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Net Energy Production Strategies with Saline and Non-saline Sewage Treatment

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ABSTRACT

Energy is becoming an increasingly serious crisis facing the world today. In order to help address this issue, municipal sewage is being regarded more as a resource than as a waste. In this study, non-saline sewage is proposed to be treated in a two-stage system of anaerobic fluidized bioreactor (AFBR) & anaerobic fluidized membrane bioreactor (AFMBR) to realize purification and methane collection simultaneously. For saline sewage, which is a big issue in Hong Kong due to the ubiquitous practice of seawater toilet flushing for a long time, a chemical fuel cell is suggested to apply after anaerobic treatment with identical AFBR & AFMBR system for non-saline sewage. Thus energy generation would occur in the fuel cell along with the conversion of sulfide to sulfur, rather than methane production since high salt concentration in saline sewage would inhibit methanogen in anaerobic process. Energy production, energy requirement, as well as net energy generation in both non-saline and saline sewage treatment processes were evaluated and compared. The result shows, AFBR & AFMBR system requires 0.058 kWh/m^3 of energy to support its operation, while the methane generated from non-saline sewage can output 0.19 kWh/m^3 of energy and the fuel cell can produce 0.14 kWh/m^3. Obviously, 0.132 kWh/m^3 and 0.182 kWh/m^3 of net energy could be acquired through non-saline and saline sewage treatment, respectively. The value of net energy production would be higher if further optimization of the treatment techniques is realized.

1. INTRODUCTION

The utilization of fossil fuels has accelerated along with the rapid development of global economy in recent years and resulted in a global energy crisis and consequent oil price increase, which has drawn considerable attention on exploration of energy-saving technologies, as well as renewable energy sources. Bioenergy has being regarded as a promising alternate to alleviate energy crisis due to its renewable source and less or even no carbon dioxide emission during combustion. Thus it will not pressure on the current global warming, which is another critical environmental concern we human beings face.

Apart from conventional bioenergy sources such as agriculture biomass and algae, wastewater is also a potential pool for energy production. Comparing with traditional wastewater plant, which always consumes a huge amount of energy accounting for about 3% of electrical energy load in developed countries [1], how to reduce the energy consumption and even obtain net energy from wastewater treatment becomes an attractive topic and its realization will definitely have profound benefits in a global scope. There are already many studies as well as applications on the energy production from municipal sewage (generally non-saline) [2,3]. In a word, energy is generally carried within the form of biogas (mainly methane) through anaerobic treatment of wastewater, and the amount of this part energy will offset and even higher than energy demand for operation of the whole plant with adequate adoption of treatment technologies.

Given the situation of water scarcity, in some locations, for example in Hong Kong, seawater toilet flushing has been practiced since 1950 [4], which generates saline sewage with a typical COD to sulfate ratio of 0.6 (2.4 mg COD/mg S) and a high sulfate concentration (~500mg/L) [5,6]. Similar kind of saline wastewater is also produced from shipboard or offshore installations [7]. Different from non-saline sewage, high concentration of salt (especially sulfate and chloride) in saline sewage would inhibit the growth of methanogens and heterotrophic denitrification microbes and hence compels microorganism community shift during anaerobic process [8]. Sulfate reducing bacteria (SRB), which use organic compounds as electron donor to reduce sulfate to sulfide, would become dominant in anaerobic system. As a result, most COD in saline wastewater can be removed and the effluent would possess a high concentration of sulfide. Sulfide, as a dangerous contaminant that promotes corrosion of metallic materials and is toxic to humans, is usually found as both dissolved and gaseous forms in saline sewage effluent after anaerobic treatment [9]. Sulfide formation is undoubtedly a serious issue in Hong Kong due to the ubiquitous practice of seawater toilet flushing. To address this, a novel technology, chemical fuel cell, is proposed in this study to remove sulfide from anaerobically treated saline sewage and generate energy through the conversion of sulfide to sulfur simultaneously.

In the present study, energy production, energy requirement by operating system, as well as net energy generation were evaluated and analyzed in anaerobic treatment process of non-saline sewage and anaerobic treatment & fuel cell process of saline case. The results will not only present an instruction to energy related issues of wastewater, but also significantly enhance the environmentally friendly and sustainable treatment of saline sewage in Hong Kong, as well as other districts adopting seawater toilet flushing.

2. METHODS

2.1 AFBR & AFMBR for Anaerobic Treatment

Considering that anaerobic treatment of sewage alone generally is not sufficient to meet the stringent effluent requirements [10-12], here anaerobic fluidized membrane bioreactor (AFMBR) is used for post-treatment of effluent from a front anaerobic fluidized bioreactor (AFBR), as Figure 1 shows. No mention the huge potential for energy-efficient treatment of various kinds of wastewater, membrane fouling can also be controlled in this system due to the direct contact between the membrane and the granular activated carbon (GAC), which is used as the fluidized medium to support biological growth. The operation parameters and conditions have been described in the previous study [2].

Both non-saline and saline sewage are proposed to utilize this AFBR & AFMBR combined anaerobic system for treatment. As for non-saline sewage, most of the contained COD was removed and converted to methane through methanogens. Here methane produced during anaerobic treatment from gas and liquid phases would be determined and collected for further energy analysis.

As for saline sewage, methanogens are heavily inhibited because of its high salt content and SRB would turn to dominant community [13]. The organic compounds in sewage would be mainly completely mineralized with sulfate as electron acceptor and leading to presence of abundant sulfide in effluent from anaerobic system.

2.2 Fuel Cell in Saline-sewage Case

In order to remove sulfide and explore energy production potential in this polishing process, a chemical fuel cell, as shown in Figure 2, was used to subsequently purify saline sewage effluent from upstream anaerobic system. In fuel cell, sulfide releases electron at anode side and the electron would transport to cathode side along the external circuit and be captured by oxygen finally. During this circle, current would be generated.

Batch mode simulation was performed in a fuel cell (150 mL working volume in anode and cathode, respectively) with sodium sulfide (Na_2S) as the main component in its anode electrolyte, and oxygen was injected into the cathode side. Sodium chloride served as electrolyte in the fuel cell system, which is compatible with the usually high concentration of chloride in saline sewage.

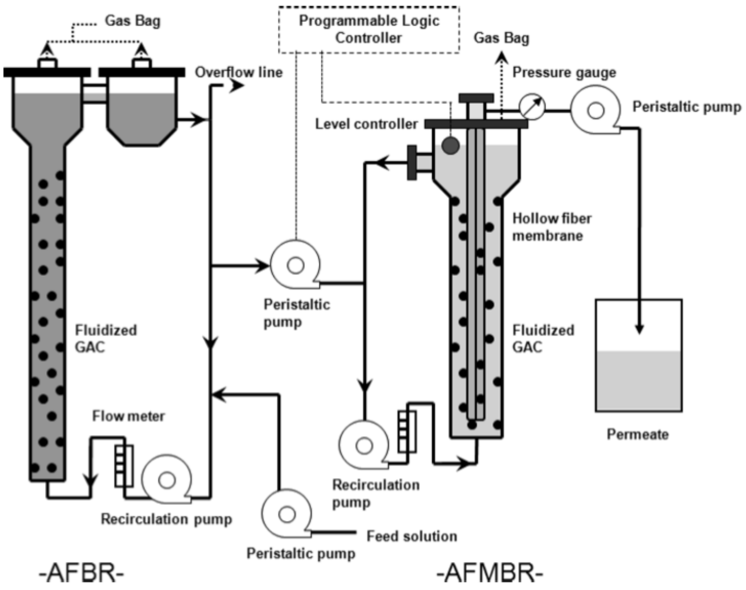


Fig.1 Schematic diagram of two-stage anaerobic system [2]

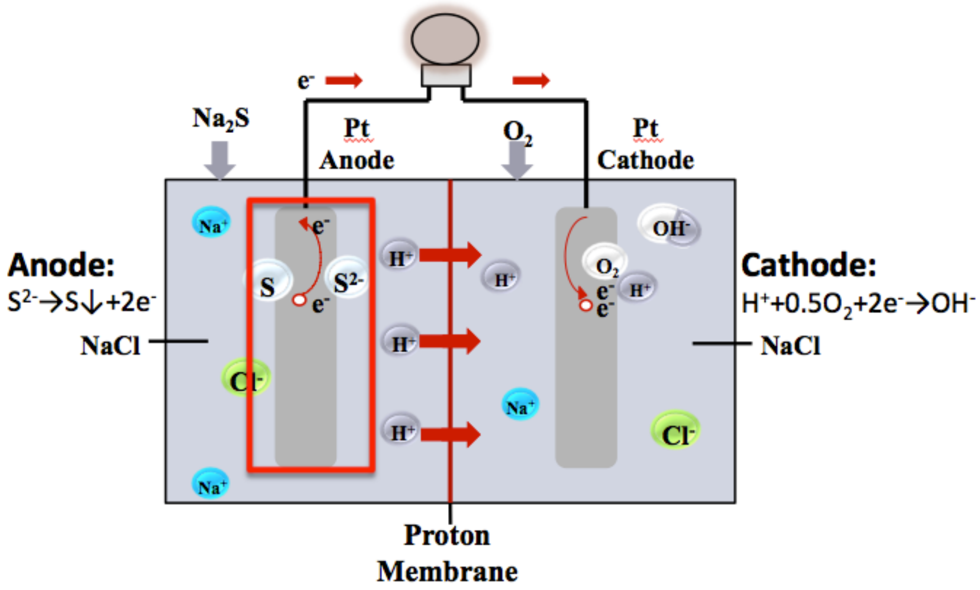


Fig. 2 The configuration of hydrogen sulfide fuel cell

2.3 Synthetic Sewage

In non-saline case, synthetic wastewater with a COD of 513mg/L was utilized as influent to feed the AFBR. The materials involved were previously described by Kim et al. [2]. In addition, 0.15 M of Na_2S solution was prepared as synthetic saline sewage effluent for fuel cell simulation test.

3. RESULT & DISCUSSION

3.1 Energy Requirement

Energy utilization for the AFBR & AFMBR combined system was evaluated through the pump power requirement equation [14].

$$P = \frac{Q\gamma E}{1000} \qquad (1)$$

Where P—Power requirement (kW);

Q—Flow rate (m^3/s), equals the reactor recycle rate;

γ—Constant, 9800 N/m^3;

E—Hydraulic pressure head (m).

Then the pumping energy requirement was calculated by the following equation,

$$W = \frac{P}{v} \qquad (2)$$

Where W—Pumping energy requirement (kWh/m^3);

v—Permeate flow rate (m^3/h)

All values of the related parameters for energy requirement of AFBR and AFMBR were listed in Table 1. For the AFMBR, a average energy loss of permeate flow through the membrane of 0.1 bar, equivalent to a hydraulic head loss E of 1.0 m and an energy requirement of 0.003 kWh/m^3 was considered besides the calculated W, yielding a total value for the AFMBR of 0.028 kWh/ m^3 [2]. It is just a small fraction of the previously reported energy requirement of 0.25-1.0 kWh/ m^3 in AMBRs, which have to use gas sparging for membrane fouling prevention [15]. To sum up, the pumping energy requirement was 0.058 kWh/m^3 for the combined AFBR & AFMBR system.

Table 1. The parameters of AFBR & AFMBR for Energy Requirement Evaluation

	Q (m^3/s)	E (m)	N (m^3/h)	Energy Loss (kWh/m^3)	W (kWh/m^3)
AFMBR	2.33×10^{-5}	0.098	9.1×10^{-4}	0.003	0.028
AFBR	3.33×10^{-5}	0.18	1.96×10^{-3}	N/A	0.03
Total Energy Requirement					**0.058**

3.2 Net Energy Production from Non-saline Sewage

During steady operation period of AFBR & AFMBR combined system at 2 h HRT, the total methane generation both in dissolved and gaseous forms was 5.88 molCH_4/m^3 wastewater, which is equivalent to 83% of the removed COD (21.2 g COD/day) and 73% of the added COD (24.1 g COD/day).

Totally, 70% of the produced methane exited with gas phase and the rest part remained in AFBR effluent as dissolved form. Namely, gaseous methane generated in AFBR alone was 4.11 molCH_4/m^3 wastewater, which represents 0.91 kWh/m^3 energy production (energy yield of methane combustion is 800 kJ/mol). This value is almost 16 times the pumping energy requirement for the combined AFBR/AFMBR system. Given energy conversion efficiencies, approximately 33% of the energy yielded by methane can be stored as electrical energy, and an overall conversion efficiency of 21% is expected to reach in consideration of energy loss in power generation equipment. Consequently, 0.19 kWh/m^3 of energy can be acquired finally from anaerobic treatment of non-saline sewage. The total energy requirement for AFBR & AFMBR (0.058 kWh/m^3) is only about 30% of this amount. It is conceivable that optimization of operation of this system should be able to reduce this energy usage further.

3.3 Net Energy Production from Saline Sewage

In batch test mode, synthetic saline sewage effluent with 0.15M Na_2S was used in anode side of the fuel cell. As Figure 3 suggests, approximately 0.11A of current was generated under 1V of potential. To calculate the energy output, the following equations were utilized,

$$I = \frac{V}{R} \qquad (3)$$

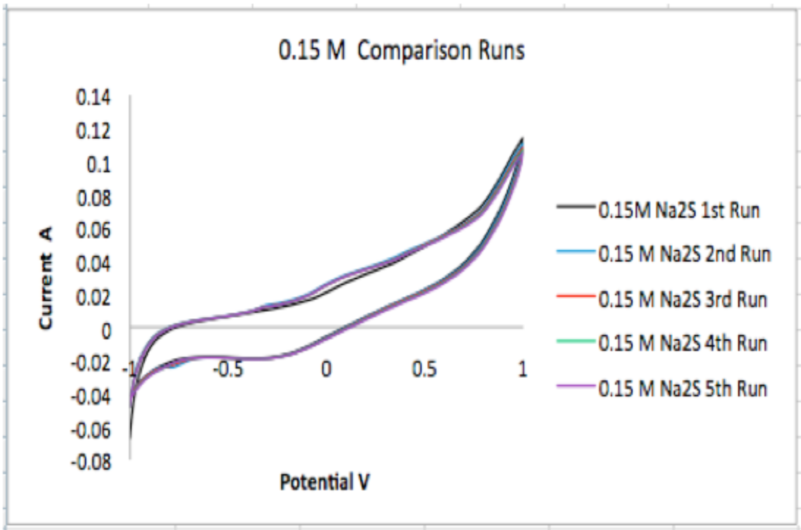
Where *I*—Current (A);

V—Voltage/Potential (V);

R—Resistance (Ω).

$$P = \frac{V^2}{R} \qquad (4)$$

Where *P* refers to Power (W), holding a value of 0.11 W in accordance with the said Eq.3 & 4. Dividing the working volume (150 mL here), there is a value of 733.33 W/m^3 for the Power density. Therefore, the energy output from the fuel cell is about 0.733 Kwh/m^3. In view of real saline sewage, a concentration of 0.0152 M sulfide could be expected after anaerobic treatment (Lu, et al., 2012 & Tam, et al., 2006). According to Figure 4, current generated in external circuit of the fuel cell would decrease with reduction of sulfide concentration. Thus 0.07 A of current was estimated for real saline sewage effluent with a sulfide concentration of 0.0152 M based on the trend line of Concentration-Current (not shown here).



	1st Run	2nd Run	3rd Run	4th Run	5th Run
Potential (V)	1	1	1	1	1
Current (A)	1.14E-01	1.11E-01	1.08E-01	1.07E-01	1.06E-01

Fig.3 Current values in 5 batch tests with 0.15M Na_2S

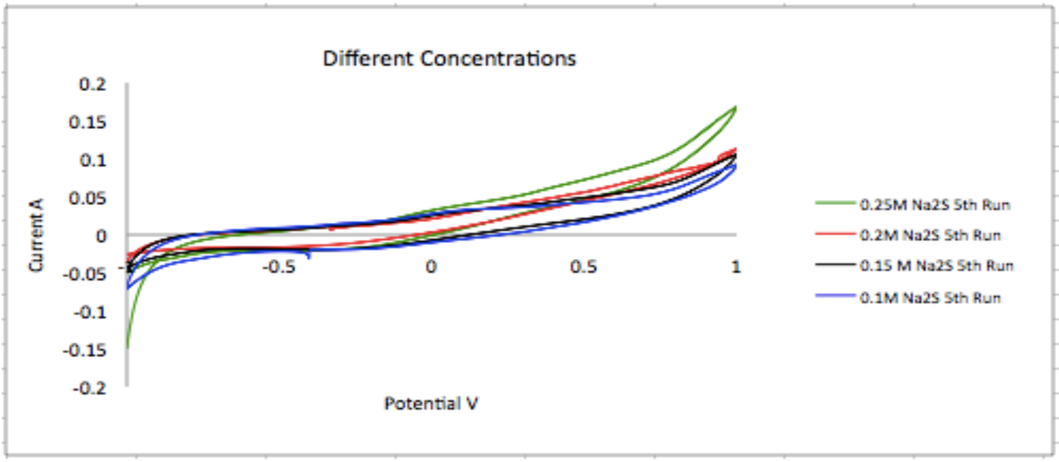


Fig. 4 Current values in different concentrations of Na_2S

In accordance with the aforementioned Eq.3 & 4, about 0.467 Kwh/m^3 of energy can be generated in fuel cell. Considering the energy loss during the power storage, energy transfer, and aeration consumption, an overall energy efficiency of 30% is expected to realize, which means that 0.14 Kwh/m^3 of energy can be acquired finally from the fuel cell. This energy output is almost as high as 2.42 times of energy requirement by the upstream AFBR & AFMBR system (0.58 Kwh/m^3).

Worth mentioning is that the sustainability of energy production in fuel cell is dependent on constant supply of sulfide in anode side. In addition, parameters such as resistance, conductivity, electrode materials, sulfide concentration and design of fuel cell have direct effect on its energy efficiency. Further optimization on the configuration and a number of operation parameters is still required to enhance the performance of the fuel cell, so as to produce more energy from treatment of saline sewage as well as other high sulfate-containing wastewater.

4. CONCLUSION

With the utilization of AFBR & AFMBR combined system and fuel cell installation, either non-saline or saline sewage becomes a kind of resource rather than a waste in this study. The low energy requirement of the proposed treatment system (0.058 Kwh/m^3) and the relatively high energy production from treatment processes, which was 0.19 for non-saline sewage from methane collection and 0.14 Kwh/m^3 for saline sewage from conversion of sulfide to sulfur in fuel cell, resulted in a net energy production of 0.132 and 0.082 Kwh/m^3, respectively.

The results demonstrate that the novel technologies mentioned in this study have profound significance on energy production and sustainable treatment of domestic wastewater given the fact of global energy crisis. Especially for locations like Hong Kong, which adopt seawater for toilet flushing, the technology combining AFBR & AFMBR treatment with fuel cell can be used as a potential alternate for sulfide removal and energy production. To enhance the development of AFBR & AFMBR and fuel cell in sewage treatment, further explorations are still required to make these new technologies more controllable and mature in the near future.

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