Economic analysis of biogas production for household using a small biogas floating tank reactor

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Abstract

Methane is normally produced by anaerobic digestion in natural ecosystems. It is one of greenhouse gases impacting global warming, so in order to reduce the natural emission of methane gas from the environment, it is proposed to utilize food scraps and pig slurry waste, normally discarded into the environment, in a closed bioreactor to generate methane for use as a household cooking fuel. The physical characteristics that were studied for mixtures of food scraps and pig slurry as the biogas ingredients included pH, chemical oxygen demand (COD), and temperature. A small biogas reactor was developed using a floating tank system with a capacity of 200 L. The payback period (PB), the net present value (NPV), and the internal rate of return (IRR) were analyzed under the various measured conditions. The biogas yields were approximately 0.18 m$^3$/day under the mesophilic process with a pH range of 5.2 – 6.5, COD loading of 22,350-36,100 mg/L-day and digestion temperature of 31-39°C for a retention time of 20 days. The economic analysis for the optimal measurement conditions obtains the payback period of 3.4 year, the net present value of 24.70 USD (790.40 Baht) and the internal rate of return by 25.3% per year.

Keywords: Biogas, renewable energy, food scraps, floating tank, economic analysis

1. Introduction

Climate change is happening slowly long enough period over a hundred year mainly impacting by greenhouse gases. Greenhouse gases have emitted to the atmosphere produced from natural and human activities. Methane is one of greenhouse gases normally generated by anaerobic digestion of organic compounds in natural ecosystem. Its potentiality to global warming harmfulness is approximately by 21 (CO$_2$ equivalent). Technology used for the conversion of organic materials to biogas have been in existence for many years, especially, biogas power plants in the industrial wastes, livestock and municipal wastes. For a large scale, upflow anaerobic sludge blanket (UASB), continuously stirred tank reactor (CSTR), aerobic covered lagoon (ACL), aerobic baffle reactor (ABR) and aerobic fixed film (AFF) have been installed to provide electricity and thermal utilization. The CSTR system supporting the food scrap of 200 kg per day from the university’s cafeteria with biogas producing of 19.3 m$^3$ per day was studied by Krittapas Singkibutra, et al. (2011). Despite the fixed dome reactor and floating tank reactor are used in the small scale such as household
and farm. The fixed dome reactor capacity of 18 m$^3$ for the cattle dung of 10 – 12 heads was installed for producing biogas by averaged of 6 m$^3$ per day (Teguh W. Widodo, et al. 2009).

Biogas production also has economic benefits, reducing energy production expenditure and benefiting communities. The biogas production from food waste of the cafeteria in schools or factories is promoted by the Ministry of Energy, Thailand since 2008 as the fuel of electrical generator or boiler substituting petroleum fuels. The biogas reactors have been developed for the suitably capacity of material loading. Krittapas Singkibutra et al. (2011) investigated the appropriate technology for biogas production and evaluation of the financial analysis for CSTR technology. Somjintana Limsook et al. (2011) studied the improvement of biogas production by mixing the glycerin into a semi-batch anaerobic reactor, while Sukanya Adisa (2008) investigated an influent parameter from food waste in two stages anaerobic digestion system. Utilization of biogas for a small combined heat and power (CHP) unit in Ireland was evaluated using a simple economics tools (J. D. Murphy et al., 2004).

This study analyzed the economics of a small biogas reactor due to its ingredients characteristics from the food scraps to produce biogas substituting LPG fuel in household. The economics parameters are payback period (PB), net present value (NPV) and internal rate of return (IRR) under the assumption of LPG price floating rate and the fixed currency rate using the experimental data of the biogas production in the weather condition of Loei province, Thailand.

2. Biogas generation

Biogas is produced when organic materials are fermented under anaerobic conditions. Biogas contains of methane (CH$_4$), carbon dioxide (CO$_2$) with trace of hydrogen sulfide (H$_2$S) and moisture content. The organic material is generally processed, liquefied, and pasteurized to rid it of pathogens and make its breakdown easier for the anaerobic bacteria. These bacteria, commonly found in soil and water, first employ enzymes to convert the organic matters into amino acids and sugars and then ferment these into fatty acids. The fatty acids are then transformed into biogas. The process is represented by the biological activity of bacteria increasing in growth rate and the specific nutritional requirement. These bacteria classify into psychrophilic, mesophilic and thermophilic strains according to their optimum temperature ranges. Psychrophilic bacteria generate biogas in temperatures range of 5°C to 15°C, while mesophilic bacteria generation temperatures ranges of 30°C to 40°C and thermophilic generation temperatures range of 50°C to 60°C. Mesophilic bacteria have an optimal temperature for growth around 35°C. It is essential for efficient operation to control stable temperature since reaction rates drop off considerably as temperature falls below 35°C and there is also a sharp drop off in activity at temperatures above 45°C, as mesophilic bacteria become inhibited by the heat. Thermophilic bacteria have an optimal temperature as close as possible to 55°C. Thermophilic digestion offers the advantages of faster reaction rates compared to mesophilic digestion, leading to shorter retention times but thermophilic systems are usually more expensive to operate as they require additional energy to maintain the higher operating temperatures. So, mesophilic digestion is suitable producing biogas due to low maintain and weather conditions. There are three stages of anaerobic digestion including hydrolysis, acetogenesis and methanogenesis respectively.
2.1 Hydrolysis

In the first stage of hydrolysis, fermentative bacteria convert the insoluble complex organic matter, such as cellulose, into soluble molecules included sugars, amino acids and fatty acids. The complex polymeric matter is hydrolyzed to monomer, such as cellulose to sugars or alcohols and proteins to peptides or amino acids by hydrolytic enzymes included lipases, proteases, cellulases, amylases, etc. The products of this stage are acetic acid (CH$_3$COOH), propionic acid (CH$_3$CH$_2$COOH), butyric acid (CH$_3$CH$_2$CH$_2$COOH), and ethanol (C$_2$H$_5$OH).

2.2 Acetogenesis

In the second stage, acetogenic bacteria or acid formers, convert the products of the first phase to simple organic acids, carbon dioxide and hydrogen expressed as a reaction; $C_6H_{12}O_6\rightarrow 2C_2H_5OH + 2CO_2$.

2.3 Methanogenesis

Finally, in the third stage methane is produced by bacteria called methane formers or methanogens in two ways: either by means of cleavage of acetic acid molecules to generate carbon dioxide and methane, or by reduction of carbon dioxide with hydrogen. Methane production is higher from reduction of carbon dioxide but limited hydrogen concentration in digesters results in that the acetate reaction is the primary producer of methane as expressed in reactions below;

CH$_3$COOH $\rightarrow$ CH$_4$ + CO$_2$.

2C$_2$H$_5$OH + CO$_2$ $\rightarrow$ CH$_4$ + 2CH$_3$COOH,

CO$_2$ + 4H$_2$ $\rightarrow$ CH$_4$ + 2H$_2$O.

The operating parameters of the digester must be controlled so as to enhance the bacteria activity and thus increase the anaerobic degradation efficiency of the system. The important parameters are pH, temperature, retention time, carbon to nitrogen ratio (C/N) total solids content (TS), organic loading rate (OLR) as chemical oxygen demand (COD), etc.

3. Experimental setup

Several types of biogas reactors have developed depending on the digestion ingredients and utilizations. Among them, a small reactor which the fermented tank capacity about 0.2 m$^3$ the same size as the gas collection capacity is used in this study. The biogas reactor consists of two parts including a fermented tank and a gas collected tank as shown a schematics of the system in Figure 1. The fermented tank is modified a plastic tank volume of 0.2 m$^3$ for food scrap loading. The gas collected tank using the water replacement system consists of a water container and a floating drum. The pig slurry is fed into the fermented tank and then filling up the food scrap from the university’s cafeteria for 5 kg per day until reach the maximum volume of the tank. The ratio of food scrap and pig slurry are 50 : 50 and 70 : 30 by volume. The pH and chemical oxygen demand (COD) are measured at the beginning and the end of digestion. The ambient air temperature and fermented temperature are also measured at the same time in evening.
Biogas volume obtained \( (V) \) each day is calculated by the measurement of the biogas velocity flowing in a tube with equation
\[
V = Avt,
\]
where \( V \) is the biogas volume \( (m^3) \), \( A \) is the cross section of the tube \( (m^2) \), \( v \) is the biogas velocity in the tube \( (m/s) \) and \( t \) is time of measurement \( (s) \).

At beginning, pH and COD of food scrap and pig slurry were measured individually using pH meter and titration method and then the mixed ingredients with those ratios of 50 : 50 and 70 : 30 respectively. The COD was also measured at the end for determining the COD removal.

### 4. Results

Table 1 represented pH of food scrap at beginning is ranged from weak acid to natural. The fluctuation might of the cooking ingredients. The pig slurry and the mixed ingredients are weak acid. The value of COD of food scrap is greater than that of pig slurry. The COD removal of a half ratio is 69.5% and the COD removal of the latter is 63.2%. The COD removal of the reactor is low comparing to the Plug Flow and CSTR reactors of 76.2% and 96.0% respectively (Kittapas Singkibutra et al., 2011). After 5 days of fermentation, biogas was produced that the pH values of the ratio of 70 : 30 was little decreasing below the ratio of 50 : 50 (see Figure 2). The minimum value trends is on the mid-period of the fermentation according to its hydrolysis stage and methanogenesis stage of the mesophilic process. The fermented temperatures were ranged from 0.6°C to 7.5°C above ambient temperature as shown in Figure 3. The fermented temperature for all ratio was high in the mid-period of the digestion. The fermented temperature of the ratio of 70 : 30 was little above the latter.

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>pH</th>
<th>COD (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>begin</td>
<td>end</td>
</tr>
<tr>
<td>Food scrap</td>
<td>6.1 – 7.6</td>
<td>-</td>
</tr>
<tr>
<td>Pig slurry</td>
<td>6.6</td>
<td>-</td>
</tr>
<tr>
<td>Food scrap : slurry by 50 : 50</td>
<td>6.5</td>
<td>22,350</td>
</tr>
<tr>
<td>Food scrap : slurry by 70 : 30</td>
<td>6.4</td>
<td>36,100</td>
</tr>
</tbody>
</table>

Figure 1 The schematics of the biogas production system in a small scale using the floating digester.
Figure 2. pH of the fermented tank on the biogas production for the ratio of food scrap : pig slurry by 50 : 50 and 70 : 30.

Figure 3. The fermented tank temperature and ambient temperature on the biogas production for the ratio of food scrap : pig slurry by 50 : 50 and 70 : 30.

Biogas obtained during the retention time of 20 days for the half ratio and the latter were 4.09 m$^3$ and 3.11 m$^3$ respectively and by averaged of 0.18 m$^3$ per day (see Figure 4).

Figure 4. The biogas volume for the ratio of food scrap : pig slurry by 50 : 50 and 70 : 30.
5. The economics analysis

The economics parameters considered for analysis are payback period (PB), net present value (NPV) and internal rate of return (IRR). The payback period is determined that is needed to get the invested capital back via the repayments. The investment with the shortest payback period is the most advantageous option. The Payback period may be easy to use, it does not take into consideration the time value of money (inflation, discount rate, etc.). The net present value is representative of the dynamic investment appraisal and a discounted cash flow method. It estimates all the cash flows, both positive (revenue) and negative (costs), of pursuing a capital, now and in the future. If the net present value is positive, the project is worth pursuing; if it's negative, the project should be rejected, and the good decision is the higher NPV. The internal rate of return is the interest rate at which the net present value of all the cash flows from a project or investment equal zero. It is generally considered worthwhile if the internal rate of return is greater than the return of an average similar investment opportunity, or if it is greater than the cost of capital of the opportunity (interested rate).

The payback period (PB) is calculated by equation;

\[ PB = \frac{Initial\; investment}{annual\; savings/\; revenue}. \]

The net present value (NPV) is determined by equation;

\[ NPV = -C_o + \sum_{i=1}^{n} C_i \frac{1}{(1 + r)^{n}}, \]

where \( C_o \) is the initial investment, \( C_i \) is the annual return of the \( i^{th} \) year, \( r \) is the interested rate per year and \( n \) is a number of year or the project period.

The internal rate of return (IRR) is calculate by equation;

\[ NPV - \frac{\sum_{i=0}^{n} C_i}{(1 + r)^i} = 0, \]

when \( i = 0 \) means the initial investment, \( C_o \) is minus and IRR equals to \( r \) of NPV calculation. IRR is determined by the numerical assumption of the interested rates until the equation to be zero. The interested rate (r) making equation to be zero, it is IRR.

The economics analysis of this paper is calculated under the assumptions of biogas weight of 1.2 kg/m\(^3\) (methane purify of 60%), biogas substituting the liquefied petroleum gas (LPG) for 0.43 kg biogas/kg LPG, the price of LPG of 24.82 Baht/kg (0.78 US/kg) and the use of biogas in household by 0.22 kg/day. The project period (\( n \)) of NPV calculation assumes equally the reactor lifetime by 5 years. The currency exchange assumes to be 32 THB / US. The results of the economics analysis represent in Table 2.
Table 2 The results of the economics analysis for biogas substituting LPG usage in household.

<table>
<thead>
<tr>
<th>Contents</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The biogas reactor cost</td>
<td>89.06 US (2,850 THB)</td>
</tr>
<tr>
<td>The reactor usage lifetime</td>
<td>5 years</td>
</tr>
<tr>
<td>The interested rate (r)</td>
<td>8% per year</td>
</tr>
<tr>
<td>Biogas obtained and usage</td>
<td>0.22 kg per day</td>
</tr>
<tr>
<td>Payback period (PB)</td>
<td>3.38 years</td>
</tr>
<tr>
<td>Net present value (NPV)</td>
<td>4.70 US (790.44 THB)</td>
</tr>
<tr>
<td>Internal rate of return (IRR)</td>
<td>25.3% per year</td>
</tr>
</tbody>
</table>

6. Conclusion

The use of food scrap mixed to pig slurry with the ratios of 50 : 50 and 70 : 30 for producing biogas was investigated. The small reactor, the floating tank reactor was performed under the mesophilic process according to the fermented temperatures in the ranged of 31°C – 39 °C. The COD loading was averaged between 22,350 and 36,100 mg/L –day, and the COD removal was approximately of 69%. The pH in the fermented tank of the half ratio was more fluctuated than that of the latter ratio. The biogas yields were approximately 0.18 m³/day or 0.22 kg/day. The biogas yield can be used for cooking fuel in household substituting to the liquefied petroleum gas.

The parameters of the economics analysis including payback period, net present value and internal rate of return were determined for the optimal conditions. The payback period obtains by 3.38 years, the net present value obtains by 24.70 US or 790.44 Baht and the internal rate of return obtains by 25.3% per year. Biogas production with the simple technology as the small floating tank digester should promoted for household because of its economized and a little maintain

Reference


Wongduen Saikung and Sudarut Posri (2013). Biogas production from food scraps, Student Project, Bachelor of Education in Physics, Loei Rajabhat University, Thailand.