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Optimization of Pressure Swing Adsorption Based Biogas Upgrading Process Using Aspen Adsorption Coupled with Design Expert Software

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Abstract: Due to large amount of biogas produced from anaerobic digestion of palm oil mill effluent, it has great potential to be used as a renewable energy in Malaysia. Before biogas can combusted, removal of impurities such as carbon dioxide is essentially necessary. However, the lack of detailed study on the process conditions and economics has restrained the deployment of this technology in this country. Therefore in this study, biogas upgrading process using pressure swing adsorption technology is simulated and optimized to minimize the payback period of initial investment. The study showed that operating pressure, residence time and flow rate were the most significant parameters. The optimized process conditions were obtained at 7.5 bar operating pressure, 450 m^3/h flow rate, 2.125 m bed length and 0.389 h residence time. The corresponding biogas methane content and payback period were 98% and 3.135 years, respectively. Comparing to other study, the optimized result showed great potential to deploy this technology in Malaysia.

Key words: Potential, optimized, technology, deployment, parameters, payback, period

INTRODUCTION

Biogas is a renewable energy formed during anaerobic digestion of organic wastes such as animal manure, palm oil mill effluent and food waste to simpler compounds (Dibyang, 2015). Table 1 shows the typical composition of biogas (Kim *et al*., 2015). Apparently, biogas contains of large amount of combustible that makes biogas a potential fuel. It burns in a clear blue flame similar to LPG. It has a calories value of 20 MJ/Nm^3. Biogas can be used for many heating purposes such as home cooking and industrial burner fuel. Furthermore, chemical energy in biogas can be converted into electricity and heat by using gas engines and compressed biogas can be used to power a vehicle.

The produced biogas and slurry from anaerobic digestion are valuable. Therefore, the amount of organic waste that produced end up deposit at the landfill is minimized. In Malaysia, Palm Oil Mill Effluent (POME) appears to be an attractive source for biogas technology.

A POME is expensive and difficult to manage because large volume of POME is generated. Raw POME cannot be discharged into the nearby river or land due to its organic and nutrient contents. Untreated POME will deplete oxygen content of a water body and threaten aquatic life.

Table 1: Composition of biogas

Components	Percentage
Methane (CH_4)	50-75
Carbon dioxide (CO_2)	25-50
Nitrogen (N_2)	0-10
Hydrogen (H_2)	0-1
Hydrogen Sulphide (H_2S)	0-3
Oxygen (O_2)	0-2

During last decade, research and development in both harvesting biogas and upgrading biogas have gained significant interest because biogas is a potential renewable energy. In addition, biogas contains methane which is greenhouse gases with higher global warming potential compare to carbon dioxide. Utilizing methane can therefore, reduce the emission of greenhouse gasses. Malaysia is the second largest palm oil producer and exporter in the world accounting 39% of world palm oil production and 44% world export. There is about 63.42 million ton of POME generated in 2015. In a typical case, 3 ton of POME is produced per ton of crude palm oil. From the amount of generated POME, 646884 tons of CH_4 will be produced using anaerobic digestion to generate electricity up to 3.5938 billion kWh. Hence, expected to support up to 342874 households in Malaysia.

Biogas contains large amount of carbon dioxide up to 30% methane while natural gas contains very low amounts of carbon dioxide up to 5%. Therefore, biogas has low energy content compare to natural gas. Thus, it is essential to increase the quality of biogas by removing unwanted substances such as hydrogen sulphide, water

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and carbon dioxide. Apart from that, biogas upgrading can reduce or prevent mechanical wear and corrosion of related equipment in which biogas is used (Yasar *et al.*, 2017). In this study, in depth analysis on carbon dioxide separation from biogas was studied by assuming that hydrogen sulphide and other unwanted component have been removed prior separation of carbon dioxide. Of all CO_2 separation technology, pressure swing adsorption appears to be the most promising, especially when considering actual industrial operation. Therefore, PSA was used in the simulation of biogas upgrading.

MATERIALS AND METHODS

Simulation

Aspen Adsim: Pressure Swing Adsorption (PSA) process was designed to produce biogas with at least 90% methane content using Aspen Adsorption Version 8.4. Aspen Adsim is a popular simulation program that is used to simulate industrial process (Fig. 1).

The process comprised of two adsorption columns filled with Zeolite 13x adsorbents at temperature 298.15 K (Augelletti *et al.*, 2017). The feed biogas is assumed to be free of water and hydrogen sulfide. The composition of simulated biogas is 70% methane and 30% carbon dioxide. In the simulation, range of process parameter is determined. The working parameter range of carbon dioxide separation by using PSA. PSA process is designed in 6-steps cycle are follow (Table 2).

Effect of process parameter such as residence time of biogas in adsorption bed content, adsorption bed length and operating pressure of PSA towards biogas methane content was studied. The main objective of the simulation is to determine range of process parameter that can produce methane content biogas with high than 90%.

Optimization of Payback Period (PBP): After obtaining suitable range of process parameters (>90% CH_4) economic analysis of PSA plant was performed. Effect of parameters towards the Payback Period (PBP) was studied using Central Composition Design (CCD) coupled with Response Surface Method (RSM) featured in Design-Expert Version 10.0.4 (Stat-Ease. Inc.) Software. The parameter range was divided into 5 levels and a design of experiments is generated. It consists of a factorial point an axial point and 6 central points. The parameter, coding and a range of studies is listed in Table 3.

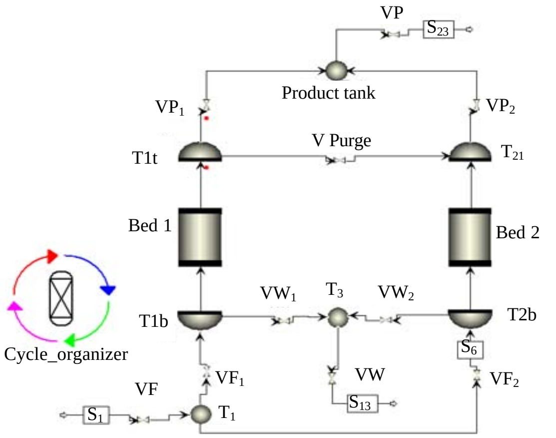

Fig. 1: Pressure swing adsorption process flow sheet

Table 2: Steps cycle of PSA operation

Steps	6 step process cycle operation
1	Pressurization of Bed 1 and depressurization of Bed 2
2	Adsorption of Bed 1 and purge of Bed 2
3	Pressure equalization
4	Depressurization of Bed 1 and pressurization of Bed 2
5	Purge of Bed 1 and adsorption of Bed 2
6	Pressurization

Table 3: Range and level of parameters

			Levels				
Parameters	Coding	Units	-2	-1	0	1	2
Bed length	x_1	m	0.5	2.125	3.75	5.375	7
Pressure	x_2	bar	5	7.5	10	12.5	15
Residence time	x_3	h	0.272	0.388	0.505	0.622	0.738
Flow rate	x_4	m^3/h	200	275	350	425	500

The design of experiment contains 30 sets of simulation in studying effect of parameters toward Payback Period (PBP). After obtaining the data from simulation, a regression mode analysis of the data is performed. The polynomial equation of the model is shown in Eq. 1:

$$y = a_0 + \sum_{i=1}^{4} a_i x_i + \sum_{i,j=1}^{4} a_{ij} x_i x_j + \sum_{i=1}^{4} a_{ij} x_i^2 \quad (1)$$

Where:

y = Predicted payback period (years)
a_0 = Offset term
a_i = Linear effect
a_{ij} = The first order effect
a_{ii} = Square effect

Each single term was analyzed for its significance towards the payback period.

RESULTS AND DISCUSSION

The ultimate purpose of this study is to optimize the process parameter to results lowest payback period for simulate PSA process. Range of the process parameter that results biogas with methane content higher than 90%

was determined using Aspen Adsim Version 8.4 Software. After that, payback period was calculated using methods described by Seider *et al.* (2009). Optimization was then performed using Design Expert Version (10.0.4) and the results are compared with actual industrial practice.

Analysis of regression model: About 30 set of simulation were generated by design expert software to analyze the effect of process parameter towards the payback period. Table 4 shows the simulation result.

R^2 are 0.062, 4.54 and 0.9967, respectively. This implies that there is 0.33% of total variability is unexplainable by the generated model. Therefore, this model could represent the actual effect of parameter studied towards payback period.

After the model was generated, Analysis of Variance (ANOVA) was used to analyze and determine significance of each parameter and interaction effect between the parameters towards payback period. The ANOVA is shown in Table 5.

The F-value of 444.2 implies that the model is significant and can be used to predict PBP in the range of process parameters. Value of probability >F lesser than 0.05 indicates the term is significant to affect the payback period while the value greater than 0.1 indicates the term is not significant. Based on the ANOVA results, x_1-x_4, x_2x_3, x_2x_4, x_3x_4 and x_4^2 are significant terms. On top of that, higher F-value indicates greater effect of the term towards payback period. Even x_2x_3, x_2x_4 and x_3x_4 were considered as significant towards payback period their F-value were 30 times less than the most significant term, x_3 (residence time). Thus, x_2x_3, x_2x_4 and x_3x_4 will not be discussed.

Table 4: Design of simulation and result

Run	Bed length (x_1)	Pressure (x_2)	Residence time (x_3)	Flow rate (x_3)	PBP (years)
1	3.750	10	0.505	350	4.432
2	3.750	10	0.505	200	6.121
3	3.750	10	0.505	350	4.432
4	5.375	12.5	0.622	275	6.694
5	7.000	10	0.505	350	4.611
6	5.375	12.5	0.622	425	5.319
7	3.750	10	0.505	350	4.432
8	3.750	5	0.505	350	3.324
9	3.750	10	0.505	350	4.432
10	3.750	15	0.505	350	5.527
11	5.375	7.5	0.388	425	3.207
12	3.750	10	0.272	350	3.303
13	5.375	12.5	0.388	425	3.998
14	2.125	7.5	0.388	425	3.119
15	2.125	7.5	0.622	425	3.891
16	2.125	12.5	0.388	425	3.882
17	2.125	7.5	0.622	275	4.828
18	2.125	12.5	0.622	425	5.090
19	3.750	10	0.505	350	4.432
20	2.125	12.5	0.388	275	4.789
21	0.500	10	0.505	350	4.267
22	3.750	10	0.738	350	5.599
23	3.750	10	0.505	350	4.432
24	5.375	7.5	0.622	275	5.076
25	2.125	7.5	0.388	275	3.847
26	3.750	10	0.505	500	3.759
27	5.375	7.5	0.622	425	4.052
28	5.375	12.5	0.388	275	4.966
29	5.375	7.5	0.388	275	3.980
30	2.125	12.5	0.622	275	6.334

Table 5: Analysis of Variance (ANOVA)

Sources	Sum of squares	Degree of freedom	Means square	F-values	Prob.>F
Model	23.66	14	1.69	444.20	<0.0001
x_1-Bed length	0.20	1	0.20	53.00	<0.0001
x_2-Pressure	7.57	1	7.57	1989.12	<0.0001
x_3-Residence time	8.27	1	8.27	2173.25	<0.0001
x_4-Flow rate	6.70	1	6.70	1760.55	<0.0001
x_1x_2	0.003969	1	0.003969	1.04	0.3233
x_1x_3	0.015	1	0.015	3.85	0.0686
x_1x_4	0.006561	1	0.006561	1.72	0.2089
x_2x_3	0.28	1	0.28	72.99	<0.0001
x_2x_4	0.067	1	0.067	17.49	0.0008
x_3x_4	0.091	1	0.091	23.81	0.0002
x_1^2	0.0001414	1	0.0001414	0.037	0.8497
x_2^2	0.00003344	1	0.00003344	0.008788	0.9266
x_3^2	0.0007620	1	0.0007620	0.20	0.6609
x_4^2	0.45	1	0.45	117.22	<0.0001

Effect of bed length (x_1) towards payback period: Smaller bed length will produce biogas with higher methane content. Similar results were also reported by Ling *et al.* (2015). Lower bed length 0.5 m produced 90% methane content while higher bed length 7 m produced only 70% methane content. Furthermore, lower bed length required less time to achieve higher methane purity. This is because smaller bed length corresponds to faster rate of carbon dioxide adsorption (Yu and Tan, 2013). Longer bed length requires higher residence time to provide sufficient time for carbon dioxide adsorption. Based on Payback Period (PBP) Model Eq. 2, the bed length term were represented by $+0.092x_1$. Positive 0.092 represented that bed length had a positive effect towards the PBP. The longer the bed length, the higher the PBP. Bed length affected annual production cost. Longer bed length requires absorbent required to fill the bed. Thus, the annual absorbent cost will increase, resulting higher production cost. Therefore, profit will eventually decrease according to Eq. 3. On top of that, simulation study also showed that lower than 0.5 m resulted undesirable decrease of methane content:

$$\text{Gross profit} = \text{Sales-Annual production cost} \tag{2}$$

Since, profit is inversely proportional to PBP, reduction in net profit will increase the PBP.

Effect of pressure (x_2) towards payback period: CO_2 adsorption on Zeolite 13x is a physical adsorption which means that it is highly affected by operating pressure. increasing pressure generally results higher extent of adsorption. If operating pressure is lowered, then desorption will occur. An adsorption will not further increase if pressure reaches saturated pressure. Based on PSA process simulation, adsorption capacity if Zeolite 13x showed an increasing trend with operating pressure until it reached 10 bar. After that, methane content in the product tank remained unchanged at 90%. On the other hand, at lower pressure such as 2 bar, carbon dioxide was not effectively adsorbed into the porous surface of Zeolite 13x. Therefore, the saturation pressure was determined as 10bar. Pressure over 10 bar will not affect methane content. Based on Payback Period (PBP) Model Eq. 2, the pressure term were represented by $+0.56x_2$ positive 0.56, represented that bed length had a positive effect towards the PBP. Higher pressure results higher PBP. Because pressure is directly proportional to the cost of adsorption columns and compressor. Equation 3 and 4 describe the relation of cost of adsorption column and compressor with operating pressure:

$$\text{Pd} = \exp\big(0.60608+0.9165[\ln(P_o)]+0.0015655\big[\ln\big(P_o\big)\big]^2 \tag{3}$$

where, P_o is operating pressure:

$$\text{Comprasser } H_p = 0.0642\times\frac{14\times\text{Flow rate}\times 0.58857^8}{0.4}\times\left(\left(\frac{P_o\times 14.5038}{14.7}\right)^{0.2857}\right)^{-1} \tag{4}$$

The increment of column and compressor cost results increased total equipment cost. Thus, total investment cost increased as well with PBP was calculated using (Eq. 5):

$$\text{PBP} = \frac{\text{Total capital investment}}{\text{Net profit}} \tag{5}$$

Since, PBP is directly proportional to total capital investment. Therefore, the increments of total capital investment will increase the PBP.

As described in previous section increasing operating pressure beyond 10 bar results no improvement of methane content. In addition, at lower operating pressure than 2 bar, carbon dioxide separation was not effective. Therefore, it is essential to find optimum operating pressure with minimum cost and highest biogas quality.

Effect of residence time (x_3) towards payback period: From Eq. 2, residence time is represented by $+0.59x_4$. Positive 0.59 represents a positive effect of residence time towards the PBP. Longer residence time results higher PBP because biogas is retained longer in the PSA column. At a fixed flow rate increasing residence time will inevitably increase the volume of the PSA column. Thus, the cost of PSA column is increased as well. Eventually, PBP will be increased. A shorter residence time may reduce the methane content of biogas. Nonetheless, it is essential to optimize the residence time for the PSA operation because carbon dioxide requires sufficient time to be adsorbed into pore of the absorbent. In addition, longer residence time is a waste of energy and time if not required by adsorption kinetics.

Effect of flow rate (x_4) towards payback period: In Eq. 2, flow rate is represented by $-0.53x_4$. Negative 0.53 indicates higher the flow rate will reduce the PBP. Increment in flow rate requires all the equipment such as PSA column, compressor and desulphurizer to be larger for higher capacity. Thus, the costing of the equipment will increase. On the other hand, higher flow rate allows more biogas to be upgraded. Thus, more electricity can be generated for revenue. Thus, optimization of flow rate to obtain minimized total capital investment and maximized revenue.

Optimization: Optimization were carried out over the operating parameters to determine optimum payback period in this study. By using design expert Version 10.0.4 (Stat-East Inc.), optimization solution was generated with the PBP criteria to be minimized and all the parameters are set within the range of this study. The purpose is to determine the lowest PBP within the range of the parameters.

The optimization results generated by the design expert software is 2.125 m bed length, 7.5 bar operating pressure, 0.389 h residence time, 425 m^3/h flow rate with the PBP of 3.135 years. This optimization is compared with related research data and industrial practice as shown in Table 6. The pressure, residence time and bed length is slightly higher due to the high 450 m^3/h flow rate. The typical production rate of POME biogas plant in Malaysia are from 137-580 m^3/h with the average of 359 m^3/h upgraded biogas production (Chin *et al*., 2013).

However, this study would be able to process 450 m^3/h flow rate of biogas which is sufficient to address the production capacity as a typical palm oil mill. In addition, shorter payback period compare to other study could interact more investment in the biogas upgrading plant. Resulting greater profit in global warming mitigation.

Table 6: Comparison of optimized PSA parameter of research and industrial practice

Flowrate (m^3/h)	Bed length (m)	Purity (%)	Residence time (h)	Pressure (bar)	Payback period (years)	References
425	2.125	98%	0.389	7.5	3.135	This study
100	1	99.4	0.2055	6.0	N/A	Knaebel *et al.* (2005)
4.8	1	97	0.333	4.0	N/A	Augelletti *et al.* (2017)
N/A	N/A	98%	N/A	8.0	N/A	Kim *et al.* (2015)
20	3	95%	N/A	10.0	4.625	Dibyang (2015)

CONCLUSION

Optimization of biogas upgrading process was successfully simulated. Significant process parameters were found to be operating pressure, residence time and flow rate. The optimized parameters were 2.125 m bed length, 7.5 bar operating pressure, 0.389 hr residence time, 425 m^3/h flow rate with payback period 3.135 years. Comparison of this study with other research showed great potential of deployment of this technology in Malaysia.

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