Proceedings of the
International Conference on Mechanical Engineering and Renewable Energy 2019
(ICMERE2019) 11 – 13 December, 2019, Chittagong, Bangladesh

ICMERE2019-PI-099

SOLUTION TO AIR POLLUTION FOR REMOVING CO_2 AND SO_2 FROM FLUE GASES: A PROSPECTIVE APPROACH

M S A Joarder [1], F Rashid [2] and T A Joarder [3]

[1,2]Department of Mechanical Engineering, Rajshahi University of Engineering & Technology (RUET), Rajshahi-6204, Bangladesh
[3]Department of Computer Science and Engineering, Rajshahi University of Engineering & Technology (RUET), Rajshahi-6204, Bangladesh
ullash24140@gmail.com[1,*], frrashed10@gmail.com[2], ussash93@gmail.com[3]

Abstract- *Among all environmental pollutions air pollution is severe which causes health and environmental problems. Air pollution on the other hand caused from different fossil-fueled vehicles and industries. This paper presents a system which reduces air pollution by capturing CO_2 and SO_2 and store CO_2 and SO_2. This proposed system reduces the CO_2 and SO_2 emissions from air of different fossil-fueled vehicles, power plants and industries and as a consequences reduce global warming and agricultural losses. This paper also represents membrane separation process with their corresponding advantages and disadvantages which is most significant for CO_2 separation. Moreover, wet flue gas desulfurization is one of the most efficient methods among all the processes for SO_2 separation and the separated CO_2 and SO_2 is used for different purposes in industry. However, due to rapid industrialization in recent years, this proposed system is significant to reduce global warming and health diseases by reducing CO_2 and SO_2 from fossil-fueled vehicles, power plants and industry.*

Keywords: air pollution, fossil fuel, global warming, membrane separation and desulfurization

1. INTRODUCTION

Different environmental pollutions like air pollution, water pollution, land pollution, solid wastes and deforestation occur due to rapid industrialization and globalization. However, among all this pollution problems, air pollution is a major concern nowadays and air pollution's causes health problem, mortality, soil damage and so on [1]. Moreover, particulate air pollution causes asthma, respiratory diseases and cardiovascular disease problems [2] and reason behind this air pollution are coal-fired power plants, fossil fueled vehicles, solid wastes incinerator, a cement plant, steel industry, paper industry, and oil shale industry which produces a lot of solid waste residue and this solid waste residue produces CO_2 which cause the main reason of air pollution [3]. On the other hand, combustion of fossil fuel produces a huge amount of CO_2 and this is one of the main energy sources which supplies about 85% of the world's energy supply [4]. On the other hand, besides this statistics coal-fired power plants operate for meeting 57 percent of energy demand from 2004 to 2030 [5]. As a consequence, fossil-fueled power plants are great contributors of air pollution which emit carbon dioxide (CO_2), sulfur oxides (SOx), nitrogen oxides (NOx), soot and particulate matter [6]. However, fossil-fueled power plants emit about 40 percent total CO_2 emissions but the main contributors are coal-fired power plant, vehicles and fuel operated industry [7]. As CO_2 emissions have a great impact on global climate because the global concentration of CO_2 in the atmosphere is increasing day by day and thus greenhouse gases and greenhouse effect is also increasing significantly in this decade [8]. Among all the greenhouse gases, CO_2 is the largest contributor for increasing earth's temperature which has the effect more than 60% of global warming as the amount of emission is too high [9]. Increasing earth's temperature causes a lot of natural disasters like floods, hurricanes, an increase in sea water level, droughts and widespread melting of ice and snow which are threatened to ecological systems and human life [10]. As a result, these make the gas stream acidic and corrosive which reduces the possibility of gas compression and the transport within the transportation system [11]. Moreover, human activity emits CO_2 which is in the order of 7 Gt/a in the late 1990s and thus CO_2 capture and storage (CCS) technology is required [5]. For this, this paper presents a solution to capture and reduce the amount of CO_2 and SO_2 from different energy-related sources and industries. In this regard, CO_2 transportation to a storage location and long-term isolation from the atmosphere which is a promising option that can reduce CO_2 emissions [12]. There are different types of CO_2 capture and storage (CCS) systems like pre-combustion, post-combustion, oxy-fuel combustion and different industrial separation techniques [13]. Post-combustion capture is a significant technology as this process captures the CO_2

from flue gases of different fossil fuel and coal-fired power plants [14]. Developing the CCS technologies is important which is a good option for the global demand of CO_2 reduction [15]. This paper represents an effective CO_2 capture and storage technology with its advantages and disadvantages for post-combustion capture on the basis of cost-effectiveness at the typical temperature, pressure, and composition of flue gases which is an effective solution to air pollution. Industries also emit flue gas which contains large amount of sulfur dioxide (SO_2) where agricultural lands damage due to the great impact of SO_2 emission. Agricultural losses due to air pollution are mainly yielded losses caused by increased levels of SO_2 (European Commission, 2005) [16]. Thus, this paper also proposed a system where SO_2 is separated from the air and reserved in the cylinder for using in different industrial purposes.

2. METHODOLOGY

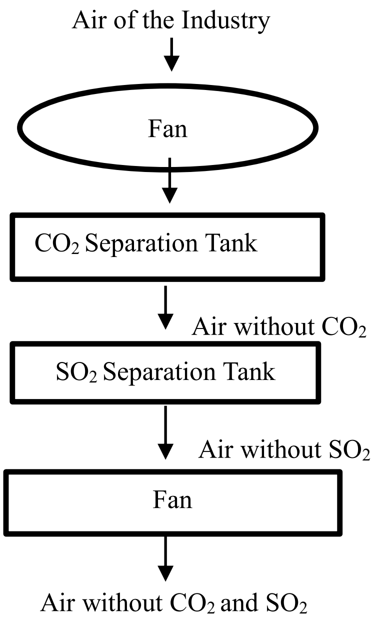

Fig.1: proposed schematic system

At first, fans are set at the top of the power plants/industry since heated air remains at the upper side of the room. Then these fans collect the air and release it to the system and in the system CO_2 separation tank captures CO_2 which is separated from air according to the following processes of CO_2 separation. After that, the remaining air passes to the SO_2 separation tank, and it is separated SO_2 from the air according to the following process of SO_2 Separation. Then the remaining gas passes to the environment and finally CO_2 and SO_2 is collected in the cylinders of system and is used for different purposes. Mainly different industries emit the CO_2 but the fossil fuel power plants emit a great amount of CO_2 which is about 33-40 percent of the total amount of CO_2 [5]. CO_2 separation is greatly required for reducing the global warming of the environment. There are different ways of CO_2 separation process for the post-combustion capture such as an absorption process, adsorption process, cryogenic distillation process and membrane separation process [17]. Among all this process membrane separation process is the most effective process, and this paper presents only membrane separation process for CO_2 separation.

2.1 CO_2 Capture Based on Membrane Separation Process

Membrane separation process has been used for CO_2 separation in different industries since the last two decades. In membrane separation process, CO_2 is separated based on pressure. Usually in flue gases, the pressure is too low and so in the membrane process for separating CO_2 the driving force is too low. When the concentration of CO_2 in the feed mixture increases, then it can separate more CO_2 [18, 19]. The particular gas diffusion through a membrane depends on the nature of the species and the interaction between membrane and species, and the membrane's chemical and physical properties [20]. Membranes are formed as hollow fibers arranged in the tube-and-shell configuration, or as flat sheets, which are typically packaged as spiral-wound modules [21]. There are a lot of advantages of using membrane separation processes as the equipment which is used in this process is simple, compact, relatively easy to operate and control, a clear process and easy to scale up [22, 23]. Besides this, the membrane equipment is compact, allowing for multistage operation, lightweight and no need for chemicals or regenerations of any absorbent in this process but require low maintenance [24]. The main disadvantages of using this process are too much energy is required for post-combustion CO_2 capture, CO_2 separation from SOx and NOx is low and for high flow rate applications, this process is not suitable [25-27]. For post-combustion CO_2 capture, this membrane should have some specifications such as high CO_2 permeability, high chemical, and thermal stability, high selectivity for CO_2 separation from flue gases, resistant to aging, resistant to plasticization, cost-effective, the low production cost for different membrane modules [28, 29]. Porous inorganic membranes, palladium membranes, polymeric membranes, and zeolites membranes are mainly used for separating CO_2 from gases. In conventional CO_2 separation processes inorganic or polymeric membrane separation processes are expected to be more efficient [30, 31].

2.1.1 CO_2 Capture Based on Polymeric Membrane

Polymeric membrane process is used in a different industry for separating CO_2 gas. Gas separation by the polymeric membrane is usually performed on dense homogenous membranes. By performing on the dense homogeneous membrane there is a close relationship between the permeability with the intrinsic permeability of the polymer [5]. The selective layer of the polymeric membrane is a nonporous film. This nonporous film transports gases across by the solution-diffusion mechanism [17]. In the polymeric membrane, there are gaps remaining present between the polymeric structures. In the polymeric structure, there is the movement of polymer chains. A channel between gaps can be formed because of the movement of the polymer chains. This channel allows gas molecule to move from one gap to another gap. Thus, in the membrane structure gas molecules can effectively be diffused. Polymers which form channels of a certain size can be used for the selective transport of gases. Gases will diffuse faster through a membrane by using large channels. Here the gas diffusion will be done at the less selectivity [5].

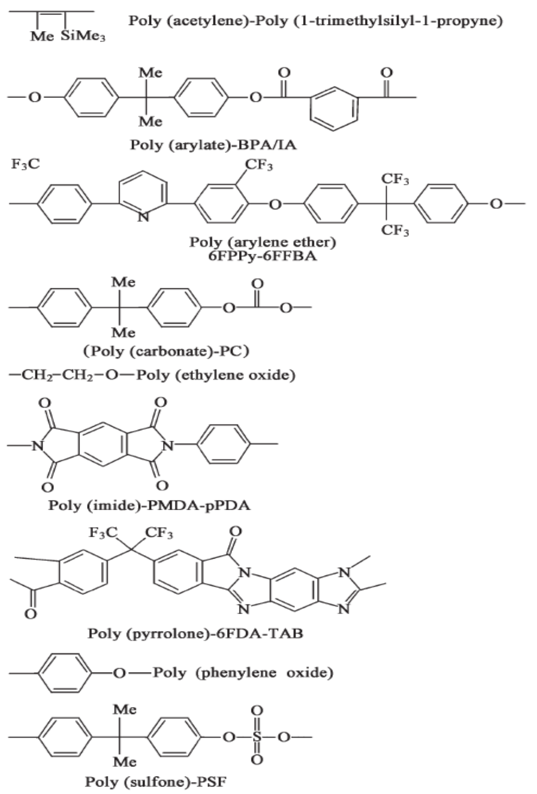

Fig.2: Examples of polymer molecular structures used for CO_2 separation [29]

2.1.2 CO_2 Capture Based on Inorganic Membrane

In membrane reactors, fuel cells and other high-temperature separations the demand of an inorganic membrane is too much. Thus, the development of the application of an inorganic membrane is growing faster than other processes [30, 31]. Based on structure the inorganic membranes are two types namely porous inorganic membrane and dense inorganic membrane. In porous inorganic member a porous thin top layer is cast on porous metal or ceramic support in porous inorganic membranes which gives mechanical strength but provides minimum mass transfer resistance. However, among all the inorganic membranes the zeolite membrane is the most important one and zeolite membranes have unique properties like size selectivity, chemical and thermal stability. For this reason, zeolite membranes are more expensive compared to other polymeric membranes [32-34]. There are limitations for the wide applications of dense inorganic membranes compared to porous inorganic membranes because in dense inorganic membranes the permeability is too low. In porous inorganic membranes, there are four main transport mechanisms for separating gases. They are Knudsen diffusion, surface diffusion, capillary condensation and molecular sieving [20, 35]. The Knudsen diffusion is best defined as the ratio of the flow of species A to that of species B as given by the inverse of square root of their molecular weight ratio [36].This process occurs in gas phase through pore sizes of membranes with a diameter d, which is smaller than the mean free path dimensions of molecules, λ, in the gas mixture and so the Knudsen number (λ/d) is much greater one compared to other [20]. Thus, in the narrow pore channel the molecules don't collide with each other but collide with the surface of the wall [24]. As the molecular weights of gaseous species are between 10 and 100, the separation selectivity of this Knudsen diffusion is too low [36]. Thus, for commercial purposes these membranes are not attractive for their low selectivity [37]. For capillary condensation to occur in porous solids, multilayer diffusion is a prerequisite where species adsorb in several layers. Initially, the gas vapor mixture permits through pores of porous inorganic membranes, and then the vapor species condense in the pores at a pressure lower than the saturation pressure at a given temperature. The multilayer diffusional flux is much larger than the gas phase flux. When the pore is blocked by condensate, preventing gas transport of other components of the gas vapor mixture, increased selectivity does occur. The condensation pressure depends on the pore size, shape and strength of the interaction between the fluid and pore walls [20]. Molecular sieving takes place when pore diameters are very small; allowing the permeation of only the smaller molecules through the pores of porous inorganic membranes while larger molecules cannot enter these pores where a selective separation based upon size exclusion is achieved [20, 38]. High selectivity and permeability are exhibited for smaller component of a gas mixture [39]. Zeolites, porous glass, micro porous silica, and molecular sieve carbons are typical examples that exhibit molecular sieving properties [40].

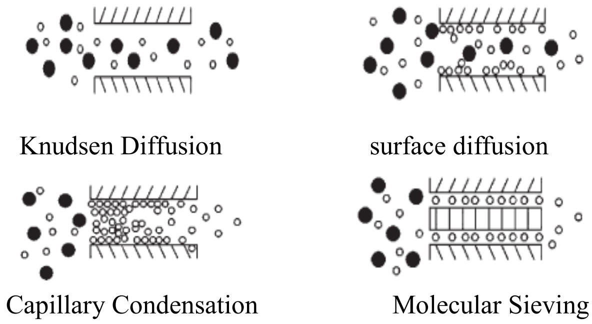

Fig.3: Transport mechanism through micro porous membranes [20]

2.2 SO_2 Separation Process

Fossil fuel power plants usually emit flue gases [41-43] which contains large amounts of sulfur dioxide (SO_2) and other pollutants [44]. Flue gas desulfurization is required for reducing sulfur dioxide. Researchers are actively exploring for the desulfurization process [44-47]. Wet flue gas desulfurization is one of the most efficient methods among all the conventional technologies which is mainly based on limestone [48].

The highest absorption of SO_2 is 1.63g SHA-Na is 0.946 mmol in the process, which is translated to 0.037g SO_2 g−1 SHA-Na. For effective desulfurization, pH of the absorption solution should be above 3.5 in this process. The products of this process were characterized by Fourier transform infrared spectroscopy and X-ray diffraction. Sludge humic acid sediment is the main product of the desulfurization, which can be used as fertilizer components [11]. Sludge sodium humate (SHA-Na) can be extracted from sludge by using alkaline treatment method [49]. There is a process for the removal of SO_2 from flue gas by using absorption solution from sludge treatment and produce fertilizer. The process is shown in Figure 4 which includes following processes (a) excess sludge is disintegrated by sodium hydroxide in a stirred reactor at the temperature of 313K. (b) The disintegrated sludge is centrifuged, and the supernatant is concentrated through a membrane filter to spray into a desulfurization tower. (c) SO_2 can be absorbed by SHA-Na in the desulfurization tower. The desulfurization liquid, which mainly contains sludge humic acid (SHA) and H_2SO_3, flows into the reactor. (d) In the reactor, SO32− is oxidized to SO42− through diffused aeration. (e) Afterward, action liquid from the reactor flows into a sedimentation tank and stands for 12h. Due to the poor solubility of SHA, SHA may be separated as sediment from an acidic solution. The separated SHA can be used as a kind of material for compound fertilizer after drying in a spray dryer. From the above process, it is believed that the removal of SO_2 by the supernatant from alkaline sludge treatment is a resourceful type of environmental protection technology for FGD [11].

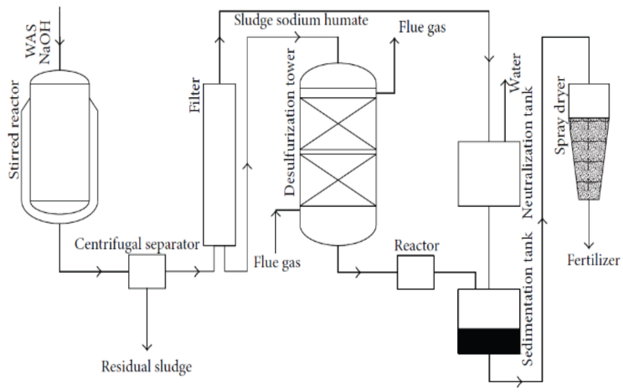

Fig.4: Simplified scheme of application of the SHA-Na for flue gas desulfurization [11].

3. RESULTS AND DISCUSSION

Figure 5 and Figure 6 represents relation between diameter and separation degree of CO_2 for process selectivity's 25 and 55 respectively with CO_2 purity requirements of 80 and 90 mol percent respectively and the operating conditions are feed CO_2 molar fraction 14 mol percent, feed flow 100 m3 h−1, permeate vacuum 30 mbar and 55 mbar respectively.

a) For 80% CO_2 purity (mol%),

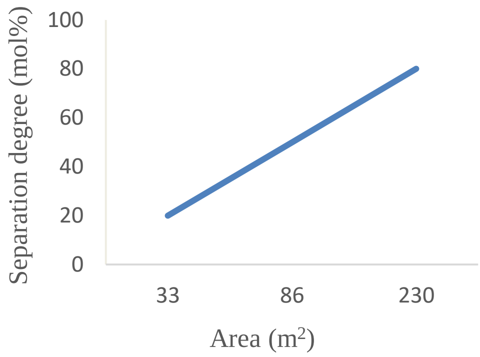

Fig.5: Separation degree (%) vs area (m^2) of single-stage membrane [13]

b) For 90% CO_2 purity (mol%),

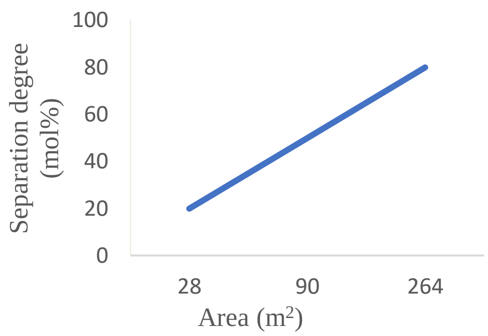

Fig.6: Separation degree (%) vs area (m^2) of single-stage membrane [13]

From Figure 5 and Figure 6 it is seen that, separation degree increases with the increase of area of membrane separator. On the other hand, for SO_2 separation, sludge sodium humate in the supernatant after alkaline sludge treatment shows great performance in SO_2 absorption which is the main technology for reducing SO_2 emissions. The desulfurization product contains mainly sludge humic acid sediment which can be used as fertilizer components.

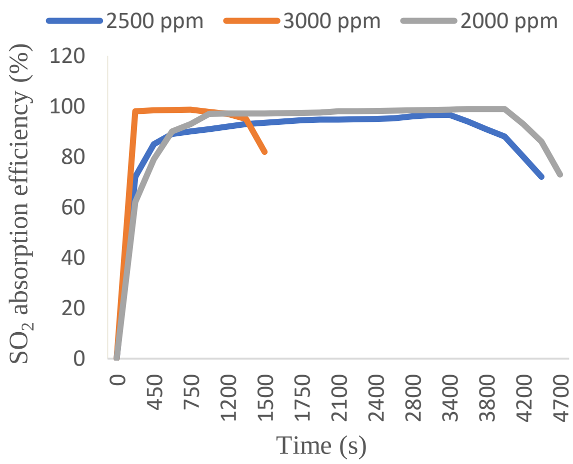

Fig.7: SO_2 absorption efficiency (%) vs time (s) (gas

flow,0.12m3/h; absorption solution, 100 mL;O2, 5 vol%; 298K) [11].

Figure 7, shows the SO_2 separation efficiency (%) with respect to time of 2000 ppm, 2500 ppm and 3000 ppm of SO_2 in outlet flue gas.

4. CONCLUSIONS

A system has been proposed in order to reduce CO_2, SO_2 pollution from fossil-fueled power plants and industries which is significant for future decades. Membrane separation processes is the major technology in industries where budget is limited, and it provides several advantages over other conventional separation processes like simplicity, better selectivity, good separation performance with high thermal and chemical stability, higher permeability, space-saving, easy to scale-up technology, and energy saving. On the other hand, SO_2 is too harmful which has a great effect on the health of the workers, agricultural lands and in different sectors. For SO_2 separation wet flue gas desulfurization is one of the most effective methods among all the technologies and the desulfurization product can be used as a useful fertilizer. If our proposed system can be used in different industries and fossil-fueled power plant, then all these CO_2 and SO_2 emissions would be reduced and thus mitigates global warming, human health, and agricultural problems.

7. REFERENCES

[1] Vafa-Arani, H., Jahani, S., Dashti, H., Heydari, J., & Moazen, S. (2014). A system dynamics modeling for urban air pollution: A case study of Tehran, Iran. *Transportation Research Part D: Transport and Environment*, *31*, 21-36.

[2] Seaton, A., Godden, D., MacNee, W., & Donaldson, K. (1995). Particulate air pollution and acute health effects. *The lancet*, *345*(8943), 176-178.

[3] Wee, J. H. (2013). A review on carbon dioxide capture and storage technology using coal fly ash. *Applied Energy*, *106*, 143-151..

[4] Supap, T., Idem, R., Tontiwachwuthikul, P., & Saiwan, C. (2009). Kinetics of sulfur dioxide-and oxygen-induced degradation of aqueous monoethanolamine solution during CO_2 absorption from power plant flue gas streams. *International Journal of Greenhouse Gas Control*, *3*(2), 133-142.

[5] Yang, H., Xu, Z., Fan, M., Gupta, R., Slimane, R. B., Bland, A. E., & Wright, I. (2008). Progress in carbon dioxide separation and capture: A review. *Journal of environmental sciences*, *20*(1), 14-27.

[6] Wang, X., Manning, W., Feng, Z., & Zhu, Y. (2007). Ground-level ozone in China: distribution and effects on crop yields. *Environmental pollution*, *147*(2), 394-400.

[7] Carapellucci, R., & Milazzo, A. (2003). Membrane systems for CO_2 capture and their integration with gas turbine plants. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, *217*(5), 505-517.

[8] Wang, M., Lawal, A., Stephenson, P., Sidders, J., & Ramshaw, C. (2011). Post-combustion CO_2 capture with chemical absorption: a state-of-the-art review. *Chemical engineering research and design*, *89*(9), 1609-1624.

[9] Yamasaki, A. (2003). An overview of CO_2 mitigation options for global warming—emphasizing CO_2 sequestration options. *Journal of Chemical Engineering of Japan*, *36*(4), 361-375.

[10] Kenarsari, S. D., Yang, D., Jiang, G., Zhang, S., Wang, J., Russell, A. G., ... & Fan, M. (2013). Review of recent advances in carbon dioxide separation and capture. *Rsc Advances*, *3*(45), 22739-22773.

[11] Zhao, Y., & Hu, G. (2013). Removal of sulfur dioxide from flue gas using the sludge sodium humate. *The Scientific World Journal*, *2013*.

[12] Zhao, L., Riensche, E., Blum, L., & Stolten, D. (2010). Multi-stage gas separation membrane processes used in post-combustion capture: Energetic and economic analyses. *Journal of membrane science*, *359*(1-2), 160-172..

[13] Zhao, L., Riensche, E., Menzer, R., Blum, L., & Stolten, D. (2008). A parametric study of CO_2/N_2 gas separation membrane processes for post-combustion capture. *Journal of Membrane Science*, *325*(1), 284-294.

[14] Metz, B., Davidson, O., De Coninck, H., Loos, M., & Meyer, L. (2005). *IPCC special report on carbon dioxide capture and storage*. Intergovernmental Panel on Climate Change, Geneva (Switzerland). Working Group III.

[15] Yu, C. H., Huang, C. H., & Tan, C. S. (2012). A review of CO_2 capture by absorption and adsorption. *Aerosol Air Qual. Res*, *12*(5), 745-769.

[16] Wei, J., Guo, X., Marinova, D., & Fan, J. (2014). Industrial SO_2 pollution and agricultural losses in China: evidence from heavy air polluters. *Journal of Cleaner Production*, *64*, 404-413.

[17] Songolzadeh, M., Soleimani, M., Takht Ravanchi, M., & Songolzadeh, R. (2014). Carbon dioxide separation from flue gases: a technological review emphasizing reduction in greenhouse gas emissions. *The Scientific World Journal*, *2014*.

[18] Favre, E. (2011). Membrane processes and postcombustion carbon dioxide capture: Challenges and prospects. *Chemical Engineering Journal*, *171*(3), 782-793.

[19] Brunetti, A., Bernardo, P., Drioli, E., Barbieri, G., Yampolskii, Y., & Freeman, B. (2010). Membrane engineering: Progress and potentialities in gas separations. *Membrane Gas Separation*, *6*, 279-312.

[20] Shekhawat, D., Luebke, D. R., & Pennline, H. W. (2003). *A review of carbon dioxide selective membranes: A topical report* (No. DOE/NETL-2003/1200). National Energy Technology Lab., Pittsburgh, PA (US); National Energy Technology Lab., Morgantown, WV (US).

[21] Wong, S., & Bioletti, R. (2002). Carbon dioxide separation technologies. *Alberta Research Council*.

[22] Aaron, D., & Tsouris, C. (2005). Separation of CO_2 from flue gas: a review. *Separation Science and Technology*, *40*(1-3), 321-348..

[23] Xu, A., Yang, A., Young, S., demontigny, D., & Tontiwachwuthikul, P. (2008). Effect of internal coagulant on effectiveness of polyvinylidene fluoride membrane for carbon dioxide separation and absorption. *Journal of Membrane Science*, *311*(1-2), 153-158.

[24] Yeo, Z. Y., Chew, T. L., Zhu, P. W., Mohamed, A. R., & Chai, S. P. (2012). Conventional processes and membrane technology for carbon dioxide removal from natural gas: A review. *Journal of Natural Gas Chemistry*, *21*(3), 282-298.

[25] Chew, T. L., Ahmad, A. L., & Bhatia, S. (2010). Ordered mesoporous silica (OMS) as an adsorbent and membrane for separation of carbon dioxide (CO_2). *Advances in colloid and interface science*, *153*(1-2), 43-57.

[26] Scholes, C. A., Chen, G. Q., Stevens, G. W., & Kentish, S. E. (2011). Nitric oxide and carbon monoxide permeation through glassy polymeric membranes for carbon dioxide separation. *Chemical Engineering Research and Design*, *89*(9), 1730-1736.

[27] Kentish, S. E., Scholes, C. A., & Stevens, G. W. (2008). Carbon dioxide separation through polymeric membrane systems for flue gas applications. *Recent Patents on Chemical Engineering*, *1*(1), 52-66.

[28] El-Azzami, L. A., & Grulke, E. A. (2009). Carbon dioxide separation from hydrogen and nitrogen: Facilitated transport in arginine salt–chitosan membranes. *Journal of Membrane Science*, *328*(1-2), 15-22.

[29] Powell, C. E., & Qiao, G. G. (2006). Polymeric CO_2/N_2 gas separation membranes for the capture of carbon dioxide from power plant flue gases. *Journal of Membrane Science*, *279*(1-2), 1-49.

[30] Damle, A. S., & Dorchak, T. P. (2001). Recovery of carbon dioxide in advanced fossil energy conversion processes using a membrane reactor. *Journal of Energy and Environment Research*, *1*(1), 77-89.

[31] Xu, Z., Wang, J., Chen, W., & Xu, Y. (2001, May). Separation and fixation of carbon dioxide using polymeric membrane contactor. In *First National Conference on Carbon Sequestration*.

[32] Kusakabe, K., Kuroda, T., & Morooka, S. (1998). Separation of carbon dioxide from nitrogen using ion-exchanged faujasite-type zeolite membranes formed on porous support tubes. *Journal of membrane science*, *148*(1), 13-23.

[33] Van den Bergh, J., Zhu, W., Gascon, J., Moulijn, J. A., & Kapteijn, F. (2008). Separation and permeation characteristics of a DD3R zeolite membrane. *Journal of Membrane Science*, *316*(1-2), 35-45.

[34] Bernal, M. P., Coronas, J., Menendez, M., & Santamaria, J. (2004). Separation of CO_2/N_2 mixtures using MFI-type zeolite membranes. *AIChE journal*, *50*(1), 127-135.

[35] Luebke, D., Myers, C., & Pennline, H. (2006). Hybrid membranes for selective carbon dioxide separation from fuel gas. *Energy & fuels*, *20*(5), 1906-1913.

[36] Way, J. D., & Roberts, D. L. (1992). Hollow fiber inorganic membranes for gas separations. *Separation science and technology*, *27*(1), 29-41.

[37] Koros, W. J., & Fleming, G. K. (1993). Membrane-based gas separation. *Journal of membrane science*, *83*(1), 1-80.

[38] Basile, A., & Gallucci, F. (Eds.). (2010). *Membranes for membrane reactors: preparation, optimization and selection*. John Wiley & Sons.

[39] Ismail, A. F., Rana, D., Matsuura, T., & Foley, H. C. (2011). *Carbon-based membranes for separation processes*. Springer Science & Business Media.

[40] Hsieh, H. P. (1996). *Inorganic membranes for separation and reaction* (Vol. 3). Elsevier.

[41] Fenger, J. (2009). Air pollution in the last 50 years–From local to global. *Atmospheric environment*, *43*(1), 13-22.

[42] Streets, D. G., & Waldhoff, S. T. (2000). Present and future emissions of air pollutants in China:: SO_2, NOx, and CO. *Atmospheric Environment*, *34*(3), 363-374.

[43] Müller, M. O., Stämpfli, A., Dold, U., & Hammer, T. (2011). Energy autarky: A conceptual framework for sustainable regional development. *Energy policy*, *39*(10), 5800-5810.

[44] Rubin, E. S. (1999). Toxic releases from power plants.

[45] Demirbas, A., & Balat, M. (2004). Coal desulfurization via different methods. *Energy Sources*, *26*(6), 541-550.

[46] Zhang, J., You, C., & Chen, C. (2010). Effect of internal structure on flue gas desulfurization with rapidly hydrated sorbent in a circulating fluidized bed at moderate temperatures. *Industrial & Engineering Chemistry Research*, *49*(22), 11464-11470.

[47] Zhou, Y., Zhang, M., Wang, D., & Wang, L. (2005). Study on a novel semidry flue gas desulfurization with multifluid alkaline spray generator. *Industrial & engineering chemistry research*, *44*(23), 8830-8836.

[48] Lancia, A., Musmarra, D., Pepe, F., & Volpicelli, G. (1994). SO_2 absorption in a bubbling reactor using limestone suspensions. *Chemical Engineering Science*, *49*(24), 4523-4532..

[49] Posner, A. M. (1966). THE HUMIC ACIDS EXTRACTED BY VARIOUS REAGENTS FROM A SOIL: PART I. YIELD, INORGANIC COMPONENTS, AND TITRATION CURVES.*Journal of Soil Science*, *17*(1), 65-78.