Removal of Hydrogen Sulphide Using Hydrogel Biochar Derived From Coal Fly Ash Through Multi Sorption Bed

M. R. M. Said and A. B. Alias,

Faculty of Chemical Engineering, Universiti Teknologi Mara

REM

Abstract— **Nowadays, great effort has been done on the finding of the utilization of coal fly ash. This is because the amount of coal fly ash generated annually is enormous and has become quite a concern because if it is not disposed properly it might bring a lot of problem to the environment. The objectives of this study were to produce hydrogel biochar coal fly ash (HBC-CFA), study the characteristics of the hydrogel produced, study its efficiency on H2S removal and compare it with hydrogel produced from the biochar of empty fruit bunch. The HBC-CFA was prepared by using several materials which were acrylamide (AAm) as the monomer, N, N'-Methylenebisacrylamide (MBA) as the crosslinker and Ammonium Persulphate (APS) as the initiator and raw coal fly ash itself. Analysis equipment that were used in the characterization of HBC-CFA were Thermogravimetric Analyzer (TGA) to study the proximate properties, Elemental Analyzer (EA) to study the ultimate properties, Brunaeur-Emmett Teller (BET) to study the surface area and Scanning Electron Microscopy (SEM) to study the morphology. For the study on its efficiency of H2S removal two parameters have been chosen which were the effect on bed loading and the effect of wetness. The number of bed used for adsorption was varied from 1 to 3 to study the effect of loading while 3 wet beds loading have been used to study the effect of wetness. For the study on bed loading, 3 beds loading recorded the most H2S gas adsorption with 209ppm adsorption value while for the study on wetness, wet bed recorded the most H2S gas adsorption with 241ppm adsorption value. The study on the comparison on characteristics between HBC-CFA and HBC-EFB showed that the HBC-CFA has higher surface area, pore volume and smaller pore diameter which were a good characteristics for and adsorbent. However, HBC-EFB has higher efficiency in H2S removal than HBC-CFA. The recorded value for 3 beds loading for HBC-EFB is 241ppm while for wetness is 262ppm. Both values are higher compared to HBC-CFA.**

Keywords— Hydrogel, Biochar, Coal Fly Ash, Hydrogen Sulphide Removal

1. INTRODUCTION

Hydrogen sulphide was considered as one of the primary inorganic contaminant exists in the atmosphere besides the oxide of nitrogen and sulphur. The source of hydrogen sulphide emission can be divided into two which are the natural sources and anthropogenic sources. Natural sources of hydrogen sulphide inlcude the emission from volcanoes, sulphur springs, undersea vents or stagnant bodies of water while from anthropogenic sources are combustion of natural gas or crude petroleum with high percentage of sulphur, agriculture operations, treatment of wastewater plants, pulp and paper operations and landfill gases from anaerobic reaction process [1].

Nowadays the largest emissions of sulphur dioxide are from the burning of fossil fuels at to generate energy such as natural gas, liquefied petroleum gas, tail gas, fuel cells and fuel used in vehicle like gasoline, diesel and jet fuels which usually consists of a fraction of hydrogen sulphide in it [2]. According to [3], hydrogen sulphide is also came out from the waste stream of several industries such as pulp and paper industry, tanning, molasses fermentation, distillery slops, citric acid production and mining. Nowadays, a lot of work has been done in removal of hydrogen sulphide especially removal of sulphur content in extracted fossil fuels. Typically, high temperature desulphurization process is used, a process which relies on the selection of the metal oxide sorbent and reactor design to remove the fraction of sulphur reside in the fossil fuels [4].

In gaseous form in the atmosphere, hydrogen sulphide easily can get access into the human through inhalation process. Because it is in gaseous form, protective organ of the human body such as the nose and tracheobronchial system cannot stop sulphur dioxide from entering the body. Low concentration of hydrogen sulphide inhaled, may not seems relevant to resulted in major respiratory diseases however it could be fatal if the gas inhaled in enormous amount. The harmful effects of hydrogen sulphide in abnormal levels are diabetes, hypertension, Alzheimer's disease and Down's syndrome [5].

However, sulphur dioxide pollution does not affect only human beings but instead everything in the environment. High concentration of hydrogen sulphide can cause toxic effects in cell and may disrupt several physiological functions in both plant and animals [6]. According to [7], high concentration of hydrogen sulphide amount absorbed by plant may disturb photosynthesis, respiration and other plant processes. Besides plant, the biggest threat that hydrogen sulphide brings to the environment is the formation of acid rain through the formation of sulphur dioxide by oxidation process. Besides that, hydrogen sulphide may also cause operational problems such as plant equipment corrosion and catalyst deactivation [8].

There are several methods used in the removal of sulphur dioxide which are absorption, adsorption and electro charging. Adsorption method in the removal of hydrogen sulphide was implemented by using regenerative adsorbent such as activated carbon, biochar, silica gel and zeolites and non-regenerative adsorbent such as calcium oxide and magnesium oxide [9]. Biochar generally used as fertilizer to improve the condition of the soil for plantation process. When biochar applied to the soil, it could effectively separate the carbon in the soil and thus could reduce global warming [10]. Biochar is a solid that is rich with carbon residue that produced from pyrolysis process of biomass from agriculture industry which usually plant-based biomass without the presence of oxygen [11].

Coal fly ash are cluster of spherical particles with a diameter ranging from 1 to 100µm and typically grey in colour, quite abrasive and mostly alkaline in nature [12]. This ash produced as a waste product during the combustion process of coal in generation of electricity. The quantity of coal fly ash generated annually is quite enormous due to large quantities of coal power plant worldwide. According to [13], the amounts of coal fly ash generated per year in China alone continuously increasing from 155 million tonnes in 2002 to 620 million tonnes in 2015.

Fortunately nowadays, most countries begin to utilize the coal fly ash. India utilize 38% of generated coal fly out of 112 metric tonnes while some Europe countries such as Denmark, Italy and Netherlands utilize 100% of the coal fly ash produced [14]. Fly ash is widely known as its usage as a raw feedstock in the production of cement and ceramic material. This is because, coal fly ash made up by components such as silicon oxide, aluminium oxide, iron oxide and calcium oxide which is which is quite similar to ceramic material in terms of their chemical stability and physical compositions [15].

Oil palm tree is an important crop worldwide, because of the edible oil that can be extracted from the oil palm fruit, and so it is usually planted in tropical areas of the world such as South America and South East Asian regions [16]. Palm oil waste can be classified into palm kernel shell (PKS), Palm oil fronds (POF) and Empty fruit bunches (EFB) in which palm kernel shell is more suitable compared to others for gasification process [17]. Empty fruit bunch is the fibrous material left after the palm oil fruit has been extracted. Usually, empty fruit bunch covered up to 22 to 25% of the fresh palm oil fruit [18]. Generally it was assumed that 90% of the biomass including empty fruit bunch from the entire palm oil tree has no practical usage [19].

However, nowadays a lot of researches have been done in order to find the proper utilization for empty fruit bunch. EFB also investigated for its purpose in the as raw material in the production of biofuel and biochemical [20]. Besides that EFB also known as its usage in the production of thermomechanical pulp (TMP) although it is still in early phase by using dry and wet blowing methods [21].

In this study, the empty fruit bunch biochar and coal fly ash will go through polymerization process by using Acrylamide (AAm) monomer to produce hydrogel biochar. The presence of the hydrogel coating of the biochar is known to help improves the adsorption efficiency by increasing the intake and holding up of water. Due to the high water content of the hydrogel plus porous structure networks, more solute can be trapped by the hydrogel component [22].

2. METHODOLOGY

2.1 Materials

Empty fruit bunch biochar and coal fly ash were obtained as gift from Master's student under the same supervisor and has been used as the raw material in this study was used in the preparation of the improved hydrogel. For the preparation of the hydrogel, acrylamide (AAm) used as monomer, N,N'-methylenebisacrylamide (MBA) as cross linker and ammonium persulfate (APS) as initiator were purchased from Sigma-Aldrich and Fluka Chemical Companies. Distilled water is used to remove unreacted monomer and to adjust the pH value of the biochar and coal fly ash.

For the study on the removal of hydrogen sulphide, multi sorption bed equipment was used. The equipment comprised with 3 beds in a 1 straight column. Each bed has a diameter of 4.8cm with height of 9.4cm. Each bed are supported by 1cm thick glass wool. Concentration of hydrogen sulphide in the gas outlet stream was detected by using Crowcon hydrogen sulphide analyzer that calibrated for 0 to 25ppm hydrogen sulphide detection.

2.2 Methods

2.2.1 Preparation of hydrogels

The preparation of the hydrogel was in accordance with procedure stated by Karakoyun [23]. The coal fly ash firstly washed with 0.1 mol/L hydrochloric acid solution for 6 hours. After that, DI water was used to wash the coal fly ash until neutral pH obtained. Then, the coal fly ash was dried in oven at 40^0C for 1 day.

1.0g of acrylamide (AAm) monomer was dissolved in 1mL of distilled water. 0.6g of the coal fly ash was mixed with 0.001g of MBA cross linker. The mixture of the coal fly ash and the cross linker then added to the AAm solution. 0.2mL of 0.1g aqueous solution of APS initiator was added to the solution to initiate the polymerization. The precursor solution immediately place into PVC straw and put in an oven at 40^0C for 30 minutes to speed up the polymerization and cross linking process. Then the precursor solution was left for 24 hours to let the polymerization and cross linking process complete. After 24 hours, the hydrogel biochar coal fly ash, HBC-CFA was taken from the straw and cut to desired size and washed with distilled water to remove unreacted monomer and low molecular weight matter from the HBC-CFA. Then the HBC-CFA was dried in vacuum oven at 40 C for 24 hours. After 24 hours the HBC-CFA was stored in desiccator until further used. The procedures repeated for EFB biochar.

2.2.2 Characterization of hydrogels

The characterization of the material used will be made before and after the polymerization process. Equipment that will be used in this study are scanning electron microscopy (SEM), elemental analyzer (EA), Brunaeur-Emmett Teller (BET), thermogravimetric analyzer (TGA) and the multi sorption bed. The scanning electron microscopy (SEM) is used to study the surface morphology and the composition of the sample, elemental analyzer (EA) is used to study the element exist on the sample and their composition, Brunaeur-Emmett Teller (BET) is used to study the specific surface area the sample provided including the pore size distributions, thermogravimetric analyser (TGA) is used to study the loss or gain of certain components on the sample whether due to decomposition, oxidation or anything else.

2.2.3Effect of bed loading

For the study on the effect of bed loading, a multi sorption bed was used. The adsorption column was purged with nitrogen gas before the experiment started. 1 cm thick glass wool beds were added to the first bed in the adsorption column. 2.54 cm or 1 inch of HBC-CFA were added to the first bed in the adsorption column. H2S concentration measuring device was attached to the effluent H2S gas stream. The temperature of the adsorption column was set at 25^0C while the flow rate and the concentration of H2S gas stream were set at 1L/min and 25ppm. The results were taken at the interval of 10s using stopwatch until the reading of the effluent gas stream reached 25ppm. All the steps were repeated by adding 2 and 3 beds of HBC-CFA in the adsorption column then by using HBC-EFB. **Fig. 1** shows the bed loading arrangement for study done for effect of bed loading

Fig. 1. Bed loading arrangement 1 bed (top left), 2 beds (top right) and 3 beds (bottom middle)

2.2.4Effect of wetness

The adsorption column was purged with nitrogen gas before the experiment started. 1 cm thick glass wool beds were added to all the beds in the adsorption column. Three 1 inch HBC-CFA beds was soaked with 10mL of distilled water each and left for few minutes. The soaked HBC-CFA beds then added into the adsorption column. The temperature of the adsorption column was set at 25^{0}C and the HBC-CFA bed was set to 3 beds for this study while the flow rate and the concentration of H2S gas stream were set at 1L/min and 25ppm. The results were taken at the interval of 10s using stopwatch until the reading of the effluent gas stream reached 25ppm. All the steps were repeated by using HBC-EFB.

3 RESULTS AND DISCUSSION

3.1 Preparation of hydrogels and their characterization

Fig. 2 shows the HBC-CFA produced for this study. The HBC-CFA produced was cut into small pieces to increase its surface area. Increase in surface area will increase the efficiency of adsorption.

Fig. 2. Hydrogel biochar coal fly ash

Table 1 Proximate analysis

Sample	Moisture (%)	Volatile (%)	Ash (%)	Fixed Carbon (%)
CFA	6.25	1.07	91.5	1.18
HBC-CFA	11.25	2.93	80.72	5.09

Table 1 shows the proximate analysis result for coal fly ash and HBC-CFA. From the table 4.1, we can see that the percentage of moisture, volatile matter and fixed carbon of HBC-CFA is higher compared to CFA at value of 11.25, 2.93 and 5.09 significantly. Coal fly ash is obtained from the combustion process of coal in power plant thus the moisture and volatile matter content must be low because both of them were released during the combustion process.

Table 2 Ultimate analysis

Sample	Nitrogen (%)	Carbon (%)	Hydrogen (%)	Sulfur (%)	Oxygen (%)
CFA	0.1153	6.8862	0.00	0.00	92.9985
HBC-CFA	8.91	24.62	3.80	0.00	62.67

Table 2 shows the ultimate analysis result for coal fly ash and HBC-CFA. HBC-CFA contains the most percentages of nitrogen, carbon and hydrogen with nitrogen at 8.91%, carbon at 24.62% and hydrogen at 3.80% while raw CFA ash has higher percentage of oxygen compared to HBC-CFA. For raw CFA, the carbon and nitrogen percentage is quite higher compared to study stated by Alessandro [24], which were carbon (2.14%) and nitrogen (0.07%). However, the composition for oxygen and hydrogen dropped from 96.14% to 92.9985% and 3.80% to 0% significantly.

Table 3 shows the BET analysis result for coal fly ash and HBC-CFA. HBC-CFA has the lower BET surface area, pore volume and pore size adsorption compared to raw coal fly ash. However, although the pores were filled with hydrogel medium, that do not mean that the efficiency of the both of them is weaken because hydrogel acts merely as a medium for transportation that help increase the adsorption power of the adsorbent.

Table 3 BET analysis

Samples	BET Surface Area $(\frac{m^2}{g})$	Pore Volume $(\frac{cm^3}{g})$	Pore Size Adsorption (Å)
CFA	3.62	0.0060	65.84
HBC-CFA	2.96	0.0013	17.74

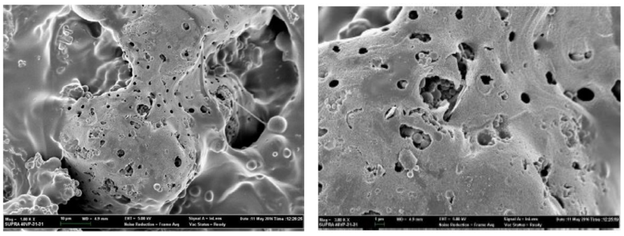

Fig. 3. SEM analysis for HBC-CFA, 1000(left), 3000(right)

Fig. 3 shows the SEM analysis result for coal fly ash and HBC-CFA at 1000 and 3000 magnify. . The pores formed on its surface are not uniform and spread across the surface in irregular shape. The pores formed on the hydrogel are very small in diameter thus this would be great for the HBC-CFA to be an adsorbent due to high surface area.

3.2 Effect of bed loading

The study on the H2S adsorption based on the adsorbent loading is crucial to the whole experiment because this study will determines the most effective adsorbent loading in the adsorption of H2S gas. . During this study, the flow rate of the H2S gas was fixed at 1L/min with concentration of 25ppm. The temperature of the bed was fixed at ambient temperature which is at 25ºC. This study was conducted by varying the amount of bed that the H2S gas has to flow through. The amount of beds used was varied from 1 bed to 3 beds loading. When the effluent gas reached 25ppm, this indicates that the bed can no longer adsorb the incoming H2S gas. Hypothetically, the more beds used the more H2S gas will be adsorbed. **Fig. 4** above shows a graph representing the amount of H2S gas adsorbed based on the amount of beds used for HBC-CFA. As we can observed from the graph, the amount of H2S adsorbed the most is by the 3 beds loadings measuring up to 209ppm of H2S gas adsorbed followed by 2 beds loadings measuring with 186ppm and lastly 1 bed loading with 169ppm. The difference in the amount of H2S adsorbed between the runs is quite small with the biggest difference are between 3 beds and 1 bed loadings with 40ppm difference.

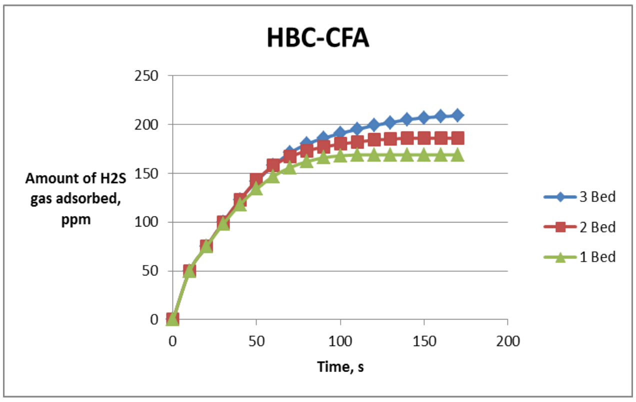

Fig. 4. Graph on effect of bed loading

3.2 Effect of wetness

In this section, the difference in the adsorption capacity between dry hydrogel and wet hydrogel are studied. This study will determines which condition of hydrogels is the best at H2S adsorption whether the wet hydrogels or dry hydrogels. The H2S gas stream flow rate was fixed at 1L/min with concentration of 25ppm. In this study, 3 beds loadings of hydrogels were used with each bed embedded with 1 inch thickness of hydrogels. The temperatures of the beds were fixed at 25^{0}C. . Hypothetically, wet hydrogels has high adsorption capacity compared to dry hydrogels. This is because wet hydrogels will offer more absorption than dry hydrogels. Furthermore, H2S gas has high solubility in water thus wet hydrogels supposed to dissolve more H2S gas than dry hydrogels.

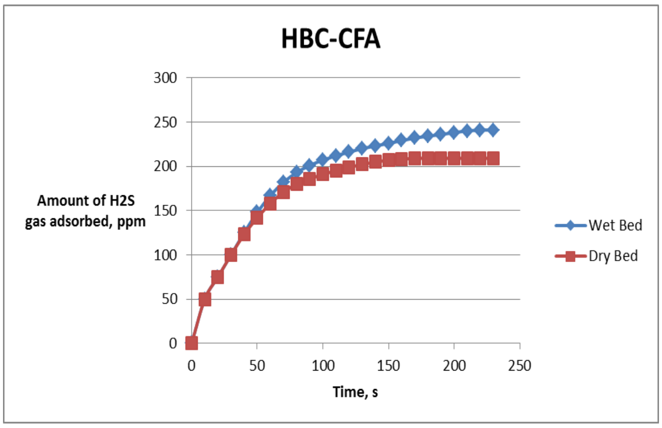

Fig. 5. Graph on effect of wetness

Fig. 5 above shows the graph plotted on the amount of H2S gas adsorbed versus time for HBC-CFA. Wet HBC-CFA has higher amount of H2S gas adsorbed measuring up to 241ppm followed by dry HBC-CFA with 209ppm of H2S gas adsorbed. The difference between the H2S gas adsorbed between wet HBC-CFA and dry HBC-CFA is 32ppm.

3.3 Comparative study

The comparative study was conducted to determine the effectiveness of hydrogel made from coal fly ash with hydrogel made from other material in this case the biochar of empty fruit bunch.

Table 4 Comparison on proximate analysis

Sample	**Moisture (%)**	**Volatile (%)**	**Ash (%)**	**Fixed Carbon (%)**
HBC-EFB	36.16	32.16	11.89	19.78
HBC-CFA	11.25	2.93	80.72	5.09

Table 4 shows the comparison on the proximate analysis result for HBC-EFB and HBC-CFA. The percentage of moisture, volatile matter and fixed carbon of HBC-EFB is higher compared to HBC-CFA. The results obtained are highly related to the raw materials used to make both hydrogels. Raw material used to make HBC-EFB which is the biochar of EFB. Before the pyrolysis process, EFB is known to have high water content in it up to 70wt% on wet basis and has low bulk density [19].

Table 5 Comparison on ultimate analysis

Sample	**Nitrogen (%)**	**Carbon (%)**	**Hydrogen (%)**	**Sulfur (%)**	**Oxygen (%)**
HBC-EFB	12.04	34.55	12.06	0.00	41.35
HBC-CFA	8.91	24.62	3.80	0.00	62.67

Table 5 shows the comparison on the ultimate analysis result for HBC-EFB and HBC-CFA. HBC-EFB has higher content of nitrogen, carbon and hydrogen. However, the content is lower compared to raw EFB as stated by Lee [20], which has 42.5% for carbon, 6.1% for hydrogen, 40.6% for oxygen and 0.7% for nitrogen. The decrease in the amount of nitrogen and carbon in

HBC-EFB is maybe because they were released during the pyrolysis process.

Table 6 Comparison on BET analysis

Samples	BET Surface Area $(\frac{m^2}{g})$	Pore Volume $(\frac{cm^3}{g})$	Pore Size Adsorption (Å)
CFA	3.62	0.0060	65.84
HBC-CFA	2.96	0.0013	17.74

Table 6 shows the comparison on the BET analysis result for HBC-EFB and HBC-CFA. HBC-CFA has the higher BET surface area, pore volume but lower pore size adsorption with $2.96 m^2 g^{-1}$, $0.0013 cm^3 g^{-1}$ and 17.74Å significantly. Furthermore the surface area of biochar greatly depends on the temperature during the pyrolysis temperature [25]. Thus at high pyrolysis temperature, more volatile substances components gain enough kinetic energy to escape the bond that holding them onto the biochar thus leaving more empty spaces [26].

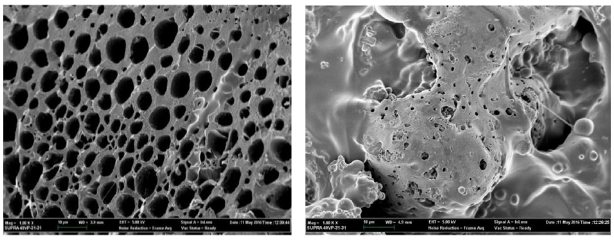

Fig. 6. SEM analysis for HBC-EFB(left) and HBC-CFA(right)

Fig. 6 shows the SEM analysis result for HBC-EFB and HBC-CFA at 1000 magnify. The pore for HBC-EFB can be seen clearly with the SEM analysis. The pore diameter of HBC-EFB is ranging from 1µm up to 10µm. The pores produced on HBC-EFB were quite uniform with circular shape. As for HBC-CFA, the pore cannot be really seen using the 1000 magnify SEM analysis due small pore diameter. This is because the raw coal fly ash itself is small in size measuring only 10µm [27]

After that we will study the comparison based on the effect on bed loading and effect on wetness. **Fig. 7** shows a graph on the comparison representing the amount of H2S gas adsorbed based on the amount of beds used for HBC-CFA and HBC-EFB. As we can observe from the graph, the most efficient adsorption of H2S gas recorded by 3 beds loadings of HBC-EFB with measured adsorption capacity of 241ppm followed by 2 beds loadings of HBC-EFB with adsorption capacity of 216ppm and then 3 beds loadings of HBC-CFA with measured value of 209ppm. According to Attari [28], raw coal fly ash generally has low adsorption capacity compared to other adsorbents. The results obtained shows that adsorbent made out from EFB has higher efficiency in adsorption of H2S gas compared to those made out from CFA.

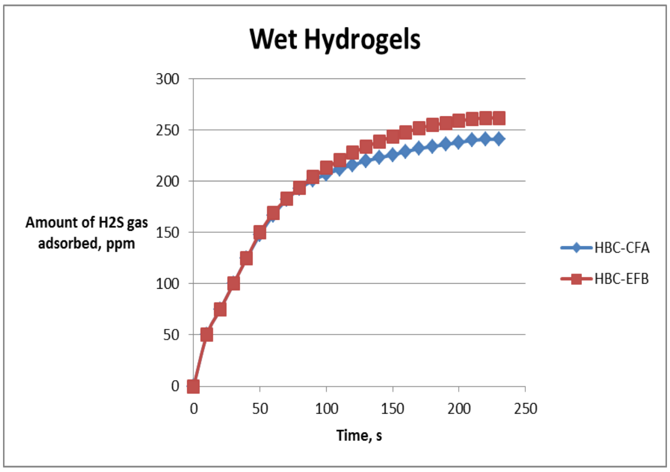

Fig. 8. Graph on comparison on effect of wetness

Fig. 8 shows a graph on the comparison representing the amount of H2S gas adsorbed based on the wetness for HBC-CFA and HBC-EFB. The difference on the H2S gas adsorbed by both hydrogels is not that much with 241ppm adsorption value for HBC-CFA and 262ppm for HBC-EFB. However, the results still shows us that hydrogels made up from EFB is superior compared to CFA in wet condition

In conclusion, the overall results on the H2S adsorption are quite low compared to other studies by other researchers. The highest adsorption value recorded in this experiment was 262ppm. There are several reasons that can be attached to the poor adsorption result for this experiment. The first one is flow rate of H2S gas. Most studies have shown that the lower the flow rate of H2S gas the higher the adsorption capacity. However, for this experiment, the lowest flow rate that can be set on the equipment used to study H2S adsorption is 1L/min. In comparison with other studies, 1L/min is quite large for the flow rate of H2S gas. The average values of flow rate usually used for adsorption study are ranging from 60mL/min up to 250mL/min.

Besides that, the maximum concentration of H2S gas used is only 25ppm due to safety reasons. This value is lower compared to other H2S adsorption studies. According to the study done by Lau [29], the concentration of H2S gas used are ranging from 1000ppm to 3000ppm. Hypothetically the higher the concentration of H2S gas used the higher the capacity of the H2S gas absorbed. Furthermore, the column used in this experiment is quite big in diameter compared to other researches. The average diameter that is commonly used for gas adsorption study is 1.27cm.

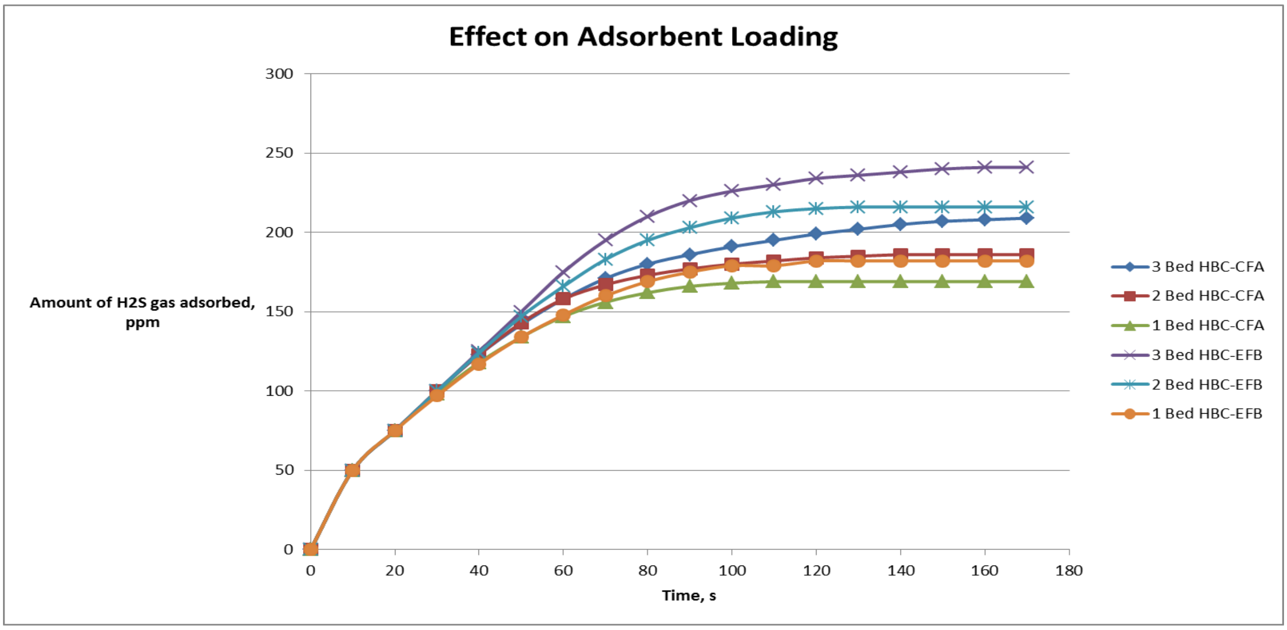

Fig. 7. Graph on comparison on effect of bed loading

4 Conclusion

In conclusion, the study on the characteristics, the study on the efficiency of hydrogen sulphide removal and the study on comparison between HBC-CFA and HBC-EFB was achieved successfully. From the characterization results we can conclude that HBC-CFA has higher BET surface area and pore volume compared to HBC-EFB. However, the proximate and ultimate results shows that HBC-EFB has higher value than HBC-CFA in most components such as moisture content, volatile matter, fixed carbon, nitrogen, carbon and hydrogen. Besides that, based on SEM images pores formed on HBC-EFB surface are much more circular and less defects compared to those formed on HBC-CFA. From the study on the efficiency of hydrogen sulphide removal, HBC-EFB observed superior than HBC-CFA in all parameters. Several suggestions and modifications can be done to the study to improve its results such as increase the parameter on the hydrogen sulphide removal study by including effect on temperature, effect on flow rate and effect on initial gas concentration.

Acknowledgment

I really wanted to express my gratitude to several important people that give as strong support all the way from nothing until the research done. This report cannot be completed without the help and guidance from those important people that do not hesitate in giving help when needed. Also thanks to Universiti Teknologi Mara for giving me the opportunity to carry out this study.

References

[1] Goldnik, E., & Turek, T. (2016). Removal of hydrogen sulfide by permanganate based sorbents : Experimental investigation and reactor modeling. *Chemical Engineering Science*.

[2] Fellah, M. (2015). Adsorption of hydrogen sulfide as initial step of H2S removal: A DFT study on metal exchanged ZSM-12 clusters. *Fuel Processing Technology*

[3] Kanjanarong, J., Giri, B., Jaisi, D., Oliveira, F., Boonsawang, P., Removal of hydrogen sulfide generated `sulfate-laden wastewater using biochar: Evaluation of efficiency and mechanisms. *Bioresource Technology*.

[4] Su, Y.-M., Huang, C.-Y., Chyyou, Y.-P., & Svoboda, K. (2016). Sulfidation/regeneration multi-cyclic testing of Fe 2 O 3 /Al 2 O 3 sorbents for the high-temperature removal of hydrogen sulfide. *Journal of the Taiwan Institute of Chemical Engineers*.

[5] Zhang, Y., Li, M., Niu, Q., Gao, P., Zhang, G., Dong, C., et al. (2017). Gold nanoclusters as fluorescent sensors for selective and sensitive hydrogen sulfide detection. *Talanta*.

[6] Li, D., Li, L., Ge, Z., Limwachiranon, J., Ban, Z., Yang, D., et al. (2017). Effects of hydrogen sulfide on yellowing and energy metabolism in broccoli. *Postharvest Biology and Technology*.

[7] Awanish. (2014). Plant responses to SO2 pollution and its amelioration. *International Journal of Plant Sciences*.

[8] Moon, J., Jo, W., Jeong, S., Bang, B., Choi, Y., Hwang, J., et al. (2017). Gas cleaning with molten tin for hydrogen sulfide and tar in producergas generated from biomass gasification. *Energy*.

[9] Al-Harahsheh, M., Shawabkeh, R., Batiha, M., Al-Harahsheh, A., & Al-Zhoon, K. (2014). Sulfur Dioxide Removal using Natural Zeolitic Tuff. *Fuel Processing Technology*.

[10] Yao, Y., Gao, B., Zhang, C., & Yang, L. (2015). Engineered Biochar from Biofuel Residue: Characterization and Its Silver Removal Potential. *Applied Material & Interfaces*.

[11] Thines, K., Abdullah, E., Mubarak, N., & Ruthiraan, M. (2016). Synthesis of magnetic biochar from agricultural waste biomass to enhancing route for waste waterand polymerapplication: A review. *Renewable and Sustainable Energy Reviews*.

[12] Lee, Y.-R., Soe, J., Zhang, S., Ahn, J.-W., Park, M., & Ahn, W.-S. (2017). Synthesis of nanoporous materials via recycling coal fly ash and othersolid wastes: A mini review. *Chemical Engineering Journal*.

[13] Sun, L., Luo, K., Fan, J., & Lu, H. (2017). Experimental study of extracting alumina from coal fly ash using fluidized beds at high temperature. *Fuel*.

[14] Gupta, N., Gedam, V. V., Moghe, C., & Labhasetwar, P. (2017). Investigation of characteristics and leaching behavior of coal fly ash,

coal fly ash bricks and clay bricks. *Environmental Technology & Innovation*.

[15] Tastan, B. (2017). Clean up fly ash from coal burning plants by new isolated fungi Fusarium oxysporum and Penicillium glabrum. *Journal of Environmental Management*.

[16] Chang, G., Huang, Y., Xie, J., Yang, H., Liu, H., Yin, X., et al. (2016). The lignin pyrolysis composition and pyrolysis products of palm kernel shell, wheat straw, and pine sawdust. *Energy Conversion and Management*.

[17] Shahbaz, M., Yusup, S., Inayat, A., Patrick, D., & Pratama, A. (2016). Application of response surface methodology to investigate the effect of different variables on conversion of palm kernel shell in steam gasification using coal bottom ash. *Applied Energy*.

[18] Or, K., Putra, A., & Selamat, M. (2016). Oil palm empty fruit bunch fibres as sustainable acoustic absorber. *Applied Acoustics*.

[19] Darmawan, A., Budianto, D., Aziz, M., & Tokimatsu, K. (2017). Retrofitting existing coal power plants through cofiring with hydrothermally treated empty fruit bunch and a novel integrated system. *Applied Energy*.

[20] Lee, H.-S., Lee, H., Ha, J.-M., Kim, J., & Suh, D. (2015). Production of aromatic compounds from oil palm empty fruit bunches by hydro- and solvothermolysis. *Industrial Crops and Products*.

[21] Nakagawa-Izumi, A., H'ng, Y., Mulyantara, L., Maryana, R., Do, V., & Ohi, H. (2016). Characterization of syringyl and guaiacyl lignins in thermomechanical pulp from oil palm empty fruit bunch by pyrolysis-gas chromatography-mass spectrometry using ion intensity calibration. *Industrial Crops and Products*.

[22] Paulino, A., Guilherme, M., Reis, A., Campese, G., Muniz, E., & Nozaki, J. (2006). Removal of methylene blue dye from an aqueous media using superabsorbent hydrogel supported on modified polysaccharide. *Journal of Colloid and Interface Science*.

[23] Karakoyun, N., Kubilay, S., Aktas, N., Turhan, O., Kasimoglu, M., Yilmaz, S., et al. (2011). Hydrogel–Biochar composites for effective organic contaminant removal from aqueous media. *Desalination*.

[24] Alessandro, M., Massimiliano, E., & Spiga, D. (2016). CO2 uptake capacity of coal fly ash: Influence of pressure and temperature on direct gas-solid carbonation. *Journal of Environmental Chemical Engineering*.

[25] Wang, Y.-Y., Lu, H.-H., Liu, Y.-X., & Yang, S.-M. (2016). Ammonium citrate-modified biochar: An adsorbent for La(III) ions from aqueous solution. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*.

[26] Ahmad Sohaimi, K., Ngadi, N., & Yacoob, N. (2014). Synthesis and Characterization of Biochars from Textile Sludge Precursors. *Synthesis and Characterization of Biochars from Textile Sludge*.

[27] Ahmaruzzaman, M. (2010). A review on the utilization of fly ash. *Progress in Energy and Combustion Science*.

[28] Attari, M., Bukhari, S., Kazemian, H., & Rohani, S. (2016). A low-cost adsorbent from coal industrial wastewater. *Journal of Environmental Chemical Engineering*.

[29] Lau, L., Nor, N., Lee, K., & Mohamed, A. (2016). Hydrogen sulfide removal using CeO2/NaOH/PSAC: Effect of process conditions and regeneration study. *Journal of Environmental Chemical Engineering*.