Mathematical Modeling and Parameters Estimation of an Anaerobic Digestion of Shrimp of Culture Pond Sediment in a Biogas Process

Jiraphon Srisertpol, Prasit Srinakorn, Adtavirod Kheawnak and Kontorn Chamniprasart

Abstract— The biogas is one type of energy and sustainable development which is important to the energy and environmental planning of Thailand. The study and analysis of the mathematical model of the biogas process can be explained the variables that affect biogas process and proposed a design for biogas reactor using shrimp pond sediment. The treatment of shrimp culture pond sediment by anaerobic digestion process could also reduce the amount of waste and produce biogas, which were the high ratio of methane can be used as renewable energy. This paper presents a mathematical modelling and parameter identification of an artificial intelligence to estimate the mathematical model of an anaerobic digestion with shrimp pond sediments in the biogas process which is a batch reaction. The principles of mass balance equations were defined the mathematical models. The equations is one stage nonlinear caused by the reaction of organic substances that are decomposed into biogas. This mathematical model was compared to the experimental data, including temperature, pH, biogas flow rate and biochemical properties of shrimp culture sediment.

Keywords— Mass Balance Equation, Anaerobic Digestion, Biogas Process, System Identification and Artificial Intelligence.

I. Introduction

THE biogas is obtained from digesting crumble organic substances of the living things which are both plants and animals. The biomass is an important renewable energy. Thailand has high effective of producing biogas because there are many products from agriculture which are source of biomass energy. This process is an anaerobic digestion caused by various kinds of microorganisms. The biogas is mostly mixed with methane (CH_4) and carbon dioxide (CO_2). Biogas which is produced from fermentative procedures has different quantities, depend on the raw materials and the condition of the fermentative procedures. The biogas has properties like fuel. It is the renewal energy that is used to replace firewood, charcoal, oil, liquid petroleum gas, etc. It is also able to apply to cooking gas directly as same as liquid petroleum gas. This is more convenience for usability than using firewood or charcoal without smoke and ash. The biogas can be applied to use in lamps or electric generators for light generation. It is also used to generate heat and applied to use with all kind of engine instead of oil. The biogas that is used for fuel energy must contain more than 50% of methane. The biochemical properties of shrimp culture pond sediment are waste of the sea shrimp farming and have high biological oxygen demand (BOD) and chemical oxygen demand (COD). Shrimp farming plays an important but controversial role in the economy development of many countries in South-East Asia because of the high economic returns and catastrophic environmental impact of production in coastal areas as shown in Fig.1 [1-3].

Fig. 1 Shrimp farming

In particular, the effluent of sediment into the coastal areas are affecting to coastal water qualities, depletion of dissolved oxygen, high amount of organic matter in adjacent soil and increased soil salinity (in inland shrimp farming) as shown in Fig.2,3. Thailand has 33,444 shrimp farms and can be produced marine shrimp about 401,300 tones. The areas of shrimp farm are $718x10^6$ m^2 in Thailand (data 1999). The marine shrimp farm produces about 1.25-3.125 kg/m^2 depending on the number of shrimp raised in ponds and the amount of feeding. Many mathematical models that are available in literatures were studied and situated model of an anaerobic digestion in biogas production from wastes and feces [4-8]. The parameters estimation and the specification of the identity of mathematical models for anaerobic digestion

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were also studied [9-10]. The control system of production was designed [11-12]. The genetic algorithm is really a powerful tool for many problems in numerical analysis and scientific computation. The genetic algorithm has been successfully applied in a variety of areas and is still finding increasing acceptance. The genetic algorithm searches parameters of PID controllers so that specifications for the closed-loop step response are satisfied. The tuned genetic

Fig. 2 Shrimp culture sediment

Fig. 3 Shrimp culture sediment in canal

algorithm was successfully applied for parameter identification [13-15]. The quality of the produced biogas is closely related to the type of biomass which is being used, the quality of waste, the duration of the batch, and also the ration between solid matter and liquid volume[16]. The effectiveness of the energy conversion of waste to biofuel may lead to the improvement of the energy efficiency in digesters via modifying their design and the operating conditions [17].

This paper presents a method of system identification and applies an artificial intelligence to estimate the mathematical model of anaerobic digestion with shrimp pond sediments in the biogas process which is a batch reaction. The principles of mass balance equations were defined the mathematical models. The equations is one stage nonlinear caused by the reaction of an organic substances that are decomposed into biogas. This mathematical model was compared to the experimental data, including temperature, pH, biogas flow rate and biochemical properties of shrimp culture sediment.

II. THE MATHEMATICAL MODEL OF AN ANAEROBIC DIGESTION IN BIOGAS PROCESS

The anaerobic digestion could be modeled as the equation with one stage nonlinear reaction scheme. The reaction of digested organic substances became biogas by using mass balance equation is obtained as follows:

$$\frac{dX}{dt} = (\mu - D)X \tag{1}$$

$$\frac{dS}{dt} = -k_1\mu X + D(S_{in} - S) \tag{2}$$

$$Q = k_2\mu X \tag{3}$$

where X is concentration of the biomass in the reactor (g/l). S is substrate concentration (g/l). S_{in} is the substrate concentration in the fluent. μ is the specific growth rate (d^{-1}). Q is biogas flow rate (l/day) and k_1,k_2 are anaerobic digestion constants in the biogas process, $D=0,\ S_{in}=0$. Then, we will have new algebraic equations as

$$\frac{dX}{dt} = \mu X \tag{4}$$

$$\frac{dS}{dt} = -k_1\mu X \tag{5}$$

We can be seen from equations (3), (4) and (5) that the specific growth rate is key parameter for the description of biomass growth, substrate consumption and production formation. The specific growth rate of bacteria depends on the temperature, pH, biogas flow rate and concentration of organic substances then expressed by the multiplication of individual terms, each of them refer to one of the influencing factors:

$$\mu(t) = \mu(S)\mu(Q)\mu(T)\mu(pH) \tag{6}$$

Meanwhile, the specific growth rate of bacteria was related to concentration of organic substances which are studied [8-9] as the following 3 equations

$$\text{Monod model:} \quad \mu(S) = \frac{\mu_{\max} S}{k_s + S} + k \tag{7}$$

$$\text{Contois model:} \quad \mu(S) = \frac{\mu_{\max} S}{k_m X + S} + k \tag{8}$$

$$\text{Haldane model:} \quad \mu(S) = \frac{\mu_{\max} S}{k_s + S + S^2/k_i} + k \tag{9}$$

where μ_{max} is maximum specific growth rate (d^{-1}) and k_s,k_m,k_i,k are constants. The influence of temperature is often modeled by an Arrhenius type law:

$$\mu(T) = a_1 \exp(-E_1/RT) - a_2 \exp(-E_2/RT) - a_3 \tag{10}$$

where T is the temperature$({}^\circ C)$, E_1,E_2 are gas energy (J/g.mole), R is the gas constant (J/g) and $a_1,\ a_2,a_3$ are constants.

For biogas process, Rozzi proposes treating the influence of pH by a parabolic law:

$$\mu(pH) = apH^2 + bpH + c \tag{11}$$

where *a, b, c* are constants.

The relationship between the specific growth rate of bacteria and the biogas flow rate could be presented as

$$\mu(Q) = \frac{k_q}{k_q + Q} + k_3 \tag{12}$$

where k_q, k_3 are constant.

In these equations the only modeling assumption is that the biomass growth term (μX) and the substrate consumption term ($k_1 \mu X$) are proportional to the biomass concentration (X). This paper is add k, k_3 in equation (7), (8), (9) and (12) for dynamic compensation of useful system identification

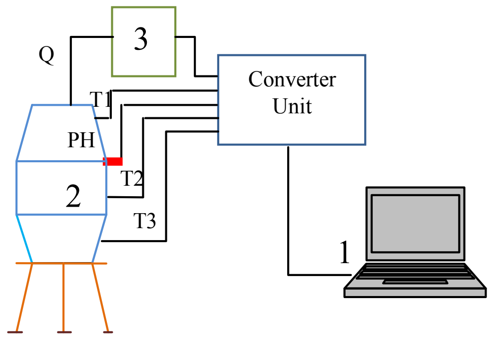

Fig. 4 Experimental setup

III. Research Procedure

In this section a description of the research procedures are given and divided topic into 4 parts experiment setup, parameter identification via genetic algorithm, experimental results and simulation results.

A. Experimental Setup

The experimental setup is designs for data collection of an anaerobic digestion with shrimp culture pond sediment in the batch process, as shown in Fig.4. Where 1- Computer is to create a program LabVIEW for the measurement and collected data of temperature, pH and biogas flow rate. 2 – A digester tank is 80 liter with shrimp culture pond sediment. 3 – Measuring system for biogas flow rate. The experimental data were occurred in analog signal and convert to digital signal via conversion unit with model NI- USB6008.

B. Parameter Identification via Genetic Algorithm

The application of an appropriate identification methodology via artificial intelligence technique can be estimated the mathematical model of an anaerobic digestion with shrimp culture pond sediment in the biogas process, as shown Fig.5. The investigation of the coefficients in the mathematical models (3), (4), (5), (7), (10), (11) and (12) is a very complex problem because of restricted information input temperature, pH, initial substrate concentration (S_0) and biogas flow rate ($Q(t)$) can be measured. Where $\tilde{Q}(t)$ is the biogas flow rate from the mathematical model of anaerobic digestion with shrimp culture pond sediment in the biogas process. *Q(t)* was compared to the biogas flow rate result from the experiment setup. Their deviation value could be obtained with sum square error (e_{ss}).

$$e_{ss} = \sum_{i=1}^{N} \left[Q(i) - \tilde{Q}(i) \right]^2 \tag{13}$$

The identical technique by Genetic Algorithm (GA) is the one method to seek answers by natural selection and GA. It will have the continually improve to find answers from one generation to the next generation like the evolution of living things [18-19]. The components of the GA cycle are populations, original species and new species. GA will have continually improved from narrow local solution to global solution. GA will finish when ending condition is consistent. Generally, the condition is amount of generations required or acceptable deviation value is required to accept the best chromosome in the group of populations.

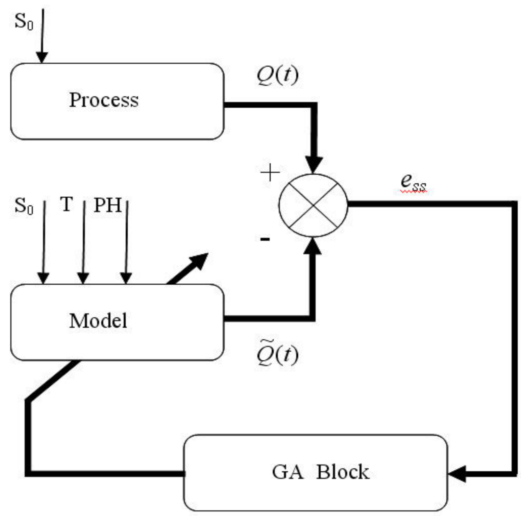

Fig. 5 Identification method

C. Experimental results

From the experiment setup, 80 kg shrimp culture pond sediment was put into a tank and fermented the sediment by anaerobic digestion in batch reactor. The transient response of biogas flow rate in biogas process is shown in Fig.6. The results showed that the biogas was occurring fast At the start of an experiment, the biogas occurs 675 cm^3. The collecting data of accumulative sum of biogas production in 30 days is 13,255 cm^3 and average biogas production is 424.35 cm^3/day which are CH_4, CO_2 and N_2 composition were 44.34%, 4.91% and 17.23% respectively. The reaction temperature varied with room temperature which is shown in Fig.7 and pH profile within 5.8 - 7.8 each day as shown in Fig. 8.

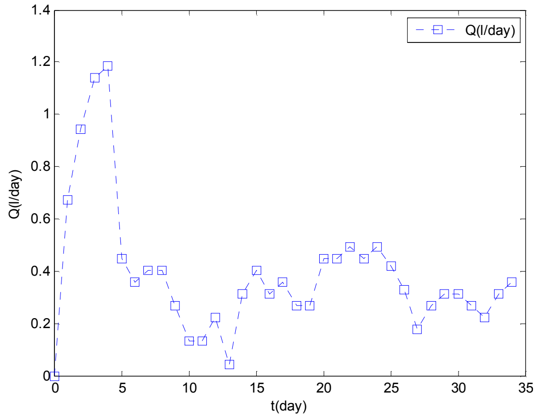

Fig.6 The transient response of biogas flow rate

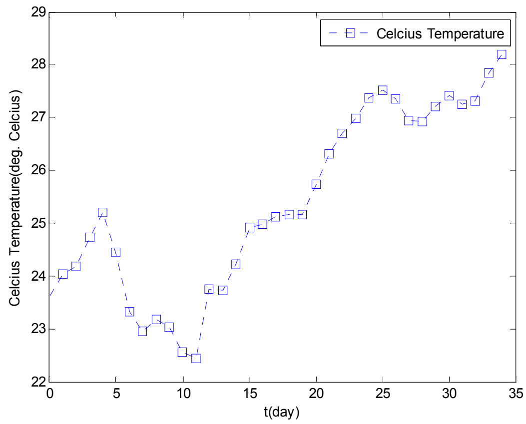

Fig.7 Temperature profile

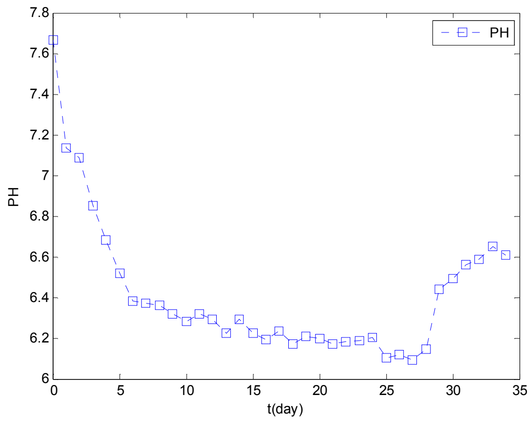

Fig.8 pH profile

There are three models that are available for finding variables in identity specification of anaerobic digestion with shrimp culture pond sediment in the biogas process. The mathematical models depend on the change of bacteria which affected by organic substances and could find that Monod model has minimum error by initial substance concentration (organic matter) which 73.5 g/l.

Table 1
Chemical Compositions of Biogas

Biogas compositions	Analyzer %
Methane ,CH_4	44.34
Carbon dioxide, CO_2	4.91
Nitrogen, N_2	17.23
Hydrogen, H_2	Non detected
Hydrogen sulfide, H_2S	Non detected

Source: Scientific Equipment Center,
Prince of Songkla University, February 2010

Table 2
Biochemical Properties of Shrimp Culture Pond Sediment

No	*Biochemical properties*	*Before*	*After*
1	pH	7.7	7.5
2	Total Solids ,mg/l	139,859	15,978
3	Total Dissolved Solids, mg/l	24,500	9,700
4	Total Suspended Solids, mg/l	112,200	5,750
5	Total Volatile Solids, mg/l	22,653	2,450
6	Total Fixed Solids, mg/l	139,603	10,922
7	Biological Oxygen Demand (BOD),mg/l	2,334	324
8	Chemical Oxygen Demand (COD),mg/l	7,840	1,197
9	Total Nitrogen, mg/l	4,300	5,000
10	Total Phosphorus, mg/l	6.24	136.95
11	Total Potassium, mg/l	816.5	662.5
12	Organic Carbon, g/l	42.7	47.3
13	Organic Matter, g/l	73.5	81.3

Source: The Center for Scientific and Technology Equipment,
Suranaree University of Technology, January 2010

The biochemical properties of shrimp culture pond sediment and chemical compositions of biogas are shown in Table.1, 2. The results of the treatment of shrimp culture pond sediment by anaerobic digestion in biogas process could reduce the sediment properties TS, TDS, TSS, BOD and COD were 89%, 60%, 95%, 86% and 85% respectively.

D. Simulation results

The identical specification of the variable via equation (7) to estimate variables, we use specific growth rate of bacteria depend on the temperature, pH, biogas flow rate data, E_1=16000 J/g.mole, E_2=34500 J/g.mole and R=1.987 J/g [2]. We studied population number and GA cycles that affect system identification as shown in Fig.9, 10. Table 3 and 4 demonstrates the error of GA program. The tests showed the population number and GA cycles increased, the error decreased but need more computation time. The estimation of the mathematical model doesn't consider the error occurred but must be considered with the principle of anaerobic digestion process [20].

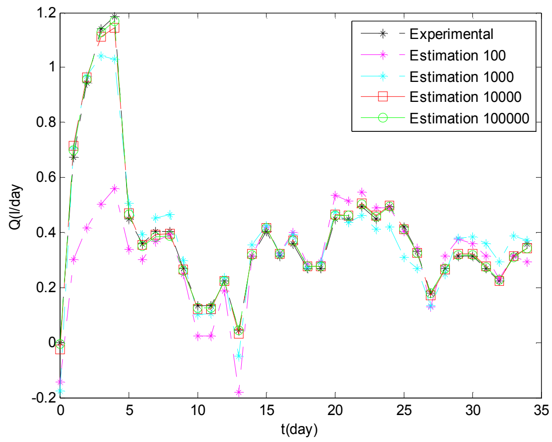

Fig.9 The responses of the GA cycles of system identification

Table 3
GA cycle

GA cycle	100	1000	10000	100000
e_{ss}	1.3676	0.1457	0.0079	0.0035

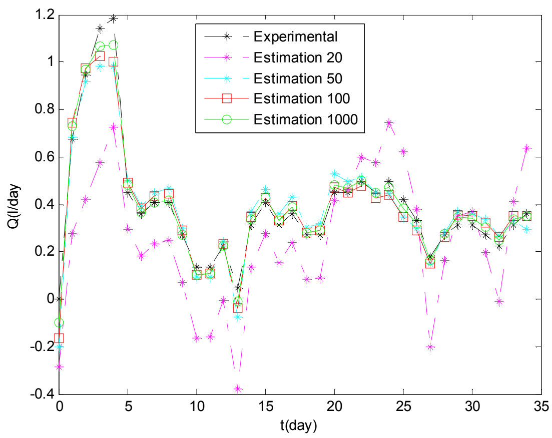

Fig.10 The responses of the population number of system identification

Table 4
Population number

Population number	20	50	100	1000
e_{ss}	2.195	0.187	0.119	0.0475

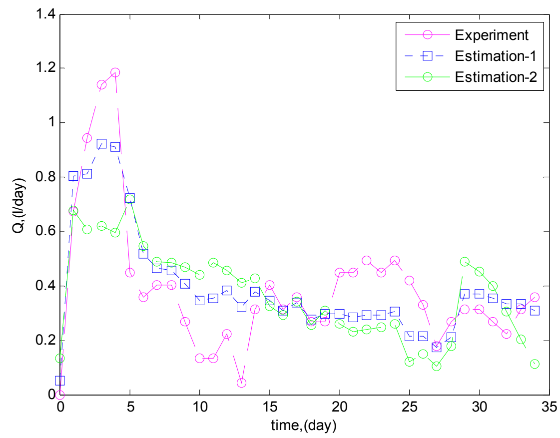

Fig.11 The responses of biogas flow rate of experimental and estimation data

Table 5
Parameter Identification for Biogas Process

Parameters	*Estimated Value-1*	*Estimated Value-2I*
k_1	0.119	2.714
k_2	3.614	0.477
$\mu_{\max}$	1.69	0.1
k_s	1.1087	20
k	-1.6654	--
a_1	2.4×10^{11}	1.92×10^{11}
a_2	-1.02×10^{23}	-8.16×10^{23}
a_3	-0.111	-0.0555
a	-5.601	-0.8257
b	76.108	11.347
c	-254.03	-38.4
k_q	9.99	1
k_3	17.084	--

The estimation of the mathematical model of anaerobic digestion with shrimp culture pond sediment in the biogas process is selected variables with 100 population numbers and 100,000 GA cycles. The best answer is to find the best chromosome in population. The GA algorithm stops when the search criteria. The estimation-1 is model with dynamic compensation (k,k_3) and estimation-2 is model without dynamic compensation (k,k_3). The k compensates unknown dynamic response of the relationship between specific growth rate and concentration of organic substances and k_3 compensates dynamic response of the relationship between specific growth rate and biogas flow rate. The error of estimation-1 is 0.7239 and estimation-2 is 1.8596.

The comparison between the responses of the mathematical model and the experimental data of biogas flow rate are shown in Fig.11. The results of parameters identification of the mathematical model are represented in Table 5.

The parameters those are estimated by the GA method are necessary to consider the accuracy in accordance with the experiment. The expression equation 7 with parameters of estimated value-I and estimated value-II were adopted by Monod model because it best fit experiment data as shown in Fig. 12.

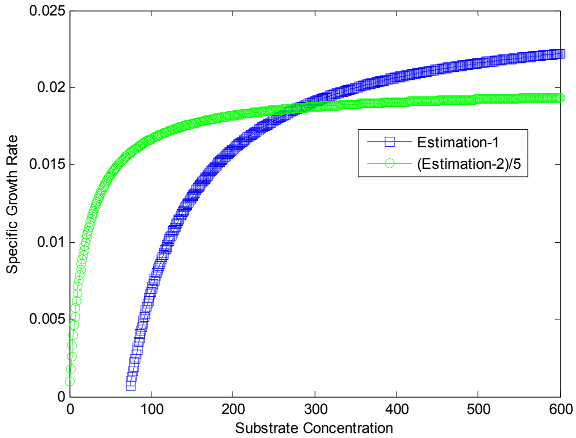

Fig.12 The Monod law

The biomass growth rate is often perfumed to be slowed down at high biomass concentration. A simple model that accommodated for this situation assumes that the specific growth rate decreases lineally with the biomass concentration and is illustrated in Fig.13.

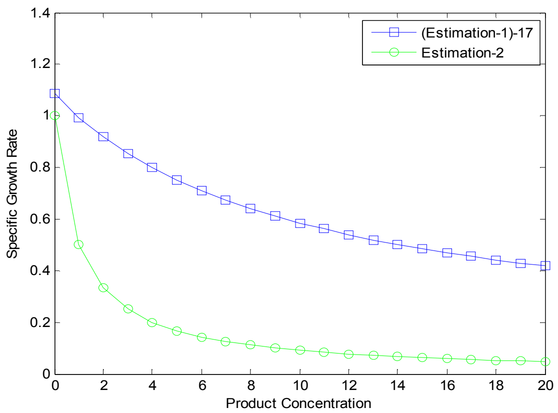

Fig.13 The Contius model

The temperature is most modeled by an Arrthenius-type law, as has been done. The expression shows that the specific growth rate increases with temperature up as shown in Fig.14. The relationship between specific growth rate and pH in biogas process is parabolic form as shown in Fig.15.

The identity specification of anaerobic digestion with shrimp culture pond sediment, the variables can be used to estimate mathematical models. The models should be tested with many cycles in order to gain the accurate variable. The variable that affect biogas flow rate should be controlled as well.

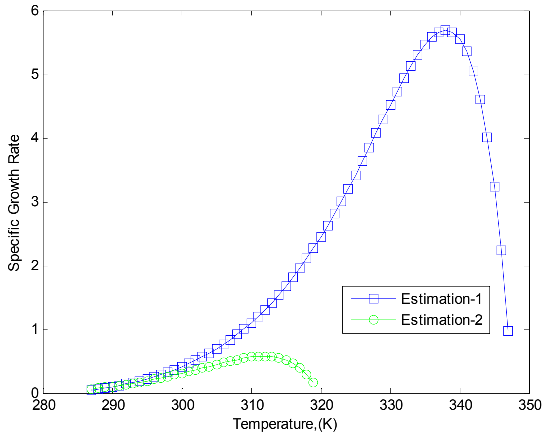

Fig.14 The relationship between specific growth rate and temperature

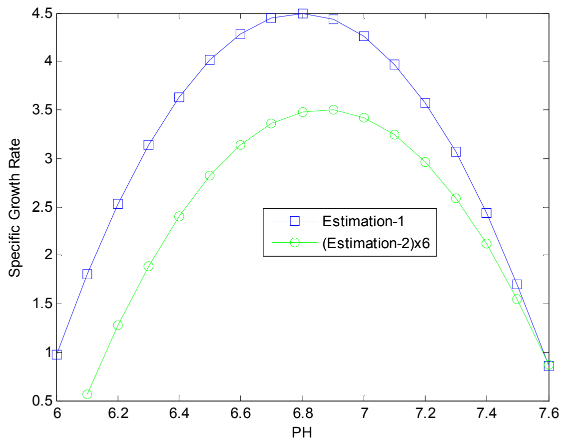

Fig.15 The relationship between specific growth rate and pH

IV. CONCLUSION

The biochemical properties of shrimp culture pond sediment after biogas process were reducing 89% of BOD and 60% of COD which effected to soil pollution and emissions (Methane, Carbon dioxide) to the atmosphere. The increase of nitrogen and phosphorus in shrimp culture pond sediment were useful for plant. This research only studied shrimp culture pond sediment from shrimp farming that do not use effective microorganisms because the biochemical properties of shrimp culture pond sediment is charge.

The shrimp culture pond sediment produces biogas via anaerobic digestion as a way solves problems of the energy and environmental management. The biogas of shrimp culture pond sediment has methane 44%, heating value 18 MJ/kg and efficiency of energy conversion 20% approximately. The total biogas of shrimp culture pond sediment can be occurred 1.65×10^{-4} m^3/kg approximately. Therefore, we can produce a biogas 2.06-5.15 $\times 10^{-4}$ m^3/m^2 approximately.

This paper presents the structure of the mathematical model and parameter identification technique that is used to estimate dynamical model of anaerobic digestion with shrimp culture pond sediment in the biogas production process. The dynamical response of the mathematical model compared to the experimental data by Genetic Algorithm method with principle of anaerobic digestion. The estimation of the mathematical model with dynamic compensation (k,k_3) illustrates results consistent with the principle of anaerobic digestion. As the results of the study, the variable from identity specification can be used to estimate biogas flow rate and applied to design experimental equipments for batch reaction of biogas production from shrimp culture pond which is appropriate to requirement and usability.

NOMENCLATURE

X concentration of the biomass in the reactor (g/l)
Q biogas flow rate (l/day)
S substrate concentration (g/l)
S_{in} substrate concentration in the fluent (g/l)
μ specific growth rate (d^{-1})
k_1,k_2 anaerobic digestion constants in the biogas process
μ_{max} maximum specific growth rate (d^{-1})
T Temperature (^oC)
k_s,k_m constant
k,k_3 dynamic compensation
E_1,E_2 gas energy (J/g.mole)
R gas constant (J/g)
a_1, a_2,a_3 constant
a, b, c constant
k_q constant

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