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Technologies and Materials for Carbon Dioxide Capture

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Abstract (10pt italic)

This paper was aims to review the technologies and materials for CO2 capture. Carbon dioxide is one of the triggers for the greenhouse effect and global warming. Some methods to reduce CO2 are separation technologies include air capture, CO2 Capture Utilization and Storage (CCUS) and CO2 Capture and Storage (CCS) technology. CCS technology have several systems namely post-combution, pre-combustion and oxy-fuel combustion. Post-combution systems can be done in various systems including absorption, adsorption, membrane, and cryogenic. Adsorption proses for CO2 capture applied with porous material such us mesopore silica, zeolite, carbon, MOF dan COF. This review was described the advantages and disadvantages of each technology for CO2 capture. Materials for CO2 adsorption also descibed in this review.

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PENDAHULUAN (INTRODUCTION)

Carbon dioxide is one of the triggers for the greenhouse effect and global warming. The concentration of CO_2 gas in the atmosphere in 2014 reached 400 ppm, the amount of which was much greater during the pre-industrialization era (Oh, 2010). Increasing the concentration of CO_2 continuously in the atmosphere will limit the ability of plants and seas to absorb CO_2 gas, so that carbon dioxide gas will be trapped in the earth's atmosphere and cause global warming which is characterized by rising earth temperatures, shifting climate, and rising sea levels (Li, J.-R.dkk., 2011: Yang, H. dkk., 2008). These problems must be addressed immediately so that global warming can be reduced.

Some methods to reduce CO_2 gas problems are separation technologies include air capture, CCUS (CO_2 Capture Utilization and Storage), and CCS (Carbondioxide Capture and Storage) technology. Technology with several systems, namely post-combution, pre-combustion and oxy-combustion (Figueroa, 2008). Post-combution systems can be done in various ways including absorption, adsorption, membrane, and cryogenic.

Description of the operation and explanation of some of these technologies will be discussed in this paper. The advantages and disadvantages of each technology will also increase the efficiency of technology that is promising for the future. The objectives of this paper is to review the technologies and materials for CO_2 capture.

METODE (METHODS)

Carbon Dioxide Separation Methods

The problem of carbon dioxide can be overcome through carbon dioxide gas separation technology as shown in Table 1.

Tabel 1. Gas Separation Technologies

Tecnology	Explanation	Reference
Air Capture	- Capture CO_2 gas up to 52% - The use of amines as gas binders is considered unsafe	Kintisch, E., (2014). *Can Sucking CO_2 Out of the Atmosphere Really Work*, Columbia: MIT Technology Review.
CCUS (*CO_2 Capture Utilization and Storage*)	- Inject CO_2 on the inside of an underground adsorbent - Dangerous when the gas pipe leaks causing contamination of ground water - Affects drinking water TDS	Bielicki, J. M. dkk., (2014). Causes and financial consequences of geologic CO2 storage reservoir leakage and interference with other subsurface resources. *International Journal of Greenhouse Gas Control*, 20. 272-284.
CCS (*CO_2 Capture and Storage*)	- Separation of combustion CO_2 gas - Derivative systems: pre-combustion, post combustion and oxy fuel combustion.	Bennaucer, K., Gielen, D., Kerr, T. & Tam, C., (2008). CO2 Capture and Storage. *International Energy Agency*, p. 15.

Based on Table 1, CCS technology was chosen and reviewed for carbon dioxide gas separation because this technology has low risk of danger and cost. The three systems derived from CCS technology are pre-combustion, post combustion and oxy fuel combustion was described in Table 2.

In pre-combustion capture, carbon and carbon dioxide in fossil fuels are separated before combustion. This fuel source is chemically converted into a stream of two gases, carbon dioxide and CO_2. The process of Pre-combustion Capture[9] is shown in Figure 1.

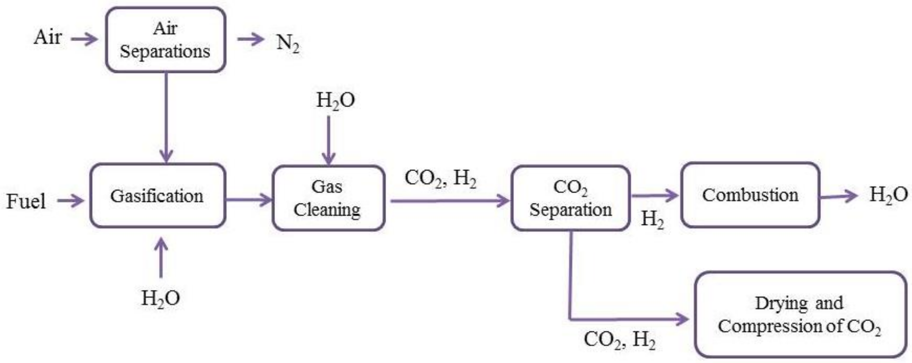

Figure 1. Flow chart of Pre-combustion Capture process

Tabel 2. CO_2 Gas Separation Technologies

Technology of CO_2 Sorption	Advantages	Disadvantages	Reference
pre-combustion	Produces synthetic gas (syngas) rich in hydrogen.	Synthetic gases (syngas) produced can cause corrosion.	Li, J.-R.dkk., (2011). Carbon dioxide capture-

Technology of CO_2 Sorption	Advantages	Disadvantages	Reference
	Capable of capturing almost 91.6% of CO_2 emissions.	The process is more complicated and the cost to build a system is very expensive.	related gas adsorption and separation in metal-organic frameworks. *Coordination Chemistry Reviews*, 255. 1791-1823.
oxy fuel combustion	The CO_2 separation process is easier because it uses methods such as absorption, membrane, cryogenic and adsorption. Cheaper operating costs	Requires quite high energy when using cryogenic and membrane methods	Miller, B.G., (2011) CO2 Capture dan Storage, In *Clean Coal Engineering Technology*, Butterworth-Heinemann, Boston, 483–511
post combustion	The results of the exhaust gas in the form of CO_2 and water (H_2O) so no CO_2 separation process is needed. Capable of capturing 92.6% CO_2 emissions.	Requires very high costs during the initial air separation process. Requires up to 98% pure oxygen so the operating costs are very high.	Figueroa J. D., Fout T., Plasynski S., Mc. Ilvried H. dan Srivastava R. D., (2008), Advances in CO2 capture technology, The U.S. Department of Energy's Carbon Sequestration Program, *International Journal of Greenhouse Gas Control*, 2l. 9–20

In Oxy-fuel Combustion is simpler than pre-combustion capture because the oxidation process uses oxygen so it only produces CO_2 and H_2O. Because the fuel used in the combustion process only produces CO_2 and H_2O, there is no need to separate the exhaust gas anymore, so that the CO_2 gas produced from this process can be directly captured. The process of Oxy-fuel Combustion[9] is shown in Figure 2.

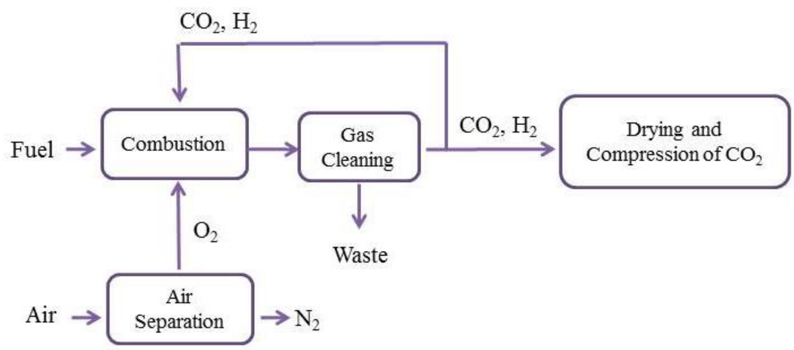

Figure 2. Flow chart of Oxy-fuel Combustion process

The last process is the post-combustion capture process. In this process, separating CO_2 is easier because it uses methods such as adsorption, membrane, cryogenic, and adsorption. The process of Post-combustion Capture (Miller, 2011) is shown in Figure 3.

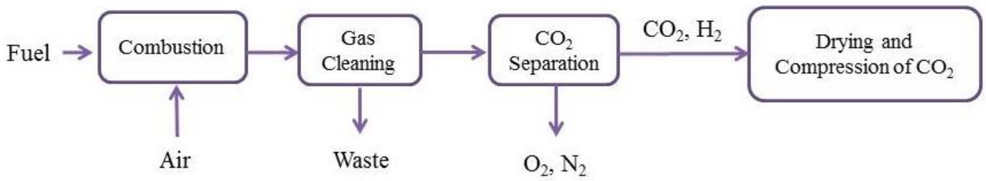

Figure 3. Flow chart of Post-combustion Capture process

The use of post-combustion capture technology has been more developed because CO_2 separation methods are simpler and more efficient than the two processes above. The use of cryogenic and membrane methods requires high energy, but this can be avoided by choosing absorbs or adsorption methods to reduce operating costs. At present, the most commonly used carbon dioxide (CO_2) separation method in the post-combustion capture technology includes absorption, cryogenic, membranes, and adsorption. A comparison of the four carbon dioxide separation methods can be seen in Table 3.

Tabel 3. CO_2 Gas Separation System

Methods	**Explanation**	**Energy Needed (MJ/Kg CO_2)**	**Pure Limit**	**The unit of time reaches the pure limit**	**Reference**
Absorption	- The interaction between adsorbent and adsorbate (CO_2 gas) is very strong so it takes very high energy to separate the adsorbent and	0.5 – 4.5	99	Hour	1. Li, J.-R.dkk., (2011). Carbon dioxide capture-related gas adsorption and separation in metal-organic frameworks. *Coordination Chemistry Reviews*, 255. 1791-1823. 2. Pirngruber G. D., Guillou F., Gomez A. dan Clausse M., (2013), A theoretical analysis of the energy

Methods	Explanation	Energy Needed (MJ/Kg CO_2)	Pure Limit	The unit of time reaches the pure limit	Reference
	adsorbate again. - The process is more complicated because CO_2 gas must be converted to solution using chemical solvents.				consumption of post-combustion CO_2 capture processes by temperature swing adsorption using solid sorbents", *International Journal of Greenhouse Gas Control*, 14. 74–83 3. Smith, N. dkk., (2013). Performance and Costs of CO_2 Capture at Gas Fired Power Plants. *Energy Procedia*, 37. 2443-2452.
Adsorbtion	- Selectivity of some materials such as zeolites is very high against CO_2 gas. - When adsorption chemically requires high energy during CO_2 desorption	0.1 – 1	95	Minute	1. Li, J.-R.dkk., (2011). Carbon dioxide capture-related gas adsorption and separation in metal-organic frameworks. *Coordination Chemistry Reviews*, 255. 1791-1823. 2. Smith, N. dkk., (2013). Performance and Costs of CO_2 Capture at Gas Fired Power Plants. *Energy Procedia*, 37. 2443-2452. 3. Cheung, O. dkk., (2013). "Adsorption kinetics for CO_2 on highly selective zeolites NaKA and nano-NaKA". *Ahallied Energy*, 112, hal. 1326-1336. 4. Pham T. D., Xiong R., Sdanler S. I. dan Lobo R. F., (2014) Experimental dan computational studies on the adsorption of CO_2 dan N_2 on pure silica zeolites. *Microporous dan Mesoporous Materials*, 185. 157–166.
Membrane	- Selectivity for CO_2 gas is still relatively low for	0.5 – 16.56	< 40	Minute	1. Li, J.-R.dkk., (2011). Carbon dioxide capture-related gas adsorption and separation in metal-organic frameworks. *Coordination*

Methods	Explanation	Energy Needed (MJ/Kg CO_2)	Pure Limit	The unit of time reaches the pure limit	Reference
	commercial use - Requires high temperatures to get high CO_2 purity				*Chemistry Reviews*, 255. 1791-1823. 2. Smith, N. dkk., (2013). Performance and Costs of CO_2 Capture at Gas Fired Power Plants. *Energy Procedia*, 37. 2443-2452 3. Kazama, S. dan Haraya, K., *(2013),* Optimization of CO_2 concentration captured by membrane technology - Possibility of reduction in CO_2 capture energy dan cost, *Energy Procedia*, ***37**. 969–975.*
Cryogenic	- The temperature used is quite low between 103°C -122°C - Less efficient because CO_2 has to be converted into a liquid with a very low temperature	0.4	99	Hour	1. Li, J.-R.dkk., (2011). Carbon dioxide capture-related gas adsorption and separation in metal-organic frameworks. *Coordination Chemistry Reviews*, 255. 1791-1823. 2. Miller, B.G., (2011) CO_2 Capture dan Storage, In *Clean Coal Engineering Technology*, Butterworth-Heinemann, Boston, 483–511. 3. Smith, N. dkk., (2013). Performance and Costs of CO_2 Capture at Gas Fired Power Plants. *Energy Procedia*, 37. 2443-2452.

The absorption and adsorption methods require lower operational costs compared to cryogenic or membrane methods. In the membrane method, selectivity to CO_2 is still very low compared to adsorption, whereas the cryogenic method requires high energy to convert $CO_{2(g)}$ to $CO_{2(l)}$ (Miller, 2011). Absorption methods generally use chemical solvents such as fluorinated solvents, ammonia solutions and ionic liquids (Li, 2011) and require high energy because of the interaction between adsorbents (chemical solvents) and adsorbate (CO_2 gas) in the form of chemical bonds, making it very difficult to separate when adsorbent regeneration. While the adsorption method uses materials such as porous silica, carbon and zeolites (Li, 2011). Based on Table 3, the adsorption method has a lower pure limit than the absorption and cryogenic methods, but has a faster time to reach the pure limit that is in units of minutes. The pure limit is the maximum purity limit obtained by using the CO_2 separation method. In addition, the adsorption method only requires lower energy when capturing CO_2 than all methods, so it is more profitable.

HASIL DAN PEMBAHASAN (RESULT AND DISCUSSION)

I. Materials for Carbon Dioxide Adsorption

Some materials which have been developed for carbon dioxide adsorption are porous materials such as mesopore silica, zeolites, carbon, MOF (metal organic framework), and COF (covalent organic framework). Several studies showing the effect of adsorption type and pore diameter on the carbon dioxide adsorption capacity can be seen in Table 4.

Tabel 4. Materials for CO_2 Capture

Material		Adsorption Type	Pore Diameter (nm)	Pore Volume (cm^3/g)	Adsorption Capacity (mmol/g)	Condition		Reference
						Temperature (°C)	Pressure (bar)	
Mesopore Silica	MCM-48	Chemisorption	2.87	1.20	1.14	25	1	Zeleňák V., Badaničová M., Halamová D., Čejka J., Zukal A., Murafa N. danGoerigk G., (2008), Amine-modified ordered mesoporous silica: Effect of pore size on carbon dioxide capture, *Chemical Engineering Journal*, 144. 336–342.
	SBA-16	Chemisorption	4.1	0.75	2.93	75	1	Son W.J., Choi J.S. dan Ahn W.S., (2008), Adsorptive removal of carbon dioxide using polyethyleneimine-loaded mesoporous silica materials, *Microporous dan Mesoporous Materials*, 113. 31–40.
Carbon	Carbon monolite	Physisorption	2	0.21	3.13	25	1	Hao G.P., Li W.C., Qian D. dan Lu A.H., (2010),

Material		Adsorption Type	Pore Diameter (nm)	Pore Volume (cm^3/g)	Adsorption Capacity (mmol/g)	Condition		Reference
						Temperature (°C)	Pressure (bar)	
								Rapid Synthesis of Nitrogen-Doped Porous Carbon Monolith for CO_2 Capture, *Adv. Material*, 22. 853–857.
Zeolite	Zeolite 13X	Physisorption	0.40	0.27	6.00	25	15	Siriwardane R., Shen M., Fisher E., Poston J. danShamsi A,. (2001), Adsorption dan desorption of CO_2 on solid sorbents, *Journal of Energy & Environmental Research*,1. 19–22.
	Zeolite NaA	Physisorption	0.66	0.30	4.21	0	1	Cheung, O. dkk., (2013). “Adsorption kinetics for CO_2 on highly selective zeolites NaKA and nano-NaKA”. *Ahallied Energy*, 112, hal. 1326-1336.
MOF	MOF-177	Chemisorption	0.43	1.59	33.50	25	32	Millward, A.R. danYaghi, O.M., (2005), "Metal−Organic Frameworks with Exceptionally High Capacity for Storage of Carbon Dioxide at Room Temperature", *J. Am. Chem. Soc.*, 127. 17998–17999.
	MOF-5	Chemisorption	0.59	0.31	2.10	25	1	

Material		Adsorption Type	Pore Diameter (nm)	Pore Volume (cm^3/g)	Adsorption Capacity (mmol/g)	Condition		Reference
						Temperature (°C)	Pressure (bar)	
COF	COF-102	Chemisorption	0.43	1.55	27.00	25	55	Furukawa, H. danYaghi, O. M., (2009), Storage of hydrogen, methane, dan carbon dioxide in highly porous covalent organic frameworks for clean energy applications, *Journal of the American Chemical Society*, 131. 8875–8883.

Mesopore silica material, MOF, and COF have a type of chemical adsorption, while carbon and zeolites are physical adsorption. Chemical adsorption requires relatively high pressure to adsorp CO_2 gas in MOF and COF materials. However, when chemical adsorption uses relatively low pressures in mesopore silica material, the adsorption ability will decrease. In addition, chemical adsorption requires high energy during desorption because there is a chemical bond between carbon dioxide and material sorbent, it could difficult to release from CO_2 capture material (Miller, 2011). In the physical adsorption on carbon and zeolite materials, the temperature and pressure used are relatively low and the carbon dioxide adsorbed is also more abundant than mesopore silica. Physical adsorption is reversible and tends to require low energy during desorption.

Besides the type of adsorption, another parameter that affects the adsorption of carbon dioxide is the pore diameter. Based on Table 4, mesopore silica has a larger pore diameter than zeolite, carbon, MOF and COF material. Carbon dioxide has a kinetic diameter of 3.3 Å (0.33 nm)[21]. The materials which suitable for CO_2 adsorption are those that have a diameter between 0.4 nm - 2 nm, and will be optimal if adsorbed by a material with a pore diameter of 0.4-0.6 nm. For this reason, zeolite, carbon, MOF and COF materials have a pore diameter suitable for CO_2 adsorption.

Another thing of affects CO_2 adsorption is the adsorption capacity. Materials that have a large adsorption capacity for CO_2 are carbon, zeolite, MOF, and COF. CO_2 adsorption capacity on the MOF and COF greater than on the carbon and zeolites, nevertheless COF and MOF are chemical adsorption where the adsorption conditions require high pressure between 30 - 50 bar. While carbon and zeolite only require 1 bar of pressure and room temperature. It causes zeolite and carbon more to be developed as CO_2 capture material. Several studies using zeolite and carbon for CO_2 Adsorption are shown in Table 5 and Table 6.

Tabel 5. Carbon Materials for CO_2 Capture

Carbon Material	Adsorption Condition		CO_2 Adsorption Capacity (%.wt)	Reference
	Temperature (°C)	Pressure		
Mesopore Carbon	16	100KPa	1.5	Saha D., Deng S.G., (2010), Adsorption equilibrium and kinetics of CO_2, CH_4, N_2O, and NH_3 on ordered mesoporous carbon, J. Colloid Interface Sci. 345. 402-409
	16	1000KPa	3	
Micropore Carbon	16	100KPa	4	Liu Y., Yang Y., Zhou Y., Zhang Y., Gao M. and Pan H. (2012) Hydrogen storage properties and mechanisms of the Mg(BH4)2–NaAlH4 system. *International Journal of Hydrogen Energy* 37. 17137–17145
Activated Carbon	16	100KPa	2.27	Z.J. Zhang, W. Zhang, X. Chen, Q.B. Xia, Z. Li, (2010) . Adsorption of CO_2 on zeolite 13X and activated carbon with higher surface area, Sep. Sci. Technol. 45. 710–719.
	16	3000KPa	21.29	
	16	0.1-0.4 bar	0.6-1.5	
	55	0.1-0.4 bar	0.25-0.8	
Activated Carbon ZTC-Y	30	1 bar	2.72	Susanti, I., and Widiastuti, N. (2019). Activation of Zeolite-Y Templated Carbon with KOH to Enhance the CO_2 Adsorption Capacity. *Malaysian Journal of Fundamental and Applied Science (MJFAS)*, 15 (2). 240-253.
Carbon ZTC-Y	30	1 bar	1.07	

Tabel 6. Zeolite Materials for CO_2 Capture

Zeolite Type	Adsorption Condition		CO_2 Adsorption Capacity (%.wt)	Reference
	Temperature (°C)	Pressure (bar)		
NaX	16	0.1-0.4	2.8-2.9	Cavenati, S., Grande, C. A. & Rodrigues, A. E., (2004). Adsorption Equilibrium of Methane, Carbon Dioxide, and Nitrogen on Zeolite 13X at High Pressure. *Journal of Chemical Engineering*, 49. 1095-1101.
	50	0.1-0.4	1.43-2.49	
	25	1	4.00	Walton K. S., Abney M. B. dan Douglas LeVan M., (2006), CO_2 adsorption in Y dan X zeolites modified by alkali metal cation exchange, *Microporous dan Mesoporous Materials*, 91. 78–84.
NaY	50	0.1-0.4	0.45-1.17	Cavenati, S., Grande, C. A. & Rodrigues, A. E., (2004). Adsorption Equilibrium of Methane, Carbon Dioxide, and Nitrogen on Zeolite 13X at High Pressure. *Journal of Chemical Engineering*, 49. 1095-1101.
	30	1	4.00	Yu L., Gong J., Zeng C. dan Zhang L., (2013), Synthesis of binderless zeolite X microspheres dan their CO_2 adsorption properties, *Separation dan Purification Technology*, 118. 188–195.
NaA	30	1	2.70	Zukal A., Arean C. O., Delgado M. R., Nachtigall P., Pulido A., Mayerová J. danČejka J., (2011), Combined volumetric, infrared spectroscopic dan theoretical investigation of CO_2 adsorption on Na-A zeolite, *MicroporousdanMesoporous Materials*, 146. 97–105.

Zeolite Type	Adsorption Condition		CO_2 Adsorption Capacity (%.wt)	Reference
	Temperature (°C)	Pressure (bar)		
	0	1	4.21	Cheung, O. dkk., (2013). “Adsorption kinetics for CO_2 on highly selective zeolites NaKA and nano-NaKA”. *Ahallied Energy*, 112, hal. 1326-1336.
NaKA	0	1	3.77	Cheung, O. dkk., (2013). “Adsorption kinetics for CO_2 on highly selective zeolites NaKA and nano-NaKA”. *Ahallied Energy*, 112, hal. 1326-1336.
CaX	25	1	17.55	Yu L., Gong J., Zeng C. dan Zhang L., (2013), Synthesis of binderless zeolite X microspheres dan their CO_2 adsorption properties, *Separation dan Purification Technology*, 118. 188–195.
13X	25	1	4.50	Siriwardane R., Shen M., Fisher E., Poston J. danShamsi A,. (2001), Adsorption dan desorption of CO_2 on solid sorbents, *Journal of Energy & Environmental Research*,1. 19–22.
	25	15	6.00	McEwen, J., Hayman, J.-D. & Yazaydin, A. O., (2013). A comparative study of CO_2, CH4 and N2 adsorption in ZIF-8, Zeolit-13X and BPL activated carbon. *Chemical Physics*, 412. 72-76.

KESIMPULAN (CONCLUSION)

Based on the description of technology and material for CO_2 adsorption above, it can be concluded that CO_2 adsorption can be carried out through absorption, adsorption, membrane and cryogenic technologies. From these techniques, the adsorption method is considered more efficient and can be applied with various porous materials such as mesoporous silica, zeolite, carbon, MOF and COF. Porous material has each advantages and disadvantages. Zeolites and carbon are more interesting to develop due to zeolites have good porosity but a small surface area and carbon has a large surface area but irregular porosity. There have been several studies that have combined carbon and zeolite materials into zeolite-templated carbon with synthetic zeolite and resulted in increased adsorption capacity.

SARAN (SUGGESTIONS)

One proposal that can be done on further research in the development of adsoption materials is combine zeolite and carbon into zeolite/carbon composite. Zeolite/carbon composite materials can be synthesized with basic materials from nature, such as rice husks, bagasse and others. By utilizing natural waste as a basic material for making composites material, the cost of making zeolite/carbon composites material becomes cheaper and the waste of natural materials can be increased in value.

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