Kinetic Evaluation of Two-Phase Anaerobic Treatment of Slaughterhouse Wastewater

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Abstract. Two-phase anaerobic treatment by a continuously stirred tank reactor (CSTR) and an upflow anaerobic sludge blanket (UASB) system was applied to treat slaughterhouse wastewater at ambient temperature, non-pH adjustment, at five different organic loading rates (OLR) of 1.39–2.60 kg COD/m³.d with the hydraulic retention time (HRT) in the range of 14.1-26.4 hr. The kinetic evaluation of the experimental data was carried out using a kinetic model derived from Michaelis-Menten and Monod equation. The maximum substrate utilization rate (k_max) and the half velocity constant (K_s) were 0.252 d⁻¹ and 586.5 mg/l, respectively. The results indicated that the applied kinetic model is capable of explaining the bio-kinetic behaviour of the CSTR-UASB system and can be used as a design criteria for two-phase anaerobic treatment treating other fat-containing wastewater.

1. Introduction

During the past decades, anaerobic treatment process has been applied for treating various types of wastewater. It has been known to be effective in removing the organic matters with significantly lower cost of operation and excess sludge management. Moreover, the biogas which is formed as final product of the process can be used as energy source for various purposes such as electricity generation or heat recovery. At present, especially, an UASB reactor has been known as one of the most effective anaerobic system globally. It has been found that an UASB system can be used for treating various types of wastewater with high efficiency on chemical oxygen demand (COD) removal. However, there are some obstacles in the treatment of fat-containing wastewater using UASB reactor. High amount of low-biodegradable matters, as regarded as protein and lipid, in this kind of wastewater are accumulated in the reactor and play as a key role of the process rate limiting, sludge wash-out and scum formation causing deterioration of system performances [1-3].

As the result, in case of treating fat-containing wastewater particularly slaughterhouse effluent, the separation of acidogenic phase and methanogenic phase might be able to minimize those mentioned problems. Two-phase anaerobic system which acid forming reactor and methanogenic reactor are separated, can serve more optimizing conditions for each bacteria group resulting in greater process stability. Since, the acidification tank could not only reduce the quantities of compounds which easily float like oil and grease to be linked with a scum layer formation at the liquid–air interface but also provided partial degradation of low-biodegradable matters before applied to consecutive methane reactor [4-5]. It has been found that two-phase anaerobic system was applied for the treatment of
complex wastewaters as an adequate removal efficiency was obtained [6-9]. Phase-separation system should thus be taken into account to minimize the problems related with slaughterhouse wastewater treatment.

The aim of this study was not only to investigate the optimum operational conditions of CSTR-UASB system for the treatment of slaughterhouse wastewater, but also to evaluate the kinetics which can be used as a design criteria for two-phase anaerobic reactor. The experiments were carried out under ambient temperature, non-pH adjustment, at five different OLRs of 1.39–2.60 kg COD/m³.d with the HRTs in the range of 14.1-26.4 hr. The kinetic model derived from Michaelis-Menten and Monod equation was applied for the kinetics evaluation.

2. Methods

2.1 Reactors
A plastic tank with a working volume of 10 l was used as acidogenic CSTRs. Each CSTR accompanied with water replacement plastic tank to collect the produced biogas and recirculating pump for homogeneous mixing within the reactor. In order to obtain designed volume corresponding to each assigned OLR, the level of discharge pipe (to an UASB reactor) was adjusted to the height of a CSTR. An effluent released from an acidogenic reactor was directly fed into an UASB reactor. An UASB reactor with a working volume of 7.67 l was used as methanogenic reactor. It was equipped with baffle as a gas-solids separator (GSS) in the upper part for separating and collecting the produced biogas, and installed with ten sampling ports. An UASB reactor also coupled with water replacement plastic tank to collect the produced biogas. The flow diagram applied in this study is illustrated in Figure 1.

![Figure 1. Flow diagram of two-phase treatment study](image)
Remarks : 1.Influent tank 2.CSTR 3.UASB reactor 4.Effluent tank 5.Gas collecting tank 6.Mixer 7.Feeding pump 8.Recirculating pump 9.Sampling ports

2.2 Wastewater and seed sludge
Raw wastewater from Chiang Mai Municipality slaughterhouse was used as influent. After passing coarse screen installed to separate large dispersed particles, wastewater was collected as grab samples from open-discharge gutter of slaughtering area and then stored at 4°C before used. Digested sludge from an anaerobic digester of Chiang Mai University wastewater treatment plant was used as seed sludge which had SS and VSS concentration of 2.6 and 2.0-2.05 g/l respectively.

2.3 Methodology
The overall performances of two-phase anaerobic treatment of slaughterhouse wastewater were determined. A CSTR was operated under HRT of 8 hr corresponding to OLRs in the range of 4.55-
4.67 kg COD/m³.d. Different operational OLRs of 1.81, 2.68, 3.59, 4.65 and 5.28 kg COD/m³.d for an UASB reactor corresponding to OLRs of 1.39, 1.83, 2.11, 2.43 and 2.60 kg COD/m³.d for CSTR-UASB system, respectively were assigned. The operational conditions applied throughout the experiment are presented in Table 1.

Table 1. The operational conditions applied throughout the experiment

| Flow rate (l/d) | CSTR HRT (hr) | CSTR OLR (kg COD/m³.d) | UASB HRT (hr) | UASB OLR (kg COD/m³.d) | CSTR-UASB HRT (hr) | CSTR-UASB OLR (kg COD/m³.d) |
|----------------|---------------|------------------------|---------------|------------------------|---------------------|-----------------------------|
| 10             | 8             | 4.57                   | 18.4          | 1.81                   | 26.4                | 1.39                        |
| 15             | 8             | 4.62                   | 12.3          | 2.68                   | 20.3                | 1.83                        |
| 20             | 8             | 4.55                   | 9.2           | 3.59                   | 17.2                | 2.11                        |
| 25             | 8             | 4.67                   | 7.4           | 4.65                   | 15.4                | 2.43                        |
| 30             | 8             | 4.59                   | 6.1           | 5.28                   | 14.1                | 2.60                        |

2.4 Analytical methods

All basic analyses were carried out according to Standard Methods [10]. The influent and effluent of CSTRs and UASB reactors were collected daily for routine analysis. pH and temperature were measured daily by pH meter. VFA composition (acetic, propionic, butyric, iso-butyric, valeric, iso-valeric) was quantified using HP gas chromatograph with helium as a carrier gas. Samples were filtered through 0.45 um GC-FC, acidified by formic acid and kept below 4 C. The temperature of the column was initially 80 C for a minute, and increase to 120 C (20 C/min), then to 205 C (6.13 C/min) and lastly 205 C for two minutes. During steady state condition of each assigned operational condition, biogas composition was analyzed twice using gas chromatograph. Mixed liquor was taken from sampling ports at the end of each operational condition to evaluate the solids profile at various height of an UASB reactor.

2.5 Kinetic model

During the steady state of each operational OLRs, the influent and effluent COD concentration, and MLVSS concentration in the reactor were measured. The half velocity constant (Ks) and the maximum specific substrate utilization rate (kmax) were evaluated by the equation derived from Michaelis-Menten and Monod model as following;

\[
X \cdot \text{HRT} / (S_0 - S_e) = \frac{K_S}{k_{\text{max}}} \cdot \frac{1}{S_e + 1/k_{\text{max}}}
\]

where, 
- \( K_S \) = half velocity constant, mg/l
- \( k_{\text{max}} \) = maximum specific substrate utilization rate, d⁻¹
- \( X \) = biomass concentration (MLVSS), mg/l
- \( \text{HRT} \) = hydraulic retention time, d
- \( S_0 \) = influent COD concentration, mg/l
- \( S_e \) = effluent COD concentration, mg/l

3. Results and discussion

Two-phase system consists of two reactors, a CSTR and UASB as acidogenic and methanogenic reactor, respectively. An acidogenic CSTR was operated under HRT of 8 hr. Meanwhile, the methanogenic UASB reactor was operated under different OLRs of 1.81, 2.68, 3.59, 4.65 and 5.28 kg COD/m³.d in order to find the optimum operational condition for slaughterhouse wastewater
treatment. Considered as a two-phase system, the CSTR-UASB system was thus operated under OLR of 1.39, 1.83, 2.11, 2.43 and 2.60 kg COD/m³.d as HRT of 26.4, 20.3, 17.2, 15.4 and 14.1 hr, respectively. The overall performance of two-phase system at all OLRs is presented in Figure 2.

![Figure 2. The overall performance of CSTR-UASB system](image)

Considering the performances of two-phase system, it can be said that the satisfied overall removal efficiency was obtained under an operational OLR in the range of 1.39-2.43 kg COD/m³.d. COD removal efficiency was appeared to be higher than 87.5% as high as above 85.7% of SS removal. More than 82.9% of FOG was eliminated. Besides, the system could maintain good operational stability throughout the course of study as the effluent pH and alkalinity were appeared to be higher than influent one. Sufficient buffer capacity was also provided as the VFA/Alk ratio was also close to 0.1 which has been known as the appropriate value for methanogenesis. Biogas yield was found to be in the range of 0.320-0.413 l/g CODremoved with methane content higher than 61.0%. Methane yield was as high as 0.289 l/g CODremoved. Eventhough an OLR of 2.43 kg COD/m³.d seems to be an optimum operational OLR with the highest COD and FOG removal, an OLR of 2.11 kg COD/m³.d is appeared to be another preferred option because of higher methane yield and specific methane production rate. As the results of that, an operational OLR in the range of 2.11-2.43 kg COD/m³.d is suggested for slaughterhouse wastewater treatment by using CSTR-UASB two-phase anaerobic system. In practice, to reach higher biogas production, an operational HRT applied for acidogenic CSTR may be reduced to less than 8 hr and OLR applied for methanogenic UASB reactor can also be decreased to less than 4.65 kg COD/m³.d resulting in the operational OLR of CSTR-UASB is drawn in mentioned range. As illustrated in Figure 3, kmax and Ks were 0.252 d⁻¹ and 586.5 mg/l, respectively.

![Figure 3. The evaluation of Ks and kmax](image)
Most of municipal slaughterhouses in Thailand are classified as a small-medium slaughterhouse. Usually, most of the slaughtered animals are pig as there are about 150-200 pigs are slaughtered daily. Another animal, such as cattle and buffaloes, are also killed but in quite less quantity. The wastewater generated by the processes is about 0.5 m$^3$/pig resulting in a 100 m$^3$ of wastewater is discharged per day. It has been known that high amount of low-biodegradable matters, such as protein and lipid, in slaughterhouse wastewater are the cause of sludge wash-out and scum formation in conventional single-phase UASB system as mentioned before. Two-phase anaerobic system is likely to be an interesting alternative to enhance treatment efficiency.

According to the outcomes obtained from the present study, CSTR-UASB system can be applied for slaughterhouse wastewater treatment. Slaughterhouse effluent can be treated with satisfied removal efficiency and high system stability. At suggested operational OLR in the range of 2.11-2.43 kg COD/m$^3$.d, high COD and FOG removal of 89.9-91.7% and 83.6-85.4%, respectively are reached. Moreover, biogas production yield of 0.350-0.412 l/g COD$_{removed}$ with high methane content is also achieved. With a wastewater volume of 100 m$^3$/d, 50 m$^3$ of biogas is obtained. The gas was used to boil hot water to be applied for various purposes in slaughterhouse. Reduce LPG consumption by approximately 700 kg/month. Treated wastewater can also be recycled for different activities such as gardening and animal shelter cleaning.

4. Conclusion
The results of this work have yielded the following conclusions;
- Methanogenesis was obviously influenced by HRT changing but was not considerably affected by pH variation in slaughterhouse wastewater acidification. It was effectively suppressed under HRT in the range of 4-9 hr and pH of 7.0.
- For CSTR-UASB system, at operational OLR in the range of 2.11-2.43 kg COD/m$^3$.d, COD, SS and FOG removal was 89.9-91.7%, 86.6-87.7% and 83.6-85.4%, respectively. Methane yield of 0.253-0.289 l/g COD$_{removed}$ and specific methane production rate of 0.0814-0.0967 l/g VSS.d with methane content higher than 61.0% was achieved.
- The maximum substrate utilization rate ($k_{max}$) and the half velocity constant ($K_s$) were 0.252 d$^{-1}$ and 586.5 mg/l, respectively.

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