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-combustion, pre-combustion and oxy-fuel combustion. Post-combustion systems can be done in various systems including absorption, adsorption, membrane, and cryogenic. Adsorption proses for CO2 capture applied with porous material such as 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 described in this review.

PENDAHULUAN (INTRODUCTION)

Carbon dioxide is one of the triggers for the greenhouse effect and global warming. The concentration of CO2 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 CO2 continuously in the atmosphere will limit the ability of plants and seas to absorb CO2 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 CO2 gas problems are separation technologies include air capture, CCUS (CO2 Capture Utilization and Storage), and CCS (Carbondioxide Capture and Storage) technology. Technology with several systems, namely post-combustion, pre-combustion and oxy-combustion (Figueroa, 2008). Post-combustion 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 CO2 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.
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 CO₂. The process of Pre-combustion Capture⁹ is shown in Figure 1.

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.

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![Figure 1. Flow chart of Pre-combustion Capture process](image)

### Table 1. Gas Separation Technologies

| Technology | Explanation | Reference |
|------------|-------------|-----------|
| Air Capture | - Capture CO₂ gas up to 52%  
- The use of amines as gas binders is considered unsafe | Kintisch, E., (2014). *Can Sucking CO₂ Out of the Atmosphere Really Work*, Columbia: MIT Technology Review. |
| CCUS (CO₂ Capture Utilization and Storage) | - Inject CO₂ 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 (CO₂ Capture and Storage) | - Separation of combustion CO₂ gas  
- Derivative systems: pre-combustion, post combustion and oxy fuel combustion. | Bennauce, K., Gielen, D., Kerr, T. & Tam, C., (2008). CO₂ Capture and Storage. *International Energy Agency*, p. 15. |

### Table 2. CO₂ Gas Separation Technologies

| Technology of CO₂ 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 CO₂ Sorption | Advantages | Disadvantages | Reference |
|----------------------------|------------|---------------|-----------|
| Oxy fuel combustion        | Capable of capturing almost 91.6% of CO₂ 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. |
| Post combustion            | The CO₂ 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 CO₂ and water (H₂O) so no CO₂ separation process is needed. Capable of capturing 92.6% CO₂ 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, 21. 9–20 |

In Oxy-fuel Combustion is simpler than pre-combustion capture because the oxidation process uses oxygen so it only produces CO₂ and H₂O. Because the fuel used in the combustion process only produces CO₂ and H₂O, there is no need to separate the exhaust gas anymore, so that the CO₂ gas produced from this process can be directly captured. The process of Oxy-fuel Combustion\(^9\) is shown in Figure 2.
The last process is the post-combustion capture process. In this process, separating CO₂ 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.

The use of post-combustion capture technology has been more developed because CO₂ 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 (CO₂) 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.

**Table 3. CO₂ Gas Separation System**

| Methods  | Explanation | Energy Needed (MJ/Kg CO₂) | Pure Limit | The unit of time reaches the pure limit | Reference |
|----------|-------------|--------------------------|------------|---------------------------------------|-----------|
| Absorption | The interaction between adsorbent and adsorbate (CO₂ gas) is very strong so it takes very high energy to separate the adsorbent and adsorbate | 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 CO₂) | Pure Limit | The unit of time reaches the pure limit | Reference                                                                                                                                 |
|---------------|------------------------------------------------------------------------------|---------------------------|------------|-----------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Adsorption    | adsorbate again.                                                             |                           |            |                                        | consumption of post-combustion CO₂ capture processes by temperature swing adsorption using solid sorbents”, *International Journal of Greenhouse Gas Control*, 14. 74–83 |
|               | - The process is more complicated because CO₂ gas must be converted to solution using chemical solvents. |                           |            |                                        |                                                                                                                                              |
|               | - Selectivity of some materials such as zeolites is very high against CO₂ gas. | 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 |
|               | - When adsorption chemically requires high energy during CO₂ desorption       |                           |            |                                        | 2. Smith, N. dkk., (2013). Performance and Costs of CO₂ Capture at Gas Fired Power Plants. *Energy Procedia*, 37. 2443-2452.                |
| Membrane      | Selectivity for CO₂ gas is still relatively low for                          | 0.5 – 16.56               | < 40 Minute|                                        | 3. Cheung, O. dkk., (2013). “Adsorption kinetics for CO₂ 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 CO₂ dan N₂ on pure silica zeolites. *Microporous dan Mesoporous Materials*, 185. 157-166.   |
| Methods | Explanation | Energy Needed (MJ/Kg CO₂) | Pure Limit | The unit of time reaches the pure limit | Reference |
|---------|-------------|---------------------------|------------|-----------------------------------------|-----------|
| Commercial Use | Requires high temperatures to get high CO₂ purity | | | | |
| Cryogenic | The temperature used is quite low between 103°C - 122°C | 0.4 | 99 Hour | | |

The absorption and adsorption methods require lower operational costs compared to cryogenic or membrane methods. In the membrane method, selectivity to CO₂ is still very low compared to adsorption, whereas the cryogenic method requires high energy to convert CO₂(g) to CO₂(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 (CO₂ 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,
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 CO₂ separation method. In addition, the adsorption method only requires lower energy when capturing CO₂ 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 CO₂ Capture**

| Material                  | Adsorption Type | Pore Diameter (nm) | Pore Volume (cm³/g) | Adsorption Capacity (mmol/g) | Condition | Reference |
|---------------------------|-----------------|--------------------|---------------------|------------------------------|-----------|-----------|
| 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 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 (cm³/g) | Adsorption Capacity (mmol/g) | Condition | Reference |
|----------|----------------|-------------------|-------------------|-----------------------------|-----------|-----------|
| Zeolite 13X | Physisorption | 0.40 | 0.27 | 6.00 | 25 | 15 | Rapid Synthesis of Nitrogen-Doped Porous Carbon Monolith for CO₂ Capture, *Adv. Material*, 22. 853–857. |
| Zeolite NaA | Physisorption | 0.66 | 0.30 | 4.21 | 0 | 1 | Siriwardane R., Shen M., Fisher E., Poston J. danShamsi A., (2001), Adsorption dan desorption of CO₂ on solid sorbents, *Journal of Energy & Environmental Research*,1. 19–22. |
| MOF-177 | Chemisorption | 0.43 | 1.59 | 33.50 | 25 | 32 | Cheung, O. dkk., (2013). “Adsorption kinetics for CO₂ on highly selective zeolites NaKA and nano-NaKA”. *Ahallied Energy*, 112, hal. 1326-1336. |
| MOF-5 | Chemisorption | 0.59 | 0.31 | 2.10 | 25 | 1 | 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. |
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 adsorb CO₂ 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 CO₂ 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 CO₂ 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 CO₂ adsorption.

Another thing of affects CO₂ adsorption is the adsorption capacity. Materials that have a large adsorption capacity for CO₂ are carbon, zeolite, MOF, and COF. CO₂ 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 CO₂ capture material. Several studies using zeolite and carbon for CO₂ Adsorption are shown in Table 5 and Table 6.
| Carbon Material          | Adsorption Condition | CO₂ Adsorption Capacity (%.wt) | Reference                                                                 |
|-------------------------|----------------------|--------------------------------|---------------------------------------------------------------------------|
| Mesopore Carbon         | 16                   | 100KPa                         | 1.5                                                                      | Saha D., Deng S.G., (2010), Adsorption equilibrium and kinetics of CO₂, CH₄, N₂O, and NH₃ 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 CO₂ 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 CO₂ Adsorption Capacity. Malaysian Journal of Fundamental and Applied Science (MJFAS), 15 (2). 240-253. |
| Carbon ZTC-Y            | 30                   | 1 bar                          | 1.07                                                                     |                                                                                             |
| Zeolite Type | Adsorption Condition | CO₂ Adsorption Capacity (% wt) | Reference |
|-------------|----------------------|-------------------------------|-----------|
| NaX         | 16 16°C, 0.1-0.4 bar | 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 50°C, 0.1-0.4 bar | 1.43-2.49                     | Walton K. S., Abney M. B. dan Douglas LeVan M., (2006), CO₂ adsorption in Y dan X zeolites modified by alkali metal cation exchange, Microporous dan Mesoporous Materials, 91. 78–84. |
|             | 25 25°C, 1 bar       | 4.00                          | Yu L., Gong J., Zeng C. dan Zhang L., (2013), Synthesis of binderless zeolite X microspheres dan their CO₂ adsorption properties, Separation dan Purification Technology, 118. 188–195. |
| NaY         | 50 50°C, 0.1-0.4 bar | 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 30°C, 1 bar       | 4.00                          | Yu L., Gong J., Zeng C. dan Zhang L., (2013), Synthesis of binderless zeolite X microspheres dan their CO₂ adsorption properties, Separation dan Purification Technology, 118. 188–195. |
| NaA         | 30 30°C, 1 bar       | 2.70                          | Zukal A., Arean C. O., Delgado M. R., Nachtigall P., Pulido A., Mayerová J. dan Čejka J., (2011), Combined volumetric, infrared spectroscopic dan theoretical investigation of CO₂ adsorption on Na-A zeolite, Microporous dan Mesoporous Materials, 146. 97–105. |
| Zeolite Type | Adsorption Condition | CO₂ Adsorption Capacity (%.wt) | Reference |
|-------------|----------------------|-------------------------------|------------|
|             | Temperature (°C)     | Pressure (bar)                |            |
| NaKA        | 0                    | 1                             | 3.77       |
| CaX         | 25                   | 1                             | 17.55      |
| 13X         | 25                   | 1                             | 4.50       |
|             | 25                   | 15                            | 6.00       |
|             |                      |                               |            |

KESIMPULAN (CONCLUSION)

Based on the description of technology and material for CO₂ adsorption above, it can be concluded that CO₂ 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 adsorption 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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**DAFTAR PUSTAKA (REFERENCES)**

[1] Oh, T.H. (2010). Carbon Capture and Storage Potential in Coal-fired Plant in Malaysia-a Review. *Renewable Sustainable Energy Rev.* 14, 2697–2709.

[2] Li, J.-R.dkk., (2011). Carbon dioxide capture-related gas adsorption and separation in metal-organic frameworks. *Coordination Chemistry Reviews*, 255. 1791-1823.

[3] Yang, H. dkk., (2008). Progress in carbon dioxide and capture: A review. *Journal of Environmental Sciences*, 20. 14-27.

[4] Figueroa J. D., Fout T., Plasynski S., Mc. Ilvried H. dan Srivastava R. D., (2008), Advances in CO$_2$ capture technology, The U.S. Department of Energy’s Carbon Sequestration Program, *International Journal of Greenhouse Gas Control*, 21. 9–20.

[5] Kintisch, E., (2014). Can Sucking CO$_2$ Out of the Atmosphere Really Work, Columbia: MIT Technology Review.

[6] Bielicki, J. M. dkk., (2014). Causes and financial consequences of geologic CO$_2$ storage reservoir leakage and interference with other subsurface resources. *International Journal of Greenhouse Gas Control*, 20. 272-284.

[7] Bennaucer, K., Gielen, D., Kerr, T. & Tam, C., (2008). CO$_2$ Capture and Storage. *International Energy Agency*, p. 15.

[8] Li, J.-R.dkk., (2011). Carbon dioxide capture-related gas adsorption and separation in metal-organic frameworks. *Coordination Chemistry Reviews*, 255. 1791-1823.

[9] Miller, B.G., (2011) CO$_2$ Capture dan Storage, In *Clean Coal Engineering Technology*, Butterworth-Heinemann, Boston, 483–511.

[10] Pirngruber G. D., Guillou F., Gomez A. dan Clausse M., (2013), A theoretical analysis of the energy consumption of post-combustion CO$_2$ capture processes by temperature swing adsorption using solid sorbents", *International Journal of Greenhouse Gas Control*, 14. 74–83.

[11] Smith, N. dkk., (2013). Performance and Costs of CO$_2$ Capture at Gas Fired Power Plants. *Energy Procedia*, 37. 2443-2452.

[12] Cheung, O. dkk., (2013). “Adsorption kinetics for CO$_2$ on highly selective zeolites NaKA and nano-NaKA”. *Ahalled Energy*, 112, hal. 1326-1336.

[13] 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.
[14] Kazama, S. dan Haraya, K., (2013), Optimization of CO₂ concentration captured by membrane technology - Possibility of reduction in CO₂ capture energy dan cost, *Energy Procedia*, 37, 969–975.

[15] 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.

[16] 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.

[17] Hao G.P., Li W.C., Qian D. dan Lu A.H., (2010), Rapid Synthesis of Nitrogen-Doped Porous Carbon Monolith for CO₂ Capture, *Adv. Material*, 22. 853–857.

[18] Siriwardane R., Shen M., Fisher E., Poston J. danShamsi A,. (2001), Adsorption dan desorption of CO₂ on solid sorbents, *Journal of Energy & Environmental Research*, 1. 19–22.

[19] 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.

[20] 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.

[21] Susanti, Indri. (2019). Polysulfone Membrane with Zeolite Filler for CO₂/CH₄ Gas Separation: a Review. *Science Education and Application Journal (SEAJ)*. 1 (1). 10-16.

[22] Saha D., Deng S.G., (2010), Adsorption equilibrium and kinetics of CO₂, CH₄, N₂O, and NH₃ on ordered mesoporous carbon, J. Colloid Interface Sci. 345. 402-409.

[23] Z.J. Zhang, W. Zhang, X. Chen, Q.B. Xia, Z. Li, (2010) . Adsorption of CO₂ on zeolite 13X and activated carbon with higher surface area, Sep. Sci. Technol. 45. 710–719.

[24] 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

[25] Susanti, I., and Widiastuti, N. (2019). Activation of Zeolite-Y Templated Carbon with KOH to Enhance the CO₂ Adsorption Capacity. *Malaysian Journal of Fundamental and Applied Science (MJFAS)*, 15 (2). 240-253.

[26] 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.

[27] Walton K. S., Abney M. B. dan Douglas LeVan M., (2006), CO₂ adsorption in Y dan X zeolites modified by alkali metal cation exchange, *Microporous dan Mesoporous Materials*, 91. 78–84.

[28] Yu L., Gong J., Zeng C. dan Zhang L., (2013), Synthesis of binderless zeolite X microspheres dan their CO₂ adsorption properties, *Separation dan Purification Technology*, 118. 188–195.

[29] 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 CO₂ adsorption on Na-A zeolite, *Microporous dan Mesoporous Materials*, 146. 97–105.

[30] McEwen, J., Hayman, J.-D. & Yazaydin, A. O., (2013). A comparative study of CO₂, CH₄ and N₂ adsorption in ZIF-8, Zeolit-13X and BPL activated carbon. *Chemical Physics*, 412. 72-76