

HYDROGEN SULFIDE ADSORPTION BY ALKALINE IMPREGNATED COCONUT SHELL ACTIVATED CARBON

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Abstract

Biogas is one type of renewable energy which can be burnt to produce heat and electricity. However, it cannot be burnt directly due to the presence of hydrogen sulfide (H_2S) which is highly corrosive to gas engine. In this study, coconut shell activated carbon (CSAC) was applied as a porous adsorbent for H_2S removal. The effect of amount of activated carbon and flow rate of gas stream toward adsorption capacity were investigated. Then, the activated carbons were impregnated by three types of alkaline (NaOH, KOH and K_2CO_3) with various ratios. The effects of various types of alkaline and their impregnation ratio towards adsorption capacity were analysed. In addition, H_2S influent concentration and the reaction temperature on H_2S adsorption were also investigated. The result indicated that adsorption capacity increases with the amount of activated carbon and decreases with flow rate of gas stream. Alkaline impregnated activated carbons had better performance than unimpregnated activated carbon. Among all impregnated activated carbons, activated carbon impregnated by K_2CO_3 with ratio 2.0 gave the highest adsorption capacity. Its adsorption capacity was 25 times higher than unimpregnated activated carbon. The result also indicated that the adsorption capacity of impregnated activated carbon decreased with the increment of H_2S influent concentration. Optimum temperature for H_2S adsorption was found to be $50^\circ C$. In this study, the adsorption of H_2S on K_2CO_3 impregnated activated carbon was fitted to the Langmuir isotherm. The fresh and spent K_2CO_3 impregnated activated carbon were characterized to study the adsorption process.

Keywords: Activated carbon, Hydrogen sulfide, Impregnation.

Abbreviations

BET	Brunauer-Emmett-Teller
CSAC	Coconut shell activated carbon
IAC	Impregnated activated carbon
POME	Palm oil mill effluent
SEM	Scanning electron microscopy

1. Introduction

Malaysia is the second largest exporter of crude palm oil in the world with 17 million tonnes produced in 2010. Hence, palm oil mills in the country produce huge amount of palm oil mill effluent (POME). POME will undergo biological treatment which produces biogas before discharged into water streams. Biogas contains methane which can be burnt to produce heat and electricity. The composition of biogas from different organic residues is 40-75% of methane (CH₄), 25-40% of carbon dioxide (CO₂), 0.5-2.5% of nitrogen (N₂), 0.1-1% of oxygen (O₂), 1-3% of hydrogen (H₂), 0.1-0.5% of hydrogen sulfide (H₂S), 0.1-0.5% of ammonia (NH₃) and 0-0.1% of carbon monoxide (CO) [1]. However this biogas cannot be burnt directly due to the presence of hydrogen sulfide (H₂S) which is toxic and highly corrosive. Its strong acid behavior could cause internal damage of a gas engine. Besides, the 'rotten-egg' smell makes it environmentally objectionable. It can be detected at concentration as low as 0.0047 ppm [2]. The exposures towards H₂S can cause nausea, lost appetite, unstable emotion and not able to concentrate in daily jobs. Therefore, H₂S must be removed before biogas can be utilized as a type of renewable energy.

Various methods can be used for H₂S removal. For instance, the gas can be scrubbed and neutralized using chemicals, adsorbed on activated carbon, condensation, masking and direct or catalytic combustion [3]. Among these methods, activated carbon is widely used as adsorbent for adsorption of low concentration of harmful gas due to its extremely porous structure and high specific surface area [4]. Water and other chemicals are not so applicable in the removal of H₂S at such low concentration (ppm level). Therefore, activated carbon acts as an agent that can concentrate the H₂S from a dilute stream. It is cheaper compare with other adsorbents such as zeolite, alumina and silica. Activated carbon can be produced from many types of agricultural biomass with different carbonizing and activating conditions depending on the properties of the biomass.

Carbonization process eliminates non carbon species on the materials to produce fixed carbon mass and rudimentary pore structure. Activation process on the other hand enhances the pore volume and creates new porosity on the carbon surface. Surface modification is subsequently performed via chemical impregnation in order to enhance the performance of activated carbon. The chemical agents used in impregnation process include NaOH, KOH, K₂CO₃, Na₂CO₃, AlCl₃, ZnCl₂, MgCl₂, H₃PO₄, HCl, H₂SO₄, HNO₃, KI and KMnO₄ [2, 3, 5, 6]. In physisorption, pollutants adhere on activated carbon by weak van der Waals' forces. If functional groups present on the activated carbon, hydrogen sulfide can be effectively captured via chemisorption and converted to sulphur at operation temperature between 24-170°C [7], thus increase the adsorption capacity. Chemical impregnation process could be classified into three stages:

pre, mid and post impregnation [8]. Pre-impregnation is widely studied and is well known as 'chemical activation' [4, 9] and the impregnated activated carbon indicated higher adsorption capacity compare to non-impregnated activated carbon. In pre-impregnation, raw biomass is mixed with chemical precursor before the carbonization process; in mid-impregnation, chemical precursor is impregnated on char carbonized before activation process; while for post-impregnation, chemical precursor is impregnated on activated carbon produced.

When the activated carbon is saturated with contaminants, it could be sent for regeneration or reactivation in order to remove the contaminants and restore the pore structure of the activated carbon so that it could be reuse. High temperature or utilization of solvent such as water and alkaline solution are involved during these processes for removing the contaminant. After a few regeneration cycles, the pore structures could collapse, and then the activated carbon has to be sent for disposal. Prior disposal, the spent activated carbon will be classified into hazardous or non-hazardous. If the contaminant does not involve hazardous component, the spent activated carbon could be sent for landfill. While the spent activated carbon with hazardous adsorbate will be sent for incineration.

In this paper, three types of alkaline (NaOH, KOH and K_2CO_3) will be impregnated on coconut shell activated carbon (CSAC). Then, the effect of alkaline type and ratio towards adsorption capacity are investigated and compared with unimpregnated CSAC. In addition, the effect of amount of activated carbon, flow rate of gas stream, influent concentration of H_2S and reaction temperature toward the H_2S adsorption capacity of impregnated CSAC were studied.

2. Experimental Section

2.1. Chemicals and reagents

The coconut shell activated carbon (CSAC) was purchased from Laju Carbon Products Sdn Bhd, Malaysia. The CSAC was 4×8 US standard mesh size, iodine number 1000 mg/g, moisture content maximum 5%, ball pan hardness minimum 95%, ash content maximum 3% and pH value from 9 to 11. Sodium hydroxide (NaOH) with purity 99%, potassium hydroxide (KOH) with purity 99% and potassium carbonate (K_2CO_3) with purity 99% that were used for impregnation were purchased from Merck Sdn Bhd, Malaysia.

2.2. Adsorbent preparation

The raw CSAC were impregnated with NaOH, KOH and K_2CO_3 using wet impregnation method. Impregnation ratios of alkaline to CSAC prepared were 0.25, 0.5, 1.0, 1.5 and 2.0 based on Eq. (1).

$$\text{Impregnation ratio of alkaline to CSAC} = \frac{\text{Mass of alkaline (g)}}{\text{Mass of CSAC (g)}} \quad (1)$$

To produce the alkaline impregnated activated carbon with ratio 0.25, 2.5 grams of alkaline was weighted and dissolved in 60 mL deionized water. Then, 10 grams of activated carbon was added into the alkaline solution. After that, the mixture was placed in a water bath shaker and shake for 60 minutes at ambient

temperature. After 60 minutes, the solution was filtered and the impregnated activated carbon was dried at 100 °C until completely dry. The prepared impregnated activated carbon was labelled as IAC_{alkaline}- ratio. For example, IAC_{NaOH}- 0.25 denotes impregnated activated carbon with NaOH at ratio 0.25.

2.3. Adsorption study

H₂S adsorption study was performed using a biogas scrubbing unit. The schematic diagram of this adsorption unit is shown in Fig. 1. In this unit, biogas is simulated by mixing three gases (methane (CH₄), hydrogen sulfide in methane and carbon dioxide (CO₂) using an Aalborg AFC26 mass flow controller. Carbon dioxide and methane will be passed through humidification system to humidify the gas stream. H₂S stream is not passed through water humidification system so that inlet H₂S concentration is not affected due to the solubility of H₂S in water. Then the gases stream combines before enters the packed bed reactor which contained impregnated activated carbon. This impregnated activated carbon was placed at the middle of the tubular column supported with 0.05 grams glass wool. In this study, various amount of impregnated activated carbon was placed in the column. Simulated biogas with 50% CO₂, varied H₂S concentration (1000-5000 ppm) and balance methane were flowed through the column at various flow rates. Effect of temperature between 30- 70 °C was studied also using a Linberg/Blue M tube furnace as the temperature controller. The outlet gas from column will be analysed by a gas analyser (IMR 6000 supplied by IMP Environmental Equipment, Inc.). The adsorption test was ended at breakthrough time, i.e., when the outlet concentration of H₂S, C reaches breakthrough concentration at $C/C_0 = 0.05$ where C_0 was the influent H₂S concentration. The H₂S adsorption capacity was calculated using Eq. (2).

$$\text{Adsorption capacity (mg/g)} = \frac{\text{H}_2\text{S concentration (ppm)} \times \text{H}_2\text{S molecular weight} \left(\frac{\text{g}}{\text{mol}} \right) \times \text{Flowrate} \left(\frac{\text{ml}}{\text{min}} \right) \times \text{breakthrough time (min)}}{\text{Amount of CSAC used (g)} \times \text{STP} \left(\frac{\text{L}}{\text{mol}} \right)} \quad (2)$$

where adsorption capacity (mg/g) = Amount of H₂S adsorbed (mg) / Amount of CSAC used (g)

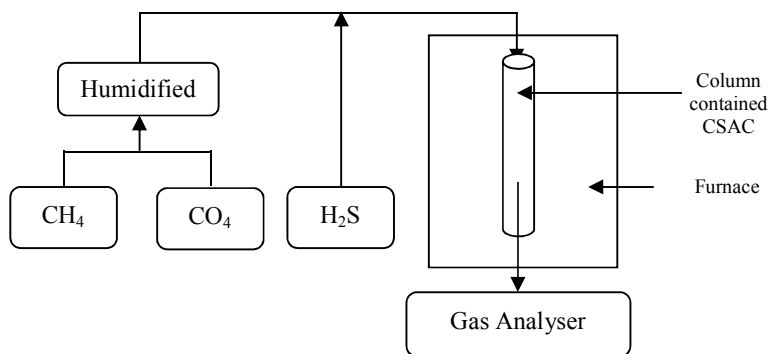


Fig. 1. Schematic Diagram of Adsorption System.

2.4. Characterization

Both fresh and spent impregnated activated carbons were characterized using SEM testing to analyse the surface morphology, crystalline structure and distribution of the alkaline salt on the samples. This SEM testing is carried out using a Leo Supra 35Vp-24-58 (supplied by Carl Zeiss, Inc.) at an accelerating voltage of 3kV. The surface area, pore volume and pore size of both fresh and spent impregnated activated carbons were measured by nitrogen adsorption desorption using an Autosorb IC Quantachrome analyser (model: ASI-MP-H).

3. Results and Discussion

3.1. Effect of adsorbent amount

Figure 2 shows that when higher amount of activated carbon was used, higher adsorption capacity would be achieved. Activated carbon is extremely porous and therefore can provide larger surface area for the adsorption process. When the amount of adsorbent was increased, the effective interfacial area would also increase. Thus, H_2S had more opportunity to contact with the adsorption site on activated carbon surface. The time taken to reach breakthrough was longer because the portion of adsorbent in front of the mass transfer zone had not yet been exposed to H_2S , hence the adsorption capacity was increased. In addition, more adsorbent donates taller adsorption section or longer contact time for H_2S molecules to adsorb into the pore structure of activated carbon.

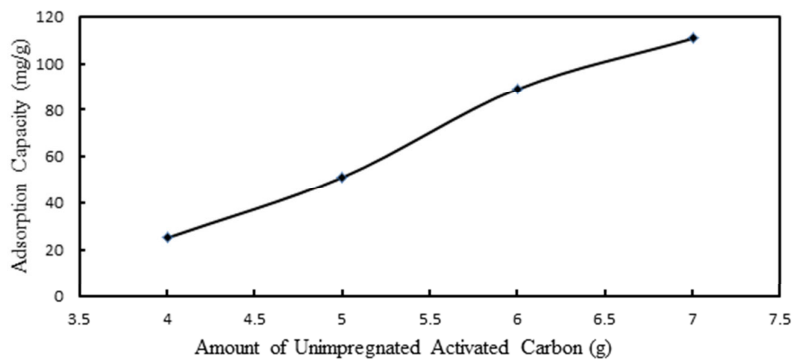


Fig. 2. Effect of Amount of Activated Carbon to H_2S Adsorption (H_2S Concentration: 2000 ppm, Temperature: 30°C).

3.2. Effect of flow rate

From Fig. 3, it can be observed that the adsorption capacity of unimpregnated activated carbon is decreasing with higher flow rate. The flow rate of gas determined the contact time between gas stream and adsorbent. When the flow rate was lower, the gas stream had longer contact time with the adsorbent; therefore more H_2S could be adsorbed. Thus, it took longer time to exceed the

ability of activated carbon to adsorb all H₂S molecules from the gas stream until it reach breakthrough and hence contributes to higher adsorption capacity.

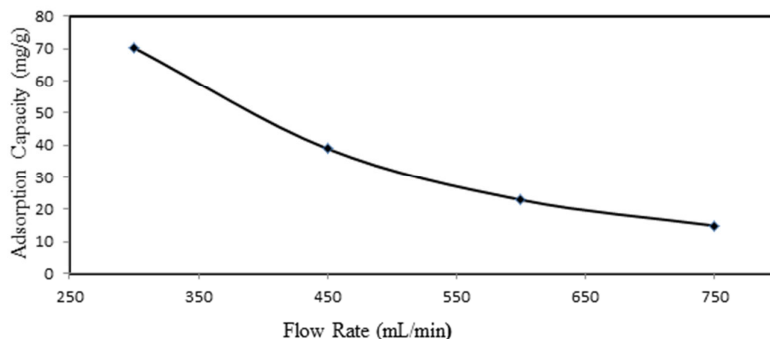


Fig. 3. Effect of Flow Rate to H₂S Adsorption (7 g of CSAC used, H₂S Concentration: 2000 ppm, Temperature: 30°C).

3.3. Alkaline impregnated activated carbon

In this study, the performance between unimpregnated activated carbon and impregnated activated carbons were compared. In this section, the H₂S concentration was raised to 3000 ppm to study the performance of activated carbon at higher concentration, at reaction temperature of 30°C with two grams of activated carbon used. Previously in section 3.1, the lowest amount of unimpregnated activated carbon used was four grams because the adsorption capacity was lower for amount of activated carbon lesser than four grams. While in this section, only two grams of impregnated activated carbon was used because the adsorption capacity was generally higher. For unimpregnated activated carbon, the breakthrough adsorption capacity was 1.5 mg/g. During adsorption process, the H₂S molecules were adsorbed on the adsorption sites by weak van der Waal's forces. The mechanism of physisorption occurred on unimpregnated activated carbon could be proposed as below. First, H₂S was diffused from bulk gas stream to external surface of adsorbent where the H₂S inlet stream contained 60% humidity. Next, the H₂S molecules diffused into macropore, mesopore and micropore region and then adsorbed to the surface in the pore as Reaction (3). After that, the adsorbed H₂S dissolved in a water film as Reaction (4) and finally the H₂S adsorbed in the water film will undergo dissociation as Reaction (5) [10].

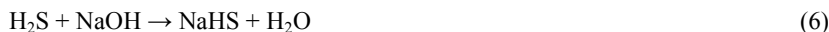


where H₂S (g), H₂S (ads-liq) and H₂S (ads) represented the H₂S in the gas, liquid and adsorbed phases, respectively.

The result showed that the performance of impregnated activated carbons were much better than the unimpregnated activated carbon. From Fig. 4, the adsorption capacities of impregnated activated carbons are ten folds higher than unimpregnated one. H₂S is an acid gas and the presence of basic group on the surface of activated carbon plays a very important role in the adsorption process.

After impregnated with alkaline chemicals, the surface condition was basic. The basic carbon surface enhances dissociation of hydrogen sulfide to HS^- and H^+ that subsequently reacts with alkaline impregnants (K^+ or Na^+) on the surface of activated carbon to produce sulfide product. Hence, H_2S can be efficiently chemisorbed by alkaline molecules impregnated on activated carbon.

For NaOH impregnated activated carbon, Fig. 4 showed that the adsorption capacity decreased when the NaOH impregnation ratio was increased. $\text{IAC}_{\text{NaOH}-0.25}$ gave the maximum adsorption capacity among NaOH impregnated activated carbons and it demonstrated a 12.3 times adsorption capacity compared to unimpregnated activated carbon. Lee et al. [11] suggested that basic hydroxide ions could largely affect the degree of adsorptivity of activated carbon. According to Chiang et al. [12], when the H_2S flow through the NaOH impregnated activated carbon, the reactions occurred on surface of activated carbon were



or



In Reactions (6) and (7), H_2S molecules reacted with NaOH molecules that was impregnated on the activated carbon to produce NaHS or Na_2S . That chemical bonding is stronger than physisorption and irreversible. However, Fig. 4 showed that the H_2S adsorption capacity of impregnated activated carbon decreased with the increment of the NaOH impregnation ratio. This might be caused by the pore blockage by the NaOH molecules on activated carbon as NaOH having smaller particle size compare to KOH and K_2CO_3 . When the activated carbons were impregnated with greater NaOH ratio, the impregnants blocked smaller pores and reduced effective surface area which caused the NaOH molecules have less contact with the H_2S molecules. Hence, the adsorption capacities were lower than $\text{IAC}_{\text{NaOH}-0.25}$.

For K_2CO_3 impregnation, a linear relationship can be observed from Fig. 4. When the K_2CO_3 impregnation ratio was increased, the increment of H_2S adsorption capacity could be observed. The result indicated that $\text{IAC}_{\text{K}_2\text{CO}_3-2.0}$ had the largest adsorption capacity among impregnated activated carbons. Besides, the performance of $\text{IAC}_{\text{K}_2\text{CO}_3-2.0}$ was two times higher comparing to $\text{IAC}_{\text{NaOH}-0.25}$. Moreover, the result indicated that H_2S adsorption via $\text{IAC}_{\text{K}_2\text{CO}_3-2.0}$ was 25 times higher than unimpregnated activated carbon. For $\text{IAC}_{\text{K}_2\text{CO}_3-0.5}$ that had the lowest performance among K_2CO_3 impregnated activated carbons was also 13.5 times of unimpregnated activated carbon. This result showed that activated carbon impregnated with K_2CO_3 generally possesses good H_2S adsorption capacity. The proposed reaction mechanism is shown below [3]



or



According to the study done by Tsai et al. [3], both reactions shows that one molecule of K_2CO_3 will react with one molecule of H_2S . At similar impregnation ratio, activated carbon impregnated with K_2CO_3 is able to react with more H_2S molecules compare to NaOH impregnated activated carbon that needed two NaOH molecules to react with one H_2S molecule. The claim can be concluded from the comparison of adsorption capacities of $\text{IAC}_{\text{K}_2\text{CO}_3-0.5}$ and $\text{IAC}_{\text{NaOH}-0.5}$.

The adsorption capacity was 20.3 mg/g for $IAC_{K_2CO_3-0.5}$, approximately twice of $IAC_{NaOH-0.5}$ (10.9 mg/g). In addition, at increased K_2CO_3 impregnation ratio, more alkaline molecules would attach on the surface of activated carbon. Consequently, more H_2S molecules could be removed. From the SEM image for K_2CO_3 impregnated activated carbon with ratio 2.0 as shown in Fig. 7(a), K_2CO_3 were attached on the surface of activated carbon without causing major pore blockage. In short, this indicated the co-occurrence of physical and chemical adsorption as stated in Tsai et al. [3] that when the H_2S adsorbed on activated carbon impregnated by K_2CO_3 , both physical and chemical adsorption exist because activated carbon surface cannot be completely occupied by K_2CO_3 .

For KOH impregnation, it can be observed that KOH impregnated activated carbons with ratio 0.25, 0.5 and 1.0 gave similar H_2S adsorption capacities compare with other impregnation ratio. For $IAC_{KOH-1.0}$, adsorption capacity is 21.4 times higher than unimpregnated activated carbon. Additional of high reactivity potassium tends to react with HS^- ions to form potassium hydrogen sulfide [11]. Therefore, KOH impregnated activated carbons were capable of adsorbing H_2S at low impregnation ratio. However, when the ratio of impregnation increased to 1.5 and 2.0, adsorption capacity decreased dramatically. This phenomenon might due to the agglomeration of KOH molecules on the surface of activated carbon and cause pore blockage. In this study, the performance of activated carbon were ranked $IAC_{K_2CO_3} > IAC_{KOH} > IAC_{NaOH} >$ unimpregnated activated carbon. This result concluded that H_2S adsorption capacity was largely enhanced after chemical impregnation process.

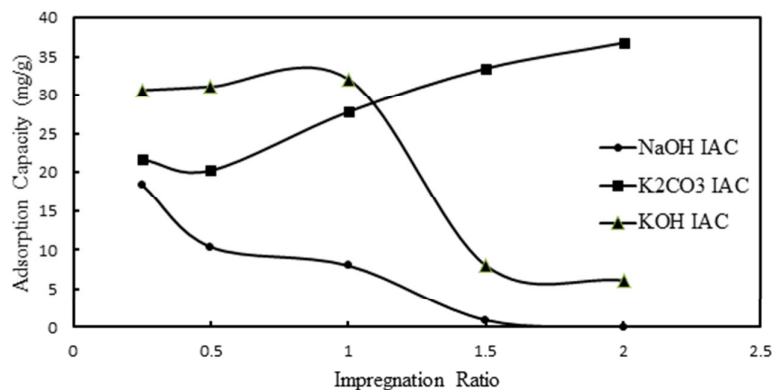


Fig. 4. Effect of Various Impregnation Ratio toward H_2S Adsorption Capacity (2 g of IAC used, H_2S Concentration: 3000 ppm, Flow rate: 450 ml/min, Temperature: 30°C).

3.4. Effect of influent H_2S concentration

Analysis of the performance of the carbons indicated that $IAC_{K_2CO_3-2.0}$ adsorption capacity was increased when the influent H_2S concentration decreased. From Fig. 5, 1000 ppm of influent H_2S concentration showed highest adsorption capacity. However, the adsorption capacity had dramatically drop when the H_2S influent concentrations was increased to 5000 ppm.

The result indicated in this study was different with the conventional research using batch experiment because in this study, dynamic adsorption was performed. The H₂S removal study done by Xiao et al. [5] showed that the influent concentration was lower, the lower mass-transfer flux was achieved from the bulk gas to the surface of activated carbon. On the other hand, higher influent concentration yields enhanced driving force along the pores, hence resulting in higher adsorption capacity. However, for our study, the effect of driving force and mass transfer flux is minimal in a dynamic adsorption. Moreover, it is limited by the rate of molecular diffusion into deeper pores and the adsorption process. When the influent H₂S concentration was lower, it allowed the impregnated activated carbon to adsorb all the H₂S from the gas stream. Hence it took longer time to reach breakthrough which resulted higher adsorption capacity. Therefore 1000ppm of influent H₂S concentration gave the maximum adsorption capacity compared to other higher concentrations.

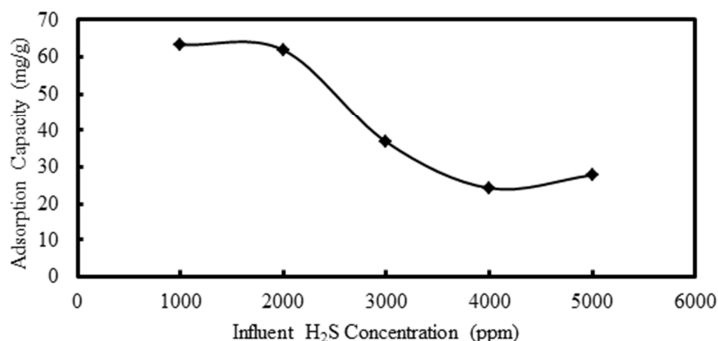


Fig. 5. Effect of H₂S Influent Concentrations on Adsorption Capacities of IAC_{K₂CO₃-2.0} (2 g of IAC used, Temperature: 30°C, H₂S flow rate: 450 ml/min).

3.5. Effect of reaction temperature

Reaction temperature plays a significant role on the adsorption processes. The effect of temperature on H₂S adsorption was shown in Fig. 6. The adsorption capacity was lowest at 30°C. H₂S adsorption test at 50°C gave the maximum H₂S adsorption capacity but slightly drops at 70°C. According to the study of Sithikhankaew et al. [13], the reactions of H₂S on impregnated activated carbon at room temperature could be proposed as physical and chemical adsorption. In this study, adsorption capacity was increased at increasing temperature from 30°C to 50°C because higher temperature could enhance chemisorptions. Higher temperature allows H₂S molecules to have higher energy to overcome the energy barrier for chemisorptions which enhances the possibility to react with potassium impregnated on activated carbon [14]. However, at operating temperature of 70°C, the performance of K₂CO₃ impregnated activated carbon slightly decreased. Higher temperature has disadvantage on the physical adsorption. As the temperature rise, the vapor pressure of the adsorbate increase and hence raising the energy level of the H₂S molecules to overcome the van der Waals' attraction and migrate back to the bulk gas phase [14]. Xiao et al. [5] reported that an increase in the operating temperature caused the decreasing in maximum capacity

of impregnated activated carbon because higher temperature might probably enhance chemisorptions but decreased the physisorption rate. Therefore, maximum operating temperature was found to be 50°C, balancing both effect from physisorption and chemisorptions.

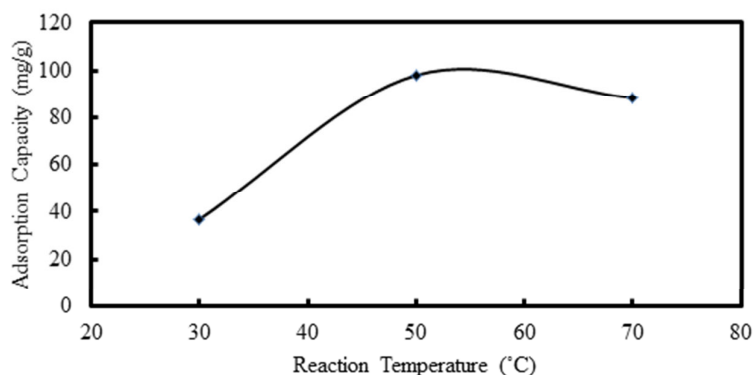


Fig. 6. Effect of Temperature on Adsorption Capacities of IAC_{K₂CO₃-2.0} (2 g IAC used, H₂S Concentration: 1000 ppm, Flow Rate: 450 ml/min).

3.6. Physicochemical characteristics

3.6.1. SEM analysis

SEM image for both fresh and spent K₂CO₃ impregnated activated carbon were shown in Fig. 7. In Fig. 7(a), a rough wave shape surface could be observed. Some white aggregates of K₂CO₃ constituent particles distributed on the surface of activated carbon were observed. Similar observation could be indicated in Tsai et al. [3] SEM study as NaOH crystal distributed on the activated carbon. In this study, the K₂CO₃ crystals formed were in irregular shape. It is observed that K₂CO₃ crystals caused only minor pore blockage. This lead to the enhancement of adsorption capacity of K₂CO₃ impregnated activated carbon compare to unimpregnated activated carbon as discussed in previous section.

Fig. 7(b) shows SEM image for spent K₂CO₃ impregnated activated carbon. A smoother surface was observed compare to fresh K₂CO₃ impregnated activated carbon. Most of the K₂CO₃ crystals were consumed in the chemical reaction with H₂S molecules. Some sphere shape particles formed on the surface of spent activated carbon could be the products of adsorption process. Little amount of irregular shape K₂CO₃ particles still can be observed to show that most of the K₂CO₃ had undergone chemisorption.

3.6.2. BET analysis

Specific surface area is one of the important properties of activated carbon that affect its adsorption capacity significantly. BET surface area, pore volume and average pore width of fresh and spent K₂CO₃ impregnated activated carbon were tabulated in Table 1. Adsorption process caused the surface area and pore volume

to decrease. The BET surface area and pore volume will be much lower if the impregnated activated carbon is allowed to react with H₂S until saturation.

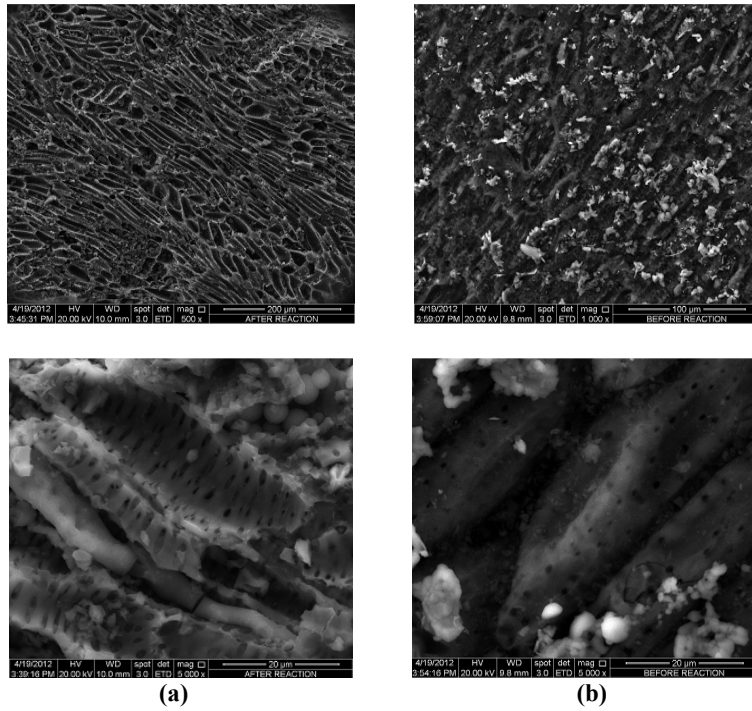


Fig. 7. SEM Image for IAC_{K₂CO₃-2.0}: (a) Fresh IAC_{K₂CO₃}; (b) Spent IAC_{K₂CO₃}.

Table 1. BET Surface Area, Pore Volume and Average Pore Width for both Fresh and Spent IAC_{K₂CO₃}.

	Fresh IAC	Spent IAC
BET Surface Area (m ² /g)	726.2	607.4
Pore volume (cm ³ /g)	0.4	0.3
Average pore width (Å)	20.5	20.0

3.7. Adsorption isotherm

Adsorption process is usually studied through adsorption isotherm. Adsorption isotherm is describing the coverage of adsorbate over the adsorbent surface. It shows the relationship between the amounts of adsorbate (amount of H₂S in this study) adsorbed on the surface of adsorbent (K₂CO₃ impregnated activated) and the pressure (for gas) or concentration (for liquid) at constant temperature.

Table 2 shows the adsorption isotherm obtained using linear method. Four types of isotherm included Langmuir, Freundlich, Temkin and Dubinin-

Radushkevich had been studied. The characteristic of these isotherms were shown in Table 2. Result indicated that the equilibrium adsorption capacity of H₂S on K₂CO₃ impregnated activated carbon from the dynamic adsorption was fit with Langmuir isotherm at R^2 closer to unity. Some characteristics of Langmuir isotherm can be found in the Table 2.

Table 2. The R^2 Values for Different Type of Isotherms obtained by Linear Method.

	Langmuir	Freundlich	Temkin	Dubidin-Radushkevich (DR)
Characteristic of isotherm	- Monolayer adsorption - Homogenous adsorption	- Multilayer adsorption - Non-uniform affinity over heterogeneous surface	- The indirect adsorbate-adsorbate interaction is taken into consideration	- Express the characteristic of porosity and pore filling mechanism.
Linearization method	$\frac{C_e}{q_e} = \frac{1}{K_L q_m} + \frac{1}{q_m} C_e$	$\ln q_e = \ln K_F + \frac{1}{n} \ln C_e$	$q_e = B \ln A + B \ln C_e$	$\ln q_e = \ln q_s - B_{DR} \varepsilon^2$
R^2	0.9448	0.8127	0.8337	0.7945

4. Conclusions

In this study, CSAC had been successfully impregnated with three types of alkaline. The result indicated that K₂CO₃ was the best chemical for impregnation because it gave the highest adsorption capacity. The maximum ratio of K₂CO₃ impregnation was found to be 2.0. Adsorption capacity of 25 times higher than unimpregnated CSAC was achieved using IAC_{K₂CO₃-2.0}. Besides, adsorption capacity was increased with larger amount of activated carbon used and decrease at increasing gas flow rate. Increasing influent H₂S concentration will also decrease adsorption capacity. 50°C was the temperature observed for maximum H₂S adsorption. Characterizations of fresh and spent IAC_{K₂CO₃-2.0} were performed and H₂S adsorption process was fitted to Langmuir adsorption isotherm successfully. In this study, complete breakthrough curve for the adsorption process was not shown because it will be studied and reported in subsequent publication.

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References

1. Sitthikhankaew, R.; Predapitakkun, S.; Kiattikomol, R.W.; Pumhiran, S.; Assabumrungrat, S.; and Laosiripojana, N. (2011). Performance of commercial and modified activated carbon for hydrogen sulfide removal from simulated biogas. *2011 IEEE First Conference on Clean Energy and Technology (CET)*, Art. No. 6041474, 1352.

2. Guo, J.; Luo, Y.; Lua, A.; Chi, R.; Chen, Y.; Bao, X.; and Xiang, S. (2007). Adsorption of hydrogen sulphide (H₂S) by activated carbons derived from oil-palm shell. *Carbon*, 45(2), 330-336.
3. Tsai, J.H.; Jeng, F.-T.; and Chiang, H.L. (2001). Removal of H₂S from exhaust gas by use of alkaline activated carbon. *Adsorption*, 7(4), 357-366.
4. Adinata, D.; Daud, W.M.A.W.; and Aroua, M.K. (2007). Preparation and characterization of activated carbon from palm shell by chemical activation with K₂CO₃. *Bioresource Technology*, 98(1), 145-149.
5. Xiao, Y.; Wang, S.; Wu, D.; and Yuan, Q. (2008). Experimental and simulation study of hydrogen sulfide adsorption on impregnated activated carbon under anaerobic conditions. *Journal of Hazardous Materials*, 153(3), 1193-1200.
6. Kim, K.-J.; Kang C.-S.; You Y.-J.; Chung M.-C.; Woo M.-W.; Jeong W.-J.; Park N.-C.; Ahn, H.-G. (2006). Adsorption-desorption characteristics of VOCs over impregnated activated carbons. *Catalysis Today*, 111(3-4), 223-228.
7. Coskun, I.; and Tellefson, E.L. (1980). Oxidation of low concentration of hydrogen sulfide over activated carbon. *The Canadian Journal of Chemical Engineering*, 58(1), 72-76.
8. Guo, J.; and Lau, A.C. (2002). Textural and chemical characterizations of adsorbent prepared from palm shell by potassium hydroxide impregnation at different stages. *Journal of Colloid and Interface Science*, 254(2), 227-233.
9. Hayashi, J.; Yamamoto, N.; Horikawa, T.; Muroyama, K.; Gomes, V.G. (2005). Preparation and characterization of high-specific-surface-area activated carbons from K₂CO₃-treated waste polyurethane. *Journal of Colloid and Interface Science*, 281(2), 437-443.
10. Yan, R.; Liang, D.T.; Tsen, L.; and Tay, J.H. (2002). Kinetics and mechanisms of H₂S adsorption by alkaline activated carbon. *Environmental Science & Technology*, 36(20), 4460-4466.
11. Lee, Y.-W.; Park, J.-W.; and Choi, D.-K. (2002). Characteristics of NO_x adsorption and surface chemistry on impregnated activated carbon. *Separation Science and Technology*, 37(4), 937-956.
12. Chiang, H.L.; Tsai, J.H.; Tsai, C.L.; and Hsu, Y.C. (2000). Adsorption characteristics of alkaline activated carbon exemplified by water vapor, H₂S, and CH₃SH gas. *Separation Science and Technology*, 35(6), 903-918.
13. Sitthikhankaew, R.; Predapitakkun, S.; Kiattikomol, R.W.; Pumhiran, S.; Assabumrungrat, S.; and Laosiripojana, N. (2011). Comparative study of hydrogen sulfide adsorption by using alkaline impregnated activated carbons for hot fuel gas purification. *Energy Procedia*, 9, 15-24.
14. Richards, JR. (2000). *Control of gaseous emissions*. ICES Ltd. 324.