res.* 48 (16) (2009) 7682–7686.

[35] M. Aziz, Y. Kansha, A. Tsutsumi, Self-heat recuperative fluidized bed drying of brown coal, *Chem. Eng. Process.* 50 (2011) 944–951.

[36] Y. Kansha, Y. Kotani, M. Aziz, A. Kishimoto, A. Tsutsumi, Evaluation of a Self-Heat Recuperative Thermal Process Based on Thermodynamic Irreversibility and Exergy, *J. Chem. Eng. Japan*, 46 (1) (2013) 87–91.

[37] Y. Liu, M. Aziz, C. Fushimi, Y. Kansha, K. Mochidzuki, S. Kaneko, A. Tsutsumi, K. Yokohama, K. Myoyo, K. Oura, K. Matsuo, S. Sawa, K. Shinoda, Exergy Analysis of Biomass Drying Based on Self-Heat Recuperation Technology and Its Application to Industry: a Simulation and Experimental Study, *Ind. Eng. Chem. Res.* 51 (2012) 9997–10007.

[38] M. Aziz, T. Oda, T. Kashiwagi, Enhanced high energy efficient steam drying of algae, *Appl. Energy* 109 (2013) 163–170.

Table 1

Energy requirements of the thermal process with and without SHR technology.

1) The energy requirement of the thermal process without SHR technology [34]:

$$Q_{non-SHR} = v \cdot c_p \cdot \Delta T_{\min}$$

where $Q_{non-SHR}$ is the total energy requirement of the conventional thermal process without SHR, v is the flow rate of the feed stream, c_p is the heat capacity and $\Delta T_{\min}$ is the minimum temperature difference in the thermal process.

2) The energy requirement of the thermal process with SHR technology [36]:

$$W_{SHR} = v \cdot c_p \cdot \left\{ 1 - \frac{T_0 + \Delta T_{\min}}{T_1 + \Delta T_{\min}} \right\}$$

where W_{SHR} is the total input energy of the SHR-based thermal process. T_0 and T_1 are the standard and inlet temperatures.

3) The energy requirement of the SHR thermal process (gas stream) [37]:

$$W_{net} = W_{com} - W_{ex}$$

where W_{com} and W_{ex} represent the shaft work of the compressor and the expander, respectively.

4) The energy requirement of the SHR thermal process (vapor/liquid streams) [38]:

$$W_{net} = W_{com}$$

$$W_{com} = H_{out} - H_{in}$$

where H_{in} and H_{out} are the enthalpy of stream in the adiabatic irreversible process.

Table 2

Simulation conditions for the conventional and proposed PSA processes.

Parameters	Value
Flow rate	600 kg/s
Feed temperature	40 °C ^b
Feed pressure	101 kPa
Compressed pressure	404 kPa
Feed gas composition ^a	
CO ₂	15 wt. %
N ₂	85 wt. %
CO ₂ recovery	95%
CO ₂ purity	99.9%

^a The composition of the feed gas was typical of a 500-MW coal-fired power plant.

^b The introduced feed gas was assumed after removing the SO_x and NO_x units.

Figure captions

Fig. 1. Schematic diagram of a typical PSA process.

Fig. 2. Flow diagram of a conventional PSA CO₂ capture process.

Fig. 3. Flow diagram of the proposed PSA CO₂ capture process.

Fig. 4. Working principle of the reaction heat transformer (RHT).

Fig. 5. T-Q diagram of the conventional PSA CO₂ capture process.

Fig. 6. T-Q diagram of the proposed PSA CO₂ capture process.

Fig. 7. Simulation results for the conventional PSA process.

Fig. 8. T-Q diagram of the conventional PSA process based on the simulation results.

Fig. 9. Simulation results for the proposed PSA process.

Fig. 10. T-Q diagram of the proposed PSA process based on the simulation results.

Fig. 11. Energy requirements of the conventional and proposed PSA processes.

Fig. 12. Comparison of the energy consumption between the conventional process and the proposed PSA process under different CO₂ concentrations.

Fig. 1. Schematic diagram of a typical PSA process.

Fig. 2. Flow diagram of a conventional PSA CO_2 capture process.

Fig. 5. T-Q diagram of the conventional PSA CO₂ capture process.

Fig. 6. T-Q diagram of the proposed PSA CO₂ capture process.

Fig. 7. Simulation results for the conventional PSA process.

Fig. 8. T-Q diagram of the conventional PSA process based on the simulation results.

Fig. 9. Simulation results for the proposed PSA process.

Fig. 10. T-Q diagram of the proposed PSA process based on the simulation results.

Fig. 11. Energy requirements of the conventional and proposed PSA processes.

Fig. 12. Comparison of the energy consumption between the conventional process and the proposed PSA process under different CO₂ concentrations.

Advanced PSA CO₂ capture process

Graphic abstract