Practical Design and Efficiency of Large-Scale Biogas Digesters for Swine Farms in Thailand

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Abstract: The objective of this work is to suggest design considerations and report operational efficiencies of CMU-UF, an up-flow anaerobic digester developed by Chiang Mai University, Thailand based on specific conditions livestock waste. CMU-UF designers have excluded temperature control units as well as mechanical agitation but instead, integrated UASB up-flow capability which can greatly reduce the initial investment. The design was supported by Thailand's Ministry of Energy to be developed in full-scale and implemented in 34 large swine farms in various regions of the country treating manure from more than 1.0 million standing pigs. Additional monitoring procedures were thus carried out on 20 chosen farms to investigate the efficiency of the installed digesters in terms of waste treatment as well as biogas production characteristics. The results indicate that an average COD removal efficiency of 87.6% can be achieved with a 4.0-6.0 days HRT and approximately 40 days SRT operation conditions. The CMU-UF has an average biogas production of 0.261 m^3/kg of removed COD, equivalent to 0.090 m^3/60-kg standing pig per day.

Keywords: Up-flow, biogas, livestock, tropical, efficiency.

1. Introduction

Livestock production has always been one the most important sectors in agricultural industries of Thailand. Annual pork meat production for both domestic consumption and exporting was reported over 800,000 MT in 2010 reflecting approximately 80 billion Baht market value with an increasing trend [1]. The distribution of pig farms density is shown in Figure 1. It is clear that farm population depends largely on logistic of meat distrubution and obviously close to bigger city like Bangkok, Chaing Mai etc. The estimate total of swine population in Thailand in 2010 reported by the department of livestock development was 8.3 million standing pigs from 8,807 registered farms [2]. The potential of biogas production from livestock manure has been estimated to be 620 million m^3 per annual for renewable energy production and utilizations [3]. Since 1995, Thailand's Ministry of Energy (MoE) has promoted many researches in development of practical biogas systems for different waste including livestock and related industries. Subidizing and feedin adder programs have been employed as the main mechanism to increase national renewable energy production espcially in biogas sector. According to MoE's renewable energy development plan 2010, biogas is expected to substitute 120 MW of electricity generation and 600 ktoe of heat per annual by 2022 [4] and [5]. Chaing Mai University (CMU) has been the main technology provider for MoE subsidizing program for livestock biogas production since 1998. Currently, there exist more than 500 operational anaerobic digestors at various scale ranging from 100 m^3DV to 12,000 m^3DV. The distribution of the biogas systems designed by CMU is illustrated by round dots in Figure 2.

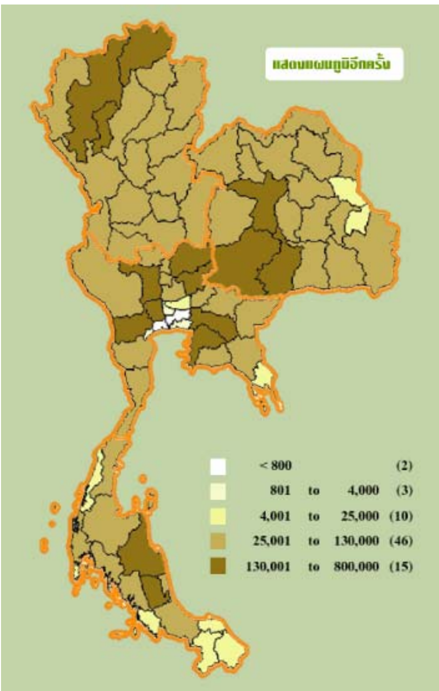


Figure 1. Standing pig population density in Thailand in 2010 (www.dld.go.th) [2].

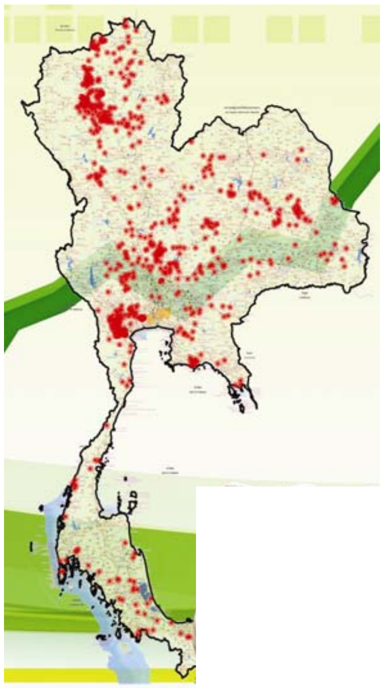


Figure 2. MoE-CMU biogas plant distribution in Thailand in 2010 (biogas.erdi.or.th) [6].

More than 90% of anaerobic digesters implemented under the MoE's subsidizing program are based on Chaing Mai University Channel Digester (CMU-CD) technology designed with simplicity and economy concept. This work, on the other hand, is focused on a more sophisicated systems, the Chaing Mai University Up-Flow (CMU-UF) digesters where the design aspects of the system are coverd in detail in section 2.1 of this text. Between 2002 and 2010, CMU-UF digesters are planned and implemented in 34 larger-scale swine farms ranging from 2,000 m^3DV to 12,000 m^3DV under the 3rd phase of MoE's subsidizing program resulting in 130,000 m^3DV in total treating manure from at least 1.0 million standing pigs everyday [6]. This work reveals essential information of CMU-UF digesters regarding proper design and developments. In addition, actual monitoring parameters were collected from selected farms and analyzed to verify operational efficiency and capability of each system.

2. Design and Measurement Methods

2.1 CMU-UF Digester Design

The CMU-UF system is aimed to be an appropriate biogas technology for larger-scale livestock farms (carry over 5,000 standing pig head) in diverse locations throughout Thailand. Designers combine the fundamentals of high rate UASB (Up-flow Anaerobic Sludge Blanket) digester [7-8] and construction simplicity of in ground covered lagoon with a benefit of relatively warm and humid ambient weather. A perspective engineering drawing of CMU-UF digester unit with a closed up view of the waste water distributor is illustrated in Figure 3. The drawing clearly shows fundamental concepts of the CMU-UF design including waste distributors, phase separators and flexible biogas storage.

The proposed up-flow velocity across the sizeable horizontal area in CMU-UF is approximately 0.04-0.12 m/hr, well in a flocculent sludge range and far below granular sludge forming range for typical UASB. Still CMU-UF is considered a high-rate anaerobic digester with average 4-6 days hydraulic retention time (HRT) and 30-40 days solid sludge retention time (SRT). Solid separation is forced to occur due to a customized up-flow behavior controlled by the gravitational elevation and length of the waste distributors piping and installed phase separation units. The CMU-UF digester is specifically designed based on actual single waste input from large-scale swine farms in Thailand which habitually use barn flushing system. While small deviation in each particular farm can be seen, a unique trend in waste characteristics can be distinguished from livestock waste from other countries or other sources. Such properties include high organic strength of approximately 5,000-25,000 mg/l of COD and high suspended solids content 2,000-15,000 mg/l SS. Information regarding waste input quality is described in detail in section 3.1 of this text.

The great challenge of CMU-UF design is not only to handle such high strength, high variation of waste aforementioned but also to be cost-effective in order to create a nationwide impact according to the MoE's focal purpose. Many configurations of existing digesters had been considered for their advantages in the design process. Agitation and heating are deemed unnecessary for the reason of low solid content (lower than 2.0%) and relatively high ambient temperature respectively [9]. Nonetheless, many features from UASB concepts are employed such as waste distribution piping and phase separators to assure consistent retention periods of liquid and sludge and thus results in acceptable effluent quality. Few modifications are also performed to prevent sludge blanket clogging which often leads to digester failure. Sludge removal capability is also crucial to stability and sustainability of every anaerobic system. CMU-UF digester has an angled floor towards its centerline and a high-solid mechanical pump is installed on a guided rail along the centerline to remove excessive sludge at a controllable amount from exact locations.

In brief, CMU-UF digester can be considered as a rectangular cross-section, low-velocity UASB digester as seen in Figure 3. In actual construction, approximately one third of digester height is located under the ground level to using soil pressure to counter-balance internal water pressure and thus reduce construction cost as illustrated in Figure 4(a). It is also noticeable that by this design the influent distribution units are positioned at the ground level for easy access and maintenance. In addition, the construction of sludge storage has also been omitted as an open sand-bed filter units as illustrated in Figure 4 (B) are applied instead to effectively dry excessive sludge drainage which can be used as soil conditioner. Finally, to complete the treatment cycle, polishing lagoons are specifically integrated to ensure that law-conforming final effluent quality.

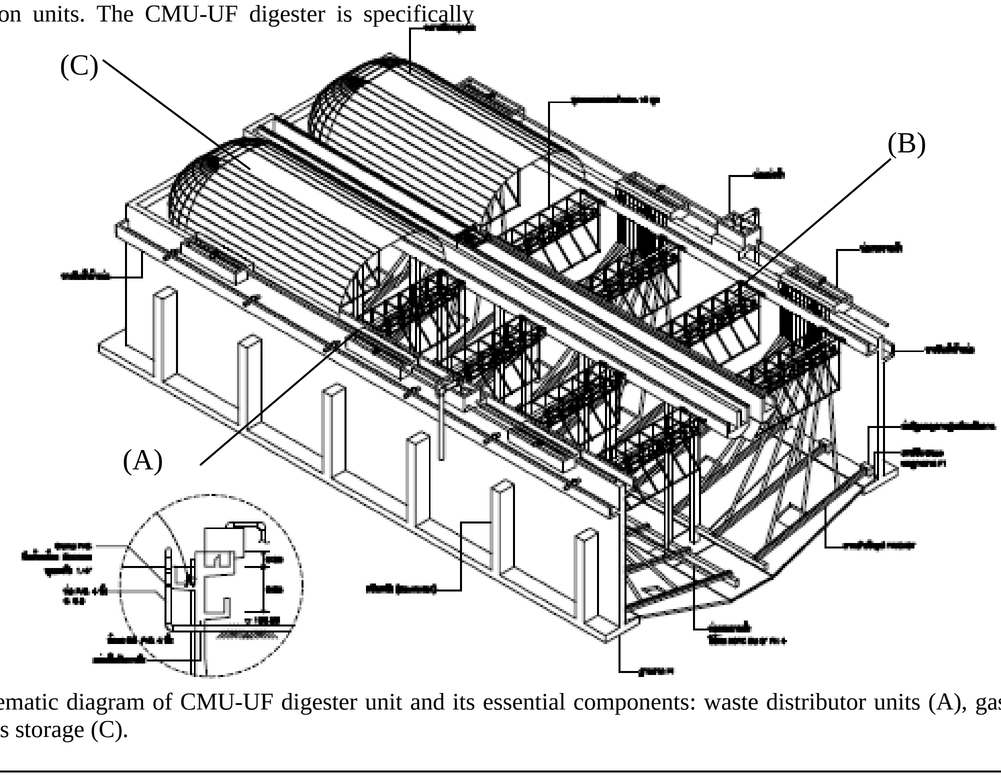


Figure 3. Schematic diagram of CMU-UF digester unit and its essential components: waste distributor units (A), gas separator (B) and flexible gas storage (C).

(A) (B)

Figure 4. (A) CMU-UF digesters from actual location, (B) Sand-bed solar-heated sludge drying units (courtesy of ERDI-Nakornping, CMU).

Table 1. Detail of data collections and standard testing methods used in this study.

No.	Parameter	Sampling Locations	Standard / Equipments
1.	COD (mg/l)	In, Ef, Fp	AWWA 2005, part 5220-C (9)
2.	BOD (mg/l)	In, Ef, Fp	AWWA 2005, part 5210-B
3.	VS (mg/l)	In, Ef, Fp	AWWA 2005, part 2540-E
4.	SS (mg/l)	In, Ef, Fp	AWWA 2005, part 2540-D
5.	TKN (mg/l)	In, Ef, Fp	AWWA 2005, part 4500-B
6.	Biogas Flow Rate (m^3/hr)	Bp	Thermal Flow Meter FCI ST98
7.	Biogas Compositions (%)	Bp	Gas Chromatography (TCD)

Table legends: In: Influent to digester, Ef: Effluent of digester, Fp: Final polishing pond, Bp: Biogas main piping

2.2 Measurements and data collection

The second objective of this work is to report efficiency and practicality of CMU-UF implemented under MoE's subsidizing program. While the program requires continuous monitoring in all implemented systems to assure their operational conditions, additional measurement was carried out at higher standards by ERDI itself for design development purpose. Collected data which allows researchers and designers to obtain insights and carry on analyses and optimizations. The list of parameters including their sampling locations and standard methods or equipments used is presented in Table 1.

As mentioned earlier, MoE's large swine farms subsidizing program supports total of 34 CMU-UF systems throughout the country. However, for the purpose of this work, 20 farms were selected based on their digester volume and locations for analyses to best represent all systems implemented. While the names and sizing of individual farms are not disclosed in this work for business reasons, the list of participating farms in MoE's program are announced publicly by EPPO [11]. Waste and biogas samples from each farm are collected after the start-up period throughout one year of commissioning period. Measurement results and analyses are presented in the following section.

3. Results and Discussions

3.1 COD, BOD and SS removal efficiency

The measuring parameters from participating farms are present by the plot of Figure 5. The figure shows an annual average of COD measurements digester influent in dark-color bars and effluent in light-color bars. Variation can be clearly seen in influent quality for individual farms ranging between 4,337 mg/l in farm 15 and 14,383 mg/l from farm 10. This is due to behavioral deviation in water usage and frequency of farm cleaning activities as well as effects of seasonal rainfall in different area. Nonetheless, the digester volume design of CMU-UF is directly based on existing standing pig heads resulting in a relatively comparable organic load rate (OLR) of 2.50-3.75 kg/m^{-3}.day^{-3} for all systems implemented. The effluent quality in terms of COD presented also shows good agreement with the trend of COD input. COD removal efficiency is also presented by triangular markers in the figure. The result clearly shows that CMU-UF efficiency in terms of COD removal is within the range of 74% to 97% with an average of 87.6%. Further investigations confirm that efficiency of digester in farm 1 is lower than expectation due to excessive water usage and thus reduce the HRT close to the lower limit of 4 days.

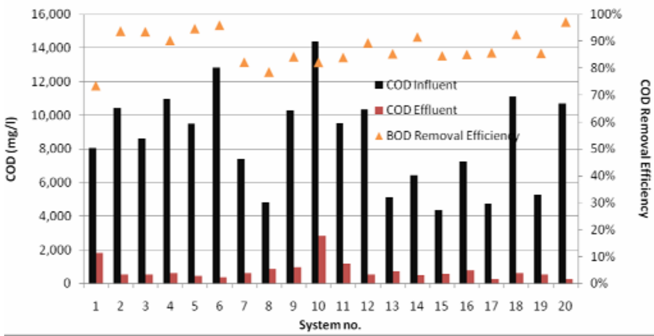


Figure 5. Average COD value of influent and effluent sampled from selected CMU-UF systems with removal efficiency comparison.

Organic loading for individual CMU-UF system in terms of BOD is also monitored; the collected data is illustrated in Figure 6. Overall, the result shows that BOD/COD ratio for swine waste in Thailand consistently ranges between 0.21-0.42 indicating relatively low biodegradable content in the influent. The BOD/COD ratio can also affect the design parameters of CMU-UF in terms of HRT and OLR of the digester. The result shows and average BOD removal efficiency of 93.1% among 20 sampled farms within the range of 87.6 – 97.8%. High BOD and COD removal efficiency indicate that CMU-UF digesters can be operated normally with swine waste within HRT and OLR ranges of 4-6 days and 2.50-3.75 kg/m^{-3}.day^{-3} respectively.

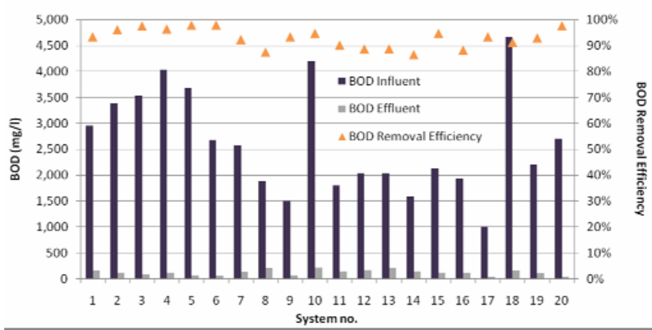


Figure 6. Average BOD value of influent and effluent sampled from selected CMU-UF systems with removal efficiency comparison.

CMU-UF systems are also designed for high suspended solid waste expected for swine waste mixture by suppressing the up-flow velocity and integrating phase separators similar to those installed in UASB digesters. Suspended solid content (SS) is also one of important monitoring parameters whose result describes the system capability in detaining and digesting suspended solid. Figure 7 shows a comparison of SS concentration between influent and effluent of each CMU-UF system and accordingly their removal efficiencies. It is noticeable that SS and COD or BOD has some connection but not very clearly, that is due to many reasons such as differences in colleting pond settling time, cleaning behavior differences and divergence of the feed. Average SS value in digester is 6,307 mg/l for influent and 550 mg/l for effluent, the average of SS removal efficiency for 20 selected systems is approximately 90.0%.

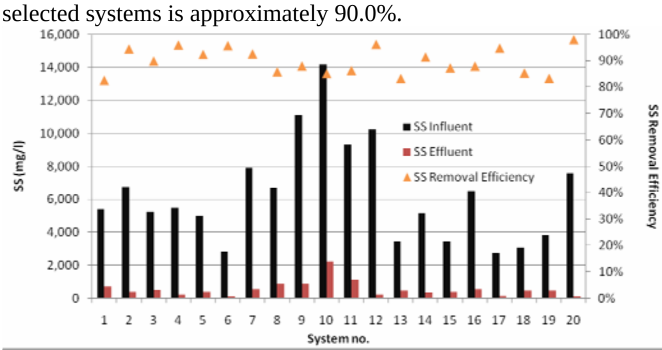


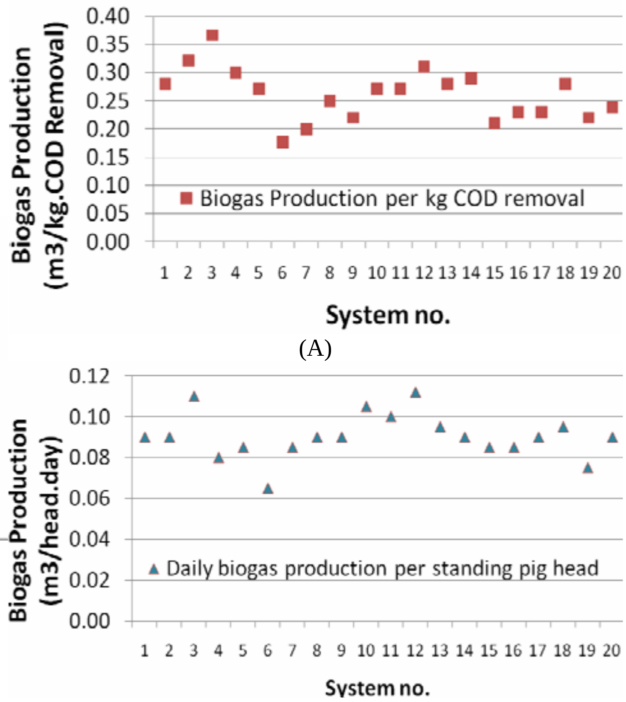
Figure 7. Average Suspended Solid (SS) of influent and effluent sampled from selected CMU-UF systems with removal efficiency comparison.

3.2 Biogas production capability

Biogas production rate is also one of the main interests to farm owners in choosing CMU-UF system. Since wastewater volume and COD concentration for individual farm is highly subjective as mentioned in section 3.1, measurement results for selected CMU-UF systems are presented in m^3/kg of COD removal for comparison purpose as illustrated in Figure 8(A). The result clearly indicates a variation in biogas production, the proportion ranges between 0.177 and 0.366 m^3/kg of COD removal with an average of 0.261 m^3/kg of COD removal with a standard deviation from this set of data of 0.046 m^3/kg of COD removal. The variation is due to many causes mainly in barn cleaning, waste collection and pre-treatment behaviors. Nonetheless the production volume in from each system is satisfyingly within design expectation of CMU-UF specification for swine waste. In addition, daily gas production per standing pig head (60-kg average) data from 20 selected farms is also presented in Figure 8(B). Some variation can be noticed between distinct systems with a good trend-wise agreement with biogas production per kg COD removal. Among 20 systems presented herein, an average of biogas production per standing pig head of 0.090 m^3/day with a standard deviation of 0.011 m^3/day can be obtained and thus can be used as key parameter for economical analysis of the project.

4. Conclusions

This work presents two aspects of Chiang Mai University - Up-flow (CMU-UF) digesters; design consideration and fundamental efficiency review. Data collected from 20 full-scale systems out of 34 implemented systems are illustrated in section 3. The key conclusions are regarding COD/BOD removal efficiencies and biogas production rates. Average waste treatment efficiencies in terms of COD and BOD removal are of 87.6% and respectively 93.1%. The up-flow nature enables CMU-UF digesters to separate and digest of high suspended solid waste with an average SS removal efficiency of 90.0%. In biogas production aspects, CMU-UF systems can produce up to an average of 0.261 m^3/kg of COD removal or 0.090 m^3/60-kg standing pig head per day. The actual value of renewable energy for the produced biogas may vary by individual farms. However, approximately 4.5 years of payback period can be achieved in implementation of CMU-UF systems under MoE's subsidizing program [6].



(B)

Figure 8. (A) Biogas Production per COD Removal, (B) Biogas Production per Standing Pig.

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Abbreviation

CMU-UF	Chiang Mai University Up-Flow Anaerobic digester
COD	Chemical Oxygen Demand (milligram/liter)
EPPO	Energy Policy and Planning, Ministry of Energy, Thailand.
MoE	Thailand’s Ministry of Energy
MT	Metric Ton (1,000 kilogram)
m^3/day	Cubic Meter per day
m^3/kg $COD_{removal}$	Cubic Meter per kilogram of removed COD
m^3/head.day	Cubic Meter per pig head per day
m^3DV	Cubic Meter of Digester Volume
mg/l	Milligram per liter