EFFECT OF SLUDGE AGES ON FORMALDEHYDE AND PHENOL REMOVAL IN PLUG-FLOW AND CSTR ANAEROBIC MBRs

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ผลของอายุสลัดจ์ในการกำจัดฟอร์มัลดีไฮด์และฟีนอลในถังเอ็มบีอาร์ไร้อากาศแบบไหลตามกันและแบบกวนสมบูรณ์

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วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
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งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษาผลของอายุสลัดจ์ในการย่อยสลายทางชีวภาพของฟอร์มัลดีไฮด์และฟีนอลซึ่งเป็นองค์ประกอบหลักของน้ำยาดองศพโดยใช้ถังเอ็มบีอาร์แบบไหลตามกันและแบบกวนสมบูรณ์ ที่ติดตั้งเมมเบรนที่มีรูพรุนขนาด 0.4 ไมโครเมตรเพื่อเก็บกักสลัดจ์และควบคุมค่าเวลากักเก็บตะกอนตามที่ต้องการ ถังกวนสมบูรณ์ทำการดำเนินการทดลองที่ค่าเวลากักเก็บตะกอนเท่ากับ 65,000 และ 6,000 วัน ในขณะที่ถังแบบไหลตามกันมีค่าเวลากักเก็บตะกอนเท่ากับ 6,010, 1,000, 100และ 50 วัน ส่วนผสมของน้ำยาดองศพและน้ำเสียชุมชนมีความเข้มข้นของฟอร์มัลดีไฮด์และฟีนอลเท่ากับ 25-435 และ 3.7-64 มก/ล ถูกป้อนเข้าสู่ทั้งสองถังเอ็มบีอาร์ ประสิทธิภาพการกำจัดฟอร์มัลดีไฮด์ที่ได้ในถังเอ็มบีอาร์แบบไหลตามกันและแบบกวนสมบูรณ์มีค่าประสิทธิภาพสูงทุกค่าความเข้มข้นของฟอร์มัลดีไฮด์ที่ใช้ ในทางกลับกันประสิทธิภาพในการกำจัดฟีนอลลดลง ที่อายุสลัดจ์ของถังกวนสมบูรณ์เท่ากับ 65,000 วันและถังแบบไหลตามกันเท่ากับ 6,010 วัน เมื่อความเข้มข้นของฟีนอลเริ่มต้นสูงกว่า 38 มก./ล. ที่อัตราส่วนผสมของน้ำยาดองศพต่อน้ำเสียชุมชนมีค่า 0.008:1 เป็นไปได้ว่า ความเข้มข้นที่สูงของฟอร์มัลดีไฮด์มีผลเสียต่อจุลชีพที่ทำหน้าที่ย่อยสลายฟีนอล อย่างไรก็ตาม ประสิทธิภาพที่ลดลงในการย่อยสลายพีนอลอาจเกิดขึ้นเมื่อจุลชีพที่ทำหน้าที่ย่อยสลายฟีนอลนั้นยังไม่ปรับตัว ซึ่งประสิทธิภาพในการย่อยสลายฟีนอลทางชีวภาพนั้นมีค่าสูงเมื่อค่าเวลากักเก็บตะกอนต่ำลงในถังเอ็มบีอาร์ทั้งสอง สมมติฐานของประสิทธิภาพในการย่อยสลายฟีนอลทางชีวภาพที่มีค่าสูงที่พบดังกล่าวคือการปรับตัวของจุลชีพซึ่งมีผลอย่างมากสำหรับถังถังเอ็มบีอาร์แบบไหลตามกันและแบบกวนสมบูรณ์ ถังเอ็มบีอาร์แบบไหลตามกันและแบบกวนสมบูรณ์

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The aim of this study was to investigate effects of sludge ages on removal efficiencies of formaldehyde (FA) and phenol, main ingredients of embalming fluid, using both the continuous stirred-tank reactor (CSTR) and plug-flow anaerobic membrane bioreactors. A microfiltration membrane module having pore size of 0.4 µm was installed inside each reactor for retaining sludge to control the sludge retention time (SRT) at the desired values. The CSTR was operated under 65,000 and 6,000 d of sludge age, whilst the plug-flow reactor was operated under 4 different SRTs, i.e. 6,010, 1,000 100 and 50 d. Ratio of embalming fluid to domestic wastewater was varied to at each studied SRT, corresponding to FA concentrations of 25 to 435 mg/l and phenol concentrations of 3.7 to 64 mg/l, respectively. Both the CSTR and plug-flow anaerobic membrane bioreactors could efficiently remove FA at all studied FA concentrations. On the other hand, these two reactors failed to efficiently remove phenol at the concentration higher than 38 mg/l under SRT of 65,000 and 6,010 d (CSTR and plug-flow reactor, respectively) corresponding to the embalming fluid to wastewater ratio of 0.008:1, due to the possible toxicity of FA on phenol degrading microorganisms. However, the deterioration of phenol removal was occurred when anaerobic microorganism possibly responsible in phenol degradation had not acclimatised to FA existence. That phenol was efficiently removed at the lower SRT on CSTR and plug-flow reactor at the ratio of 0.008:1 proved the assumption that microbial acclimatization had greater effect on both CSTR and plug-flow reactor.

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LIST OF ABBREVIATIONS

AnMBR	Anaerobic Membrane Bioreactor
ASBBR	Anaerobic Sequencing Batch Biofilm Reactor
ASTM	American Society for Testing and Materials
AWWA	American Water Works Association
BTU	British Thermal Unit
°C	Degree Celsius
$CaCO_3$	Calcium Carbonate
C_6H_5OH	Phenol or carbolic acid
CH_4	Methane
CH_3CH_2COOH	Propiomic acid
$CH_3CH_2CH_2COOH$	Butyric acid
CHOH	Formaldehyde
COD	Chemical oxygen demand
CO_2	Carbon dioxide
CO_3^{2-}	Carbonate
CSTR	Continuous Stirred Tank Reactor
d	day
DNA	Deoxyribonucleic Acid
EGSB	Expanded granular sludge bed
F/M	Food per Microorganism
FA	Formaldehyde
H_2	Hydrogen gas
HCO_3^{2-}	Bicarbonates
hr	Hour
HRT	Hydraulic Retention Time
K	Potassium
$kgCOD/m^3.d$	Kilogram Chemical oxygen demand per Cubic Meter. Day
$kgFA/m^3.d$	Kilogram formaldehyde per Cubic Meter. Day
$kgPhenol/m^3.d$	Kilogram phenol per Cubic Meter. Day
kPa	Kilogram pascal

L	Liter
L/d	Liter per day
μm	Micrometer
m	Meter
MBR	Membrane Bioreactor
mg/l	Milligram per Liter
min	Minute
NaClO	Sodium hypochlorite
O_2	Oxygen
OH^-	hydroxide
P	Phosphorous
PLR	Phenolic Loading Rate
PVDF	Polyvinylidene difluoride
RNA	Ribonucleic Acid
s	Second
SBR	Sequencing batch reactor
SRT	Solids Retention Time
N	Nitrogen
NH_3	Ammonia
NaCl	Sodium Chloride
UASB	Upflow Anaerobic Sludge Blanket
UV	Ultraviolet Absorbtion
VFAs	Volatile Fatty Acids
VOC	volatile organic compound
w	week

CHAPTER I

INTRODUCTION

1.1 Motivation

Embalming fluid is a common solution used for disinfection and preservation of biological materials in some hospitals and industries. Its main ingredients comprise water, formaldehyde (FA) and phenol. However, if exposed in high concentration, embalming fluid has acute effects to skin, eyes, and nose. FA reacts to DNA, RNA and protein directly and is the reason for cell damaging and the death of microorganisms (Lu and Hegemann, 1998). A 0.5% of FA solution kills all species of microorganisms in a period of 6-12 h. Moreover, FA is proved to be toxic and carcinogenic, when exposed at high concentration to the living organisms (Oliveira et al., 2004). The toxicity of FA ranks in the first place of chemical released by industries (Edwards, 1999). However, FA is biodegradable in anaerobic system. Many types of reactors, i.e. batch reactor (Lu and Hegemann, 1998), fluidized bed bioreactor (Moteleb et al., 2002), horizontal flow anaerobic immobilized sludge reactor (Oliveira et al., 2004), upflow anaerobic fixed film reactor (UAFB) (Raja Priya et al., 2009) and anaerobic sequencing batch biofilm reactor (Pereira and Zaiat, 2009), were utilised in the studies of FA removal. The results from these studies showed that higher FA concentration could be applied when the microorganisms were given longer time to acclimatise. Moreover, the degradation was found to be greatly enhanced in the presence of a co-substrate (Omil et al., 1999).

Phenol is used in commercial products such as pharmaceutical products, disinfectants and petrochemicals. It is water soluble, highly mobile, and likely to reach drinking water sources downstream from discharges. At low concentrations, it inhibits microorganism growth in biological treatment process. A concentration of phenol higher than 1 mg/l affects watery life. Consequently, restrictive effluent discharge limit of less than 0.5 mg/l is enforced. Moreover, phenols are carcinogenic, mutagenic and teratogenic (Autenrieth et al. 1991).

Anaerobic biological process is an alternative treatment for removing phenol. Fang, et al. (1997) observed phenol's effects on cell activity when increased phenol loading rate at low HRT in UASB reactor. Wanawan and Patiroop (2010) investigated performance of anaerobic filter in removing formaldehyde and phenol in the synthetic embalming fluid using domestic wastewater as co-substrate. In their study, the possible inhibition of phenol anaerobic degradation was observed in the presence of FA. The maximum phenol concentration which could be efficiently treated in the anaerobic filters was 32 mg/L at 12h-HRT (Wanawan and Patiroop, 2010). Both FA and phenol removal were found to be successfully achieved in the plug-flow anaerobic reactor, especially in anaerobic filter (Wanawan and Patiroop, 2010). Long SRT and selection of specific microorganisms along reactor length were claimed to contribute to its success. Of these two factors, SRT has been reported to be more important (Speece, 1996). It is interesting, therefore, to investigate if a reactor operated under plug-flow and CSTR flow regime coupled with a membrane module to control the desired SRT could efficiently remove these compounds at different concentrations using the domestic wastewater as co-substrate.

1.2 Objective

The aim of this study was to investigate effects of sludge ages on removal efficiencies of formaldehyde and phenol, as main ingredients of embalming fluid, using both the CSTR and plug-flow anaerobic membrane bioreactors. The specific objectives were:

1.2.1 To compare performance for FA and phenol removal between the plug-flow and CSTR anaerobic membrane bioreactors.

1.2.2 To study effects of embalming fluid to wastewater ratios on removal efficiencies of FA and phenol, using the plug flow and the CSTR anaerobic membrane bioreactors.

1.3 Scope of this work

1.3.1 All experiments were conducted using both the CSTR and plug-flow anaerobic membrane bioreactors. Both reactors were made from the clear acrylic, having the working volume of 20 L for the plug flow and 14 L for the CSTR.

1.3.2 Membrane modules installed inside both of reactors, were made from polyvinylidene difluoride (PVDF) with pore size 0.4 μm. These membrane modules were used to retain sludge for the precise SRT adjustment.

1.3.3 The domestic wastewater used in this study was collected from an equalisation tank of Chiang Mai University wastewater treatment plant.

1.3.4 Embalming fluid was synthesised using analytical grade FA and phenol at the ratio of deionized water: FA: phenol of 100: 4: 1 by volume, the real ratio used at Maharaj Hospital, Chiang Mai.

1.3.5 The CSTR was operated under 65,000 and 6,000 d, while the plug flow reactor was operated under SRTs of 6,010, 1,000, 100 and 50 d. SRT was controlled by varying amounts of sludge wasted from each reactor.

1.4 Benefits of this work

1.4.1 Understanding the role of flow regimes in FA and phenol degradation under anaerobic condition.

1.4.2 Effects of sludge retention time and on reactor performance can be used in the operation of plug-flow and CSTR anaerobic membrane bioreactors in treating phenol and formaldehyde.

CHAPTER II

THEORY BACKGROUND AND LITERTURE REVIEWS

2.1. Anaerobic treatment

Anaerobic treatment process is a biological process (Equation 2.1) in which organic compounds are converted to carbon dioxide (CO_2) and methane (CH_4), negating the use of oxygen needed as electron acceptor.

$$\text{CHONS (Organic compounds)} \longrightarrow CH_4 + CO_2 \qquad \text{(Eq.2.1)}$$

The conversion process from organic matters to final end products is carried out by specific anaerobic microorganisms such as methanogens bacteria, which are the most environmentally responsive group and composed of many species with different cell patterns. The anaerobic process constitutes four steps (Figure 2.1) which occurred as followed;

Step 1 Hydrolysis

Hydrolysis is a process for degradation of large organic compounds, i.e. carbohydrate, protein and fat into simple monomer compounds such as amino acid and glucose. This step is occurred by extracellular enzymes produced from microorganisms.

Step 2 Acidogenesis or Fermentation

Products from the hydrolysis step are absorbed as an aliment for cell, then they are converted into volatile fatty acid (VFA), i.e. acetic, butyric and propionic acid. Meanwhile, hydrogen and carbon dioxide are also produced. The end products of acidogenesis step are depended on substrate types and partial hydrogen pressure.

Step 3 Acetogenesis

Acetogenic bacteria transform the VFA from the acidogenesis step into substrates for methanogenic microorganisms (Equation 2.2 and 2.3). Production of methane requires specific substrates such as acetic acid, formic acid and hydrogen.

$$CH_3CH_2COOH + H_2O \longrightarrow CH_3COOH + CO_2 + H_2 \quad \text{(Eq.2.2)}$$

$$CH_3CH_2CH_2COOH + 2H_2O \quad 2CH_3COOH + 2H_2O \quad \text{(Eq.2.3)}$$

This step can be occurred at low hydrogen partial pressure. Transformation of VFA into acetic acid cannot happen under high hydrogen partial pressure condition.

Step 4 Methanogenesis

Acetic acid and hydrogen gas are converted into final products, i.e. methane and carbon dioxide gas by methanogenic bacteria. This reaction is called mehanogenesis or methanogenic phase.

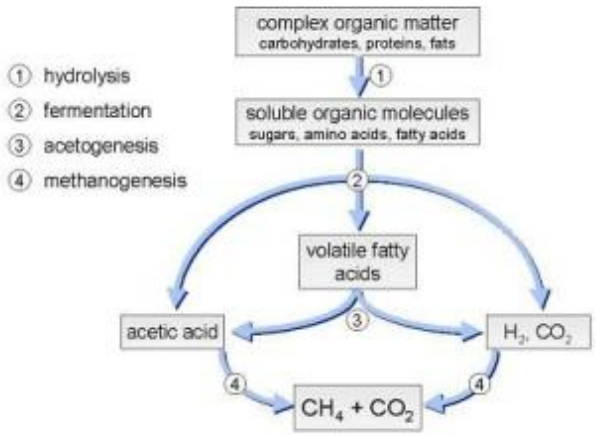

Figure 2.1 Four steps in Anaerobic Process

(Source: http://www.ted-biogas.org/index.php?id=3)

2.2. Rationale of anaerobic process

2.2.1 Advantages

2.2.1.1. Low production of solids and land requirements.

Anaerobic process generates about 20% of sludge compared to that of aerobic process. It decreases cost of the sludge treatment and space requirement.

2.2.1.2. Low energy consumption

Aerobic process usually requires approximately 500-2000 kWh of energy per 1000 kg of oxygen transfer, consumed 10000 BTU in the generation of 1 kWh of electricity approximately. On the other hand, anaerobic process requires no oxygen transfer but generated $12x10^6$ BTU as CH_4 per 1000 kg of COD converted to CH_4 (Speece, 1996).

2.2.1.3. Production of energy from biogas

The biogas generated is a source of utilizable energy. The energy generated is more than the energy required, 1.16 kWh of electricity is produced for every 1 kg of COD removal by anaerobic process.

2.2.2 Disadvantages

2.2.2.1. Sensitive microorganisms

Anaerobic bacteria are sensitive to small variation of the environment. Consequently, the process is relatively vulnerable to upset. Monitoring of operation and close process control are required to avoid process failure.

2.2.2.2. Operation consideration

Anaerobic processes require long start-up time, their sensitivity to possible toxic compounds, operational stability, the potential for odor production, and corrosiveness of the digester gas are considered to be problematic. However, with proper wastewater characterization and process design these problems can be avoided and/or managed.

2.3. Concept of reactors

2.3.1 Continuous stirred tank reactor (CSTR)

CSTR is also known as continuous flow stirred tank reactor. Most industrial fields utilise this type of reactor. Influent and effluent are fed and drawn through reactor continuously. Moreover, it is commonly equipped with baffle and a mixer that is operated for enough mixing. It is assumed that fluid in the reactor is perfectly stirred. Concentration is equal at every point in the reactor. The reaction is homogenously occurred in the reactor, resulting in concentration and compositions of effluent being equal to those in the reactor (Figure 2.2). The operation inside CSTR is mostly under steady-state condition in which the feed stream flow rate and its composition are constant with respect to time.

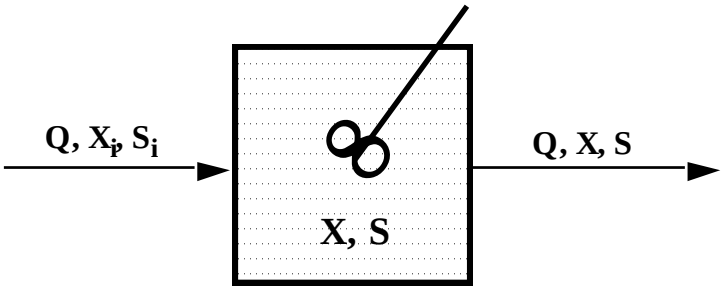

Figure 2.2 CSTR

(Q: flow, X_i: influent biomass, S_i: influent substrate, X: biomass, S: substrate)

2.3.2 Batch reactor

Batch reactor (Figure 2.3) is a container added with reactants, then sealed and adjusted for temperature, allowing reaction to be occurred. The reactor has no continuous influent and effluent. The contents of the batch reactor are completely stirred so that the concentration of each species is homogenously mixed within the container. The batch reactor can contain a single or multiple phases of content such as water, solid and air. The concentration in the reactor may alter with time because of transformation process (e.g., chemical reaction and phase changes). The container is opened and the products are displaced after some reaction period. Analysis of the

batch reactor only considers processes in the reactor and not including transport across its boundaries.

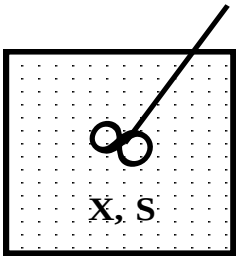

Figure 2.3 Batch reactor

(X: biomass, S: substrate)

2.3.3 Plug flow reactor

The plug-flow reactor (Figure 2.4) is conceptually shown as a tube through which fluid flows. The velocity of fluid is regular over the cross-section. The tube is under steady state at all axial positions, so that the fluid velocity is steady throughout of the reactor. The plug-flow reactor has no stirring in the axial direction of the tube. The transportation of the direction is occurred by advection. The mixing may (or may not) be occurred in the radial direction. The consideration of the plug-flow reactor relates to analyzing processes that occurred as the advection of fluid along the axis of the tube.

Figure 2.4 Plug flow reactor

(Q: flow, S_i: influent substrate, S_e: effluent substrate)

2.4. Some popular types of anaerobic reactor

2.4.1 Anaerobic contact reactor

Anaerobic contact process is similar to the aerobic activated sludge system. It provides for separation of seed organisms. The main problem occurred in anaerobic contact process is the rising biomass because of bubble generation and float in the settling tank (Speece, 1996). Biomass loss with the effluent is also a serious problem because the quantity of microorganisms produced is so much lesser than the aerobic process. Therefore, the small biomass loss can significantly affect process stability, as well as effluent quality. To solve this problem, a degasifier is generally needed to minimised floating biomass in the separation step.

2.4.2 Anaerobic filter reactor

The anaerobic filter reactor utilizes the high tank similar to the filter tank, containing media such as small rocks or plastics. Wastewater is fed to the reactor in the up-flow mode, in which media is submerged all the time. Bacteria attach to the media in the reactor, thus effluent can be clear without sedimentation tank. Nevertheless, this reactor has major problem in distributing wastewater and clogging of the media bed by suspending solids. Locating a setting tank before an aerobic filter can alleviate the clogging problem.

2.4.3 Up-flow anaerobic sludge blanket (UASB)

Due to problem of the costly media, engineer designs UASB reactor which does not require media. Bacteria are forced to form into large particles, which settle by their own mass. Wastewater is fed in the up-flow mode making particles floating in the reactor. However, achieving the large sludge particle can be problematic as anaerobic microorganisms tend not to grow into the granular form.

2.4.4 Anaerobic Membrane Bioreactor (AnMBR)

AnMBR has received great attention in recent years. The prominent point of AnMBR is that this type of anaerobic reactor can be operated under the precisely controlled SRT. However, the major problem of AnMBR is membrane fouling that is obstacle for the process operation. This problem can be solved by soaking in some chemical such as NaClO. The main objective of AnMBR is to improve the efficiency of the biological process and to produce high-quality effluent. Because biological treatment and membrane separation are rather distinct processes, the combined AnMBR process is relatively complex. Many parameters have to be considered such as solid concentrations, SRT and HRT in the biological step as well as the flux rate, material costs, and the energy cost of the membrane separation. The treatment and disposal of the waste sludge also needs to be considered.

2.5. Factors affecting anaerobic process

2.5.1. pH

Methanogens prefer nearly neutral pH in the range of 6.5 to 8.2. The end products in each step, e.g. VFAs can alter the pH, which is harmful for methanogens because they are adversely sensitive to pH outside the suitable range. Decrease of biogas production or methanogen die-off can be observed as the results of inappropriate pH. However, too basic pH also poses negative effect on COD removal. For example, under pH 9.1-10.0 COD removal efficiency, biogas production and membrane filtration operation of a submerged anaerobic membrane bioreactor were found to be deteriorated significantly (Jane gao et al., 2010).

2.5.2. Bicarbonate alkalinity

Bicarbonate alkalinity is considered as the buffering capacity of anaerobic system. Under low buffering capacity condition, small increase of VFA can lead to dramatic decrease of pH.

2.5.3. Temperature

Microbial systems are affected by temperature in terms of metabolic rate, growth, and solubility of substrates. An anaerobic microorganism works well under two optimal temperature ranges; the mesophilic temperatures (30 to 37 °C) and thermophilic temperature (55 to 65 °C). Anaerobic process can be carried out under psychrophilic (<20 °C) but reaction rates are decreased significantly.

2.5.4 Solid Retention time

Solid retention time (SRT) is an important factor for biological process. Species of bacteria require appropriate SRT to allow microorganism's growth especially for anaerobic bacteria. For example, higher methane production is produced by a longer SRT because methanogenesis has more stability (Huang et al., 2010).

2.5.5 Hydraulic retention time

The efficiency of an anaerobic reactor may be adversely affected by drastic variations in flow and concentration. The effect of hydraulic mainly depends on the applied hydraulic retention time (HRT), sludge retention time (SRT), intensity and duration of the variations, sludge properties and the reactor design. Volatile fatty acids (VFA) accumulated can be a typical reactor response during overloading, and during sudden variations in hydraulic and organic loading rates. Hydrogen partial pressure is a significant function to control the proportion of the various intermediate products of the anaerobic reactions. Under high H_2 pressure condition, can be a shift in the metabolic pathway to a less desirable route, resulting in a ratio shift between VFA producers (acidogens and acetogens population) and consumers (methanogens). The partial pressure of hydrogen gas inside the reactor might extend to values exceeding 10^{-4} atm, which may then cause a shift in the metabolic pathway. When slowly growing methanogens cannot adequately and rapidly remove all H_2 produced by the H_2 producing bacteria (e.g. in case the sludge contains insufficient hydrogen

consuming organisms), this may result in a distinct inhibition of the degradation of propionate, butyrate and lactate (Leitao et al., 2006).

2.6. Embalming fluid

Embalming fluid is a colorless liquid used in medical process for disinfection, fungicide and preserve biological materials. This liquid has acute effects to skin, eyes, and nose, if exposed in high concentration. Embalming fluid usually contains the mixer of water, formaldehyde, and phenol at the ratio of approximately 100: 4: 1 by volume. However, embalming fluid could be treated by biological process especially by anaerobic process. The details of both compounds are shown as following;

2.6.1 Formaldehyde (FA)

Formaldehyde is a chemical in aldehyde group of organic compounds, commonly used in commercial products such as making preservative, disinfectants and other in hospitals, industries and chemical laboratories.

2.6.1.1. Physical characteristics of formaldehyde

Formaldehyde is a colorless liquid causing irritant and inflammable fume. This is because this compound is a volatile organic compound (VOC), which becomes a gas at normal room temperatures. It has density of 1.09 g/cm^3 and flashing point =56 °C, melting point = -92 °C and boiling point = -21 °C (Udomsinroj, 2003).

2.6.1.2. Toxicity of formaldehyde

Formaldehyde reacts to DNA, RNA and protein directly and the reason for cell damaging and the death of microorganisms (Lu and Hegemann, 1998). A 0.5% of FA solution kills all species of microorganisms in a period of 6-12 h. Moreover, FA is proved to be toxic and carcinogenic to the living organisms (Oliveira et al., 2004).

2.6.2 Phenol

Phenol or carbolic acid (C_6H_5OH) is an organic compound containing aromatic ring and bonds with the hydroxyl group and used in commercial products such as pharmaceutical products, disinfectants and petrochemicals.

2.6.2.1. Physical characteristics of phenol

Phenol is found both in liquid and solid forms. This compound has high boiling point and low melting point because of hydrogen bonds. It has solubility about 1 g in 100 g of water. Most of derivative phenols are color compounds but pure phenol has colorless. However, when oxidized phenol and can be changed to red color

2.6.2.2. Toxicity of phenol

Phenols inhibit microorganism growth in biological treatment process. A concentration of phenol higher than 1 mg/L affects watery life. Consequently, restrictive effluent discharge limit of less than 0.5 mg/L is enforced. Moreover, phenols are carcinogenic, mutagenic and teratogenic (Autenrieth et al., 1991).

2.7. Application of membrane technology

Combining membrane technology with biological reactors for the treatment of wastewaters has led to the development of two typical membrane bioreactors; for solid retention and separation of priority organic pollutant from wastewater. The coupling of a membrane to a bioreactor has increased interest both academically and commercially because of the inherent benefits of the process offered over conventional biological wastewater treatment systems.

A membrane bioreactor process for separation and retention of biological sludge is generally regarded as one alternative to the conventional activated sludge process. The combine of activated sludge biodegradation and membrane separation is

known as membrane bioreactor process (MBR). A membrane is invented in order to achieve the reasonable mechanical strength and sustain a high throughput of a desired permeate with a high degree of selectivity.

2.7.1 MBR process description

The main type of membrane utilised in wastewater treatment is microfiltration (pore size from 0.1-0.4 μm) and ultrafiltration (pore size from 2-50 nm). There are two configurations of MBR systems depend on the location of membranes modules as submerged membrane bioreactors and externally pressured cross flow MBR.

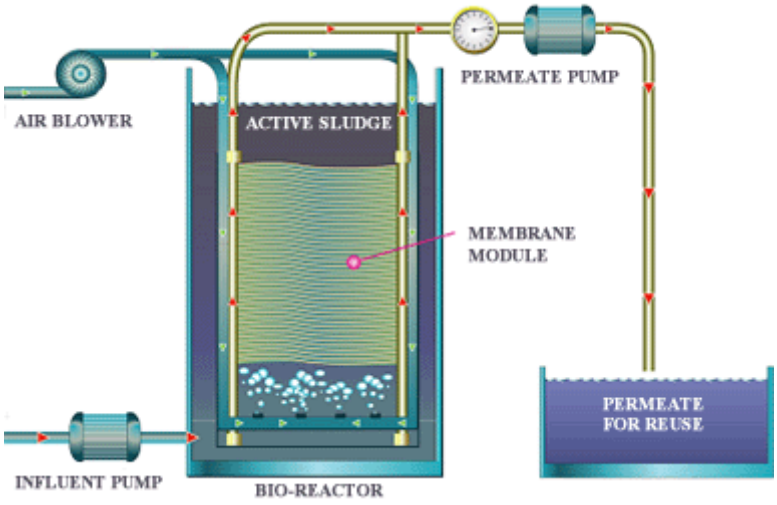

Figure 2.5 Submerged membrane bioreactor system

(Source: http://www.nordcap.se/Tec.html)

Submerged membrane bioreactor system (Figure 2.5) is based on a filtration procedure with membranes that are immersed in the biomass, either inside the bioreactor itself or in a separate tank. The membranes are directly immersed in the bioreactor or a separate tank and filtration takes place by using vacuum from the

inside of the membrane. Membrane fouling is prevented by the flow of air bubbles along the membrane surface or periodic backwashing.

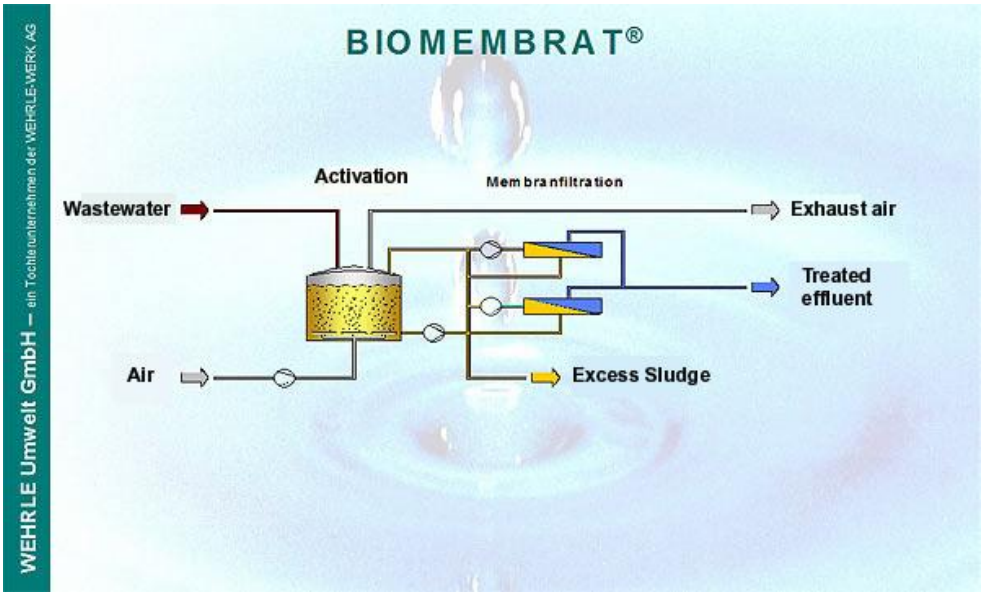

Figure 2.6 Externally pressured cross flow Membrane Bioreactor

(Source:http://www.wehrle-umwelt.com/membrane-bioreactor-biomembrat)

Externally pressured cross flow MBR (Figure 2.6) is the use of cross-flow membrane modules in combination with mixed liquor in the bioreactor being circulated through the membrane. Although relatively simple to operate, they require high-speed pumping devices. It leads to the high operation cost and specify a high level of shear stress on the biological suspension. Shear stress normally involves the breakage of microbial floc and subsequent damage to microbial activities (Cho and Lee, 1996).

2.7.2 Advantage and disadvantage of MBR

2.7.2.1 Advantages

Though being considered as an expensive type of reactor, membrane will proceed to decrease in cost in the coming years. MBR has been proved to be

more efficiency than conventional biological treatment process in the following ways (Vivanathan et al, 2000);

2.7.2.1.1 Very high effluent quality, reuse of wasted effluents comes into view, which makes it a sustainable technology. They can be used for cooling, toilet flushing, lawn watering, or with further polishing as process water.

2.7.2.1.2 The absence of the secondary settler, the space required for MBR will be less.

2.7.2.1.3 Sludge retention time can be completely controlled in MBR. Therefore, a very long SRT can be retained resulting in the complete retention of slow-growing microorganisms such as methanogens bacteria.

2.7.2.1.4 Biomass concentration can be greater than conventional systems. It can be up to 30g/L in MBR. Therefore, the system can tolerate high volumetric loading rate. The reactor volume can also be reduced.

2.7.2.1.5 Low sludge loads resulting in low sludge production. Low F/M and low wastage of biomass are the result of this. Chaize and Huyard (1991) have shown that for treatment of domestic wastewater, sludge production is greatly reduced if the age is between 50 and 100 days.

2.7.2.1.6 In the membrane filtration process, the removal of bacteria and viruses can be carried out without adding any chemical.

2.7.2.2 Disadvantages

2.7.2.2.1 High capital cost and operating cost.

2.7.2.2.2 Limited experience to utilise for membrane in wastewater reuse

2.7.2.2.3 Lack of interest by the membrane manufacture.

2.8 Literature review

Oliveira et al. (2004) used horizontal-flow anaerobic immobilized sludge reactor to investigate the degradation and toxicity of formaldehyde. The reactor dimension was 1 m long and 50.4 mm diameter, and used polyurethane foam cubes as the media. The reactor was operated in the temperature controlled chamber. The synthetic wastewater was prepared with formaldehyde and COD concentrations in the range of 26.2 to 1158.6 mg/L and 51.6 to 1,798 mg/L, respectively. Before being utilized, the reactor was used in treating phenolic synthetic wastewater at concentrations of 50 to 1200 mg/L for 1 year.

The rapid acclimatization period was observed and attributed to the previous reactor operation with phenol synthetic wastewater. The high biomass retention was provided by the polyurethane foam, resulting the short startup time (20 days). The formaldehyde and COD removal efficiencies were 99.7% and 92%, respectively. The effluent formaldehyde concentrations were found to be varied as the influent concentration increased. The accumulations of volatile fatty acids were not observed in the system because the biomass entirely degraded these compounds to methane gas. Moreover, the formaldehyde degradation was completed at a hydraulic retention time of 4.8 h which was essentially less than those reported in other studies. The microorganism could acclimatize to substances and the products in the reactor, consequently the toxicity and inhibition problems were not occurred.

Pereira and Zaiat (2009) investigated the degradation of formaldehyde in a lab-scale anaerobic sequencing batch biofilm reactor (ASBBR). The biomass was immobilized in the polyurethane foam matrices. Formaldehyde contained in the synthetic wastewater was in the range of 31.6 to 1104.4 mg/L. The ASBBR was operated at 35 C with 8 h sequential cycles for 212 days.

The removal efficiency of formaldehyde was 99.3 % with average effluent formaldehyde concentrations of 3.6 to 1.7 mg/L. Formaldehyde degradation rate was increased as initial formaldehyde concentration increased from around 100 to 1100 mg/L. The COD of the effluent was high (500 mg/L) because non-degradable compounds were found to accumulate. As the result, there was toxic effect to the

formaldehyde degrading. Results of this work implied that formaldehyde degradation was more appropriate in continuous-flow reactors with flow pattern close to plug flow rather than the CSTR as the growth of specific biomass depended on the reactor's length and adapt to specific compounds or products in the reactor (Oliveira et al., 2004). All of microorganism in the CSTR contacted with toxic substances leading to the inhibition and accumulation of products.

Wanawan and Patiroop (2010) investigated performance of anaerobic filter in removing formaldehyde and phenol in the synthetic embalming fluid using domestic wastewater as co-substrate. Plastic bioball was used as media because of its durability and high specific surface area. The start-up period was about 2 weeks until stability of COD removal efficiency was attained. The embalming fluid was fed to anaerobic filter that proportion of formaldehyde and phenol concentration was stepwise increased. Both anaerobic reactors are operated at the HRT of 6 h and 12 h, respectively.

Anaerobic filter operated at 12 h HRT could remove studied toxic substances more efficiently than at 6 h. FA was removed efficiently at all studied initial concentrations 19.6 to 1373 mg/l, whilst phenol was almost completely removed only when initial concentrations lower than 15.3 mg/l and 32.6 mg/l in 6h- and 12h-HRT reactors, respectively. The possible inhibition of phenol anaerobic degradation was observed in the presence of FA. The maximum ratio of embalming fluid to domestic wastewater which could be efficiently treated in the anaerobic filters were 0.002 : 1 and 0.004 : 1 by volume for 6h- and 12h-HRT reactors, respectively.

The anaerobic treatment of phenol in synthetic wastewater under thermophilic condition in Up-flow Anaerobic Sludge Blanket reactor (UASB) was studied by Fang et al (2004). The synthetic wastewater contains 630 mg/l of phenol, corresponding to 1500 mg/l of COD and organic loading rate of 0.9 g-COD/l.d. The reactor operated under temperature of 55 ^{o}C with hydraulic retention times of 60, 48, 40 and 28 h for 224 days. The UASB reactor was fed with phenol and sucrose as co – substrate during the startup period. After steady state, this reactor was fed with only phenol as the sole carbon source.

The phenol removal efficiency was 99% at hydraulic retention time of 40 h. When HRT was lowered to 28 h, the removal efficiency decreased to 77%. This implied that the bioactivity was obstructed by the increased phenol – loading rate at low HRT. However, the accumulation of volatile fatty acid was not observed in the reactor thoughout the operation period, indicating that UASB reactor was appropriate for the treatment of phenol containing wastewater.

Bolanos et al. (2001) studied phenol degradation in horizontal – flow anaerobic immobilized biomass reactor under mesophilic conditions. The reactor was made from bore – silicate tube with polyurethane foam cubes as the media. The reactor was operated for 8 months under temperature of 30 ^{o}C at hydraulic retention time 12 h. Phenol as the sole carbon and energy source was added under step – increased concentration from 50 to 1,200 mg/l. Trace metals, solution of salts and vitamins, were added as nutrient.

The start-up period was 33 days with phenol concentration 50 mg/l. The reactor fed with influent COD concentration of 1,028 mg/l achieved 98% and 99% COD and phenol removal efficiency, respectively. The result indicated that phenol degradation at very high concentrations could be achieved in the reactor containing adapted microorganism.

Scully et al. (2006) studied anaerobic biological treatment of phenol at 9.5–15 ºC in an expanded granular sludge bed (EGSB)-based bioreactor. Two expanded granular sludge bed (EGSB)-based bioreactors, R1 and R2, were employed to mineralise a volatile fatty acid-based wastewater. R2 influent wastewater was supplemented with phenol at an initial concentration of 500 mg/l (Phenolic Loading Rate (PLR), 1 kg/m^{3}d^{1}), reduced treatment efficiency was observed in day 106 and the R2 COD removal rate was 59%. Analysis of R2 effluent samples taken indicated the accumulation of phenol to a level of 253 mg/l. The operational temperature of R1 (control) and R2 was reduced by stepwise decrements from 15 C through to a final operating temperature of 9.5 C. COD removal efficiencies of 90% were recorded in both bioreactors at the conclusion of the trial (day 673), when the phenol concentration in R2 effluent was below 30 mg/l.

The initial introduction of phenol to R2 influent was followed by an acclimation phase of 25 days, after which stable COD and phenol removal was then recorded. Acclimation periods are a significant consideration and instances of between 20 and 100 d have previously been reported during treatment of phenolic wastewaters. In spite of the obvious completion for acclimation phase during day 93-142, the 100% increase of the PLR on day142 resulted in the accumulation of phenol in R2 effluent, thus suggesting the retarded adaptation of the R2 biomass to the increased PLR. This was emphasized by the withdrawal of phenol from the R2 influent (day 262 -273), which resulted in the sudden improvement of the COD removal efficiency. In addition, and upon the reintroduction of phenol (day 273-424) to R2 influent, a 60 d acclimation period was observed prior to improved (90%) of COD removal efficiency. Nevertheless, and despite the lengthy acclimation required, 99% of phenol was removed from the R2 influent wastewater in day 273-424, which resulted in a concentration of 4 mg/l in R2 effluent on day 416, thus highlighting the feasibility of psychrophilic anaerobic digestion of phenolic wastewaters at the applied PLR of 2 kg/m^3d^1.

Eiroa et al. (2004) studied the biodegradation and effect of formaldehyde and phenol on the denitrification process. The experiment was operated in lab-scale, first in anoxic batch assays and then in a continuous anoxic reactor. The biodegradation of formaldehyde of 260 mg/l and phenol concentrations in the range of 30 to 580 mg/l was investigated in batch assays. Phenol biodegradation was only found at initial concentrations of 30 and 180 mg/l. The denitrification process was inhibited at phenol concentrations higher than 360 mg/l .Studies were also done using a continuous anoxic upflow sludge blanket reactor in which formaldehyde removal efficiencies more than 99.5% were found at all the formaldehyde concentrations. Phenol removal efficiencies above 90.6% were obtained at phenol influent in the range of 27 and 755 mg/l. Nevertheless, when the phenol concentration was increased to 1010 mg/l, its removal efficiency decreased. These results indicated that the continuous anoxic treatment of wastewaters with high phenol concentrations in the presence of formaldehyde and nitrate can be undertaken, even it is necessary to control the phenol concentration applied to the system.

There have been several studies investigating performance of different types of anaerobic reactors in removing formaldehyde and phenol. It has also been reported that reactor operated under plug flow reactor regime tends to have higher formaldehyde and phenol removal efficiencies compared to those attained from the CSTR. Apart from the specific microorganisms grow along the plug flow reactor's length which has been found to be responsible in degrading these toxic compounds and their degradation products, roles of sludge ages on the performance of the reactor is of great interest. Moreover, it would be interesting to find out whether or to what extent the sludge age can improve performance of the anaerobic reactor operated under different flow regimes in stimulating removing both formaldehyde and phenol from the wastewater.

CHAPTER III

METERIALS AND METHODS

3.1 Wastewater and Inoculum

Domestic wastewater was collected from the equalization tank of the wastewater treatment plant at Chiang Mai University.This treatment plant receives in average 8,000 m^3/day of wastewater generated from Maharaj hospital and Chiang Mai University. Average COD concentration of the wastewater was 202.4±22.5 mg/l. Inoculum used in seeding the studied reactors was collected from a sludge digester of the same treatment plant. This sludge supposed to be already acclimatised to the domestic wastewater to shorten the start-up period. TSS and VSS of the inoculum were equal to 5985 mg/l and 4090 mg/l, respectively.

3.2 Embalming fluid

Embalming fluid was synthesised using analytical grade FA (ACI Labscan, Poland) and phenol (Panreac, Spain) at the ratio of deionised water : FA : phenol of 100 : 4 :1 by volume. At this ratio, concentrations of FA and phenol were 35,322 mg/l and 5,280 mg/l, respectively. The synthesised embalming fluid was found to be acidic with the pH of 5, and therefore contained no significant amount of alkalinity. The properties of FA and phenol are concluded in Table 3.1.

Table 3.1 Chemical properties of FA and phenol

Properties	FA	Phenol
Molecular formula	CHOH	C_6H_5OH
Molar mass	30.02 g/mol	94.11 g/mol
Density	1.09 g/cm^3	1.0576 g/cm^3
Flashing point	56 °C	79 °C
Melting point	-92 °C	40.9 °C
Boiling point	-21 °C	182 °C
Solubility in water	Very high	8.3 g/100 ml (20 °C)

3.3 Anaerobic reactor

3.3.1 Plug-flow reactor

The plug-flow reactor (Figure 3.1 and 3.2) was made from the clear acrylic and divided into 2 parts. The first was a main reaction part with the dimension of 0.12x0.97x0.35 m, corresponding to the working volume of 20 L. Along the reactor length of this reaction part, 6 sampling ports were installed for water sampling with the gap between each port of 0.12 m. The second part was allocated for membrane installation having the dimension of 0.12x0.30x0.35 m or 9 L of working volume. Both influent and effluent were delivered in and out using peristaltic pumps. The influent pump was controlled by a level switch, while the timer switch (Figure 3.5) is utilized for the effluent pump control.

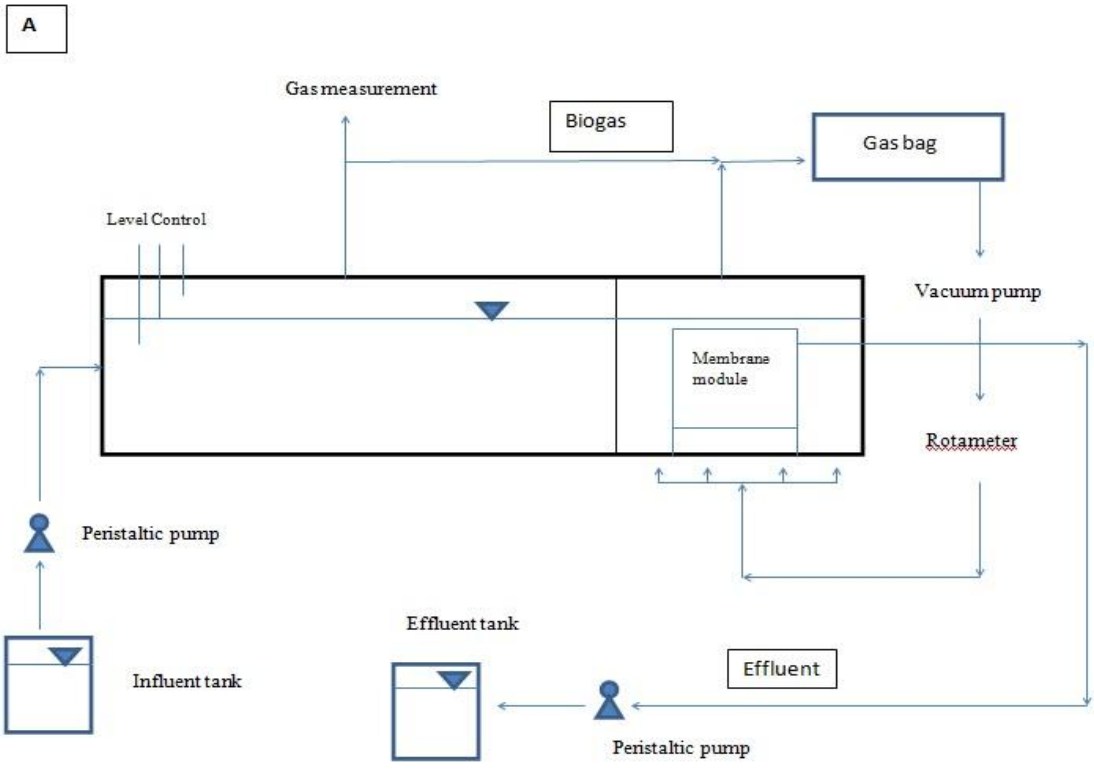

Figure 3.1 Flow diagram of reactor set-up of the plug-flow anaerobic membrane bioreactor

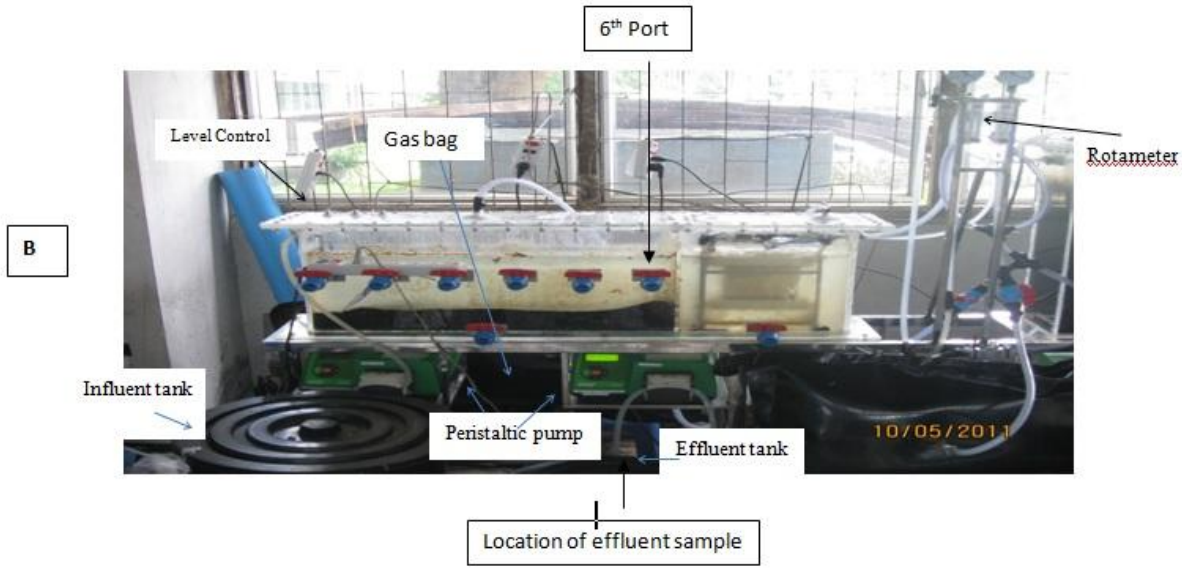

Figure 3.2 Reactor set-up of The plug-flow anaerobic membrane bioreactor

3.3.2 CSTR

The CSTR (Figure 3.3 and 3.4) was made from the clear acrylic**,** having the dimension of 0.2x0.2x0.6 m, corresponding to the working volume of 14 L. Wastewater was stirred by scouring gas

Both influent and effluent were delivered in and out using two individual peristaltic pumps. Like those used in the plug-flow reactor, the influent pump was controlled by a level switch, while the timer switch (Figure 3.5) was utilized for the effluent pump control.

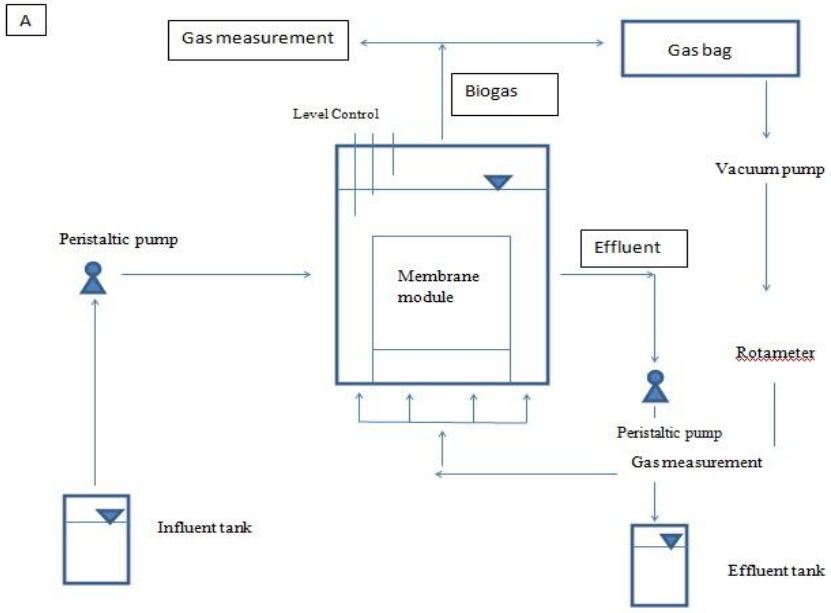

Figure 3.3 Flow diagram of reactor set-up of the CSTR anaerobic membrane bioreactor

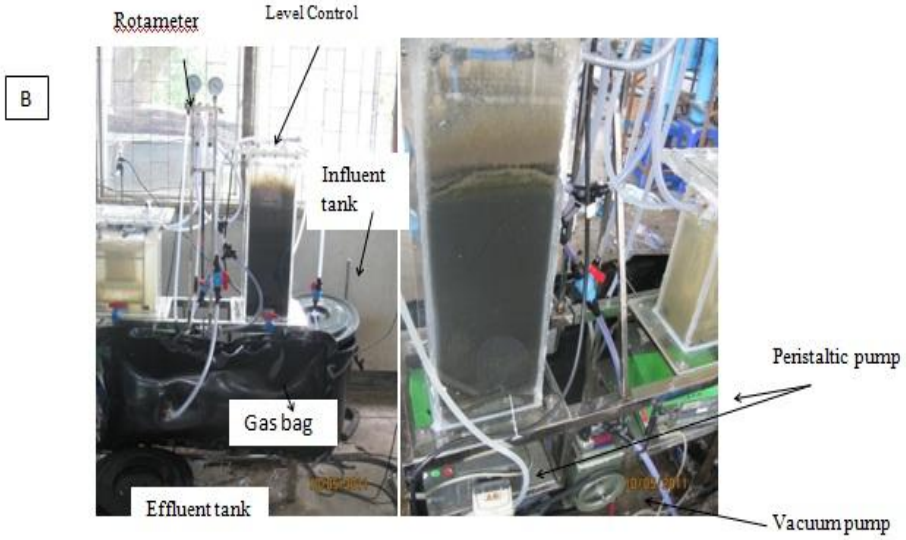

Figure 3.4 Reactor set-up of the CSTR anaerobic membrane bioreactor

Figure 3.5 the Timer Switch Control

3.3.3 Membrane module

Membrane modules (Figure 3.6) utilised in this study was supplied by Mitsubishi Rayon Company. The main function of membrane module installed inside each reactor is for retaining sludge inside the reactor for the precise SRT adjustment. The submerged MF membrane (Table 3.2) was made from polyvinylidene difluoride (PVDF) with pore size 0.4 µm. Specifications and air requirement for each module are presented in Table 3.2.

Table 3.2 Specification for membrane modules

Specification	Membrane for Plug-flow reactor	Membrane for CSTR
Dimension (cm)	22x9.4x25	15x9.4x39
Total surface area (cm^2)	0.13	0.13
Scouring gas requirement (l/min)	30	15
Membrane element	3	3

The membrane modules were operated by intermittent filtration (operate 7 min/ stop 1 min) and recirculated N_2 gas for membrane scouring to avoid membrane clogging. Rotameter was used to control scouring N_2 gas requirement in each reactor. For cleaning procedure, the 3000 mg/l of NaClO solution was used for membrane soaking when the filtration pressure reaches 15 kPa.

3.3.4 Membrane Scouring System

To avoid membrane clogging, the membrane used in both studied reactors was scouring by 99.9% N_2 gas. Scouring gas requirement (Table 3.2) was provided by a 0.5 hp vacuum pump (Masashi Seisakusho Ltd., Japan). This scouring gas was continuously circulated through the membrane module via a gas bag and distributed by perforated tube located under each membrane module. A rotameter was utilized for scouring gas flow rate control. Biogas generated from each reactor is measured by water displacement method (Figure 3.7) controlled to have the constant water head at 5 cm.

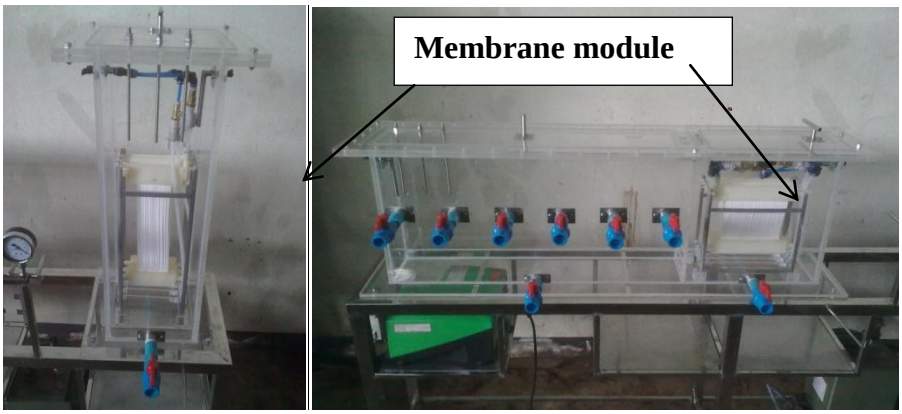

Figure 3.6 Membrane modules for CSTR and Plug-flow anaerobic reactors

Figure 3.7 Water displacement method

However, during the course of all experiments biogas could not be collected. This was because there were leakages of circulated gas from the reactor. These leakages could not be stopped, even though there were attempts to seal all the connected tubings and other possible points. Therefore amounts of generated biogas could not be measured in this work.

3.4 Reactor start-up

To start up the reactors, inoculum was added up to 30% of the working volume and the domestic wastewater was fed into each reactor at the desired flow rate until the steady state was reached considering from COD removal efficiency fluctuation not more than 10% (RSD≤10%).

3.5 Experimental Design

For both plug-flow and CSTR reactors, ratio of embalming fluid to domestic wastewater was varied corresponding to different FA and phenol concentrations. Ranges of FA and phenol concentrations used in this study were in the range of those concentrations reported to affect the anaerobic reactor performance by Wanawan and Patiroop, 2010.

Table 3.3 shows conditions used for experiments conducted with the plug-flow reactor. This reactor was operated under 4 different SRTs, i.e. 6,010, 1,000, 100 and 50 d.

Table 3.3 Experimental conditions for plug-flow reactor

Experiment	SRT (d)	Experimental period (d)	Embalming fluid : Domestic wastewater Ratio (v:v)	Influent concentration (mg/l)		
				COD*	FA	Phenol
Start-up	6,010	16	0:1	239±9.4	-	-
1		14	0.0007:1	289±28.0	26±1.2	5.0±0.1
2		16	0.002:1	325±29.3	69±1.5	11±0.6
3		12	0.004:1	361±16.0	137±6.2	20±0.5
4		14	0.008:1	467±23.4	243±22.3	40±2.4
5		14	0.013:1	655±18.9	435±22.9	64±2.8
6	1,000	12	0.0007:1	241±26.7	26±2.1	5.0±0.3
7		12	0.002:1	258 ±13.9	66±3.8	11±0.1
8		16	0.004:1	350±26.2	137±7.4	21±1.0
9		14	0.008:1	519±36.2	245±10.4	40±0.6
10	100	7	0.004:1	357±18.8	129±7.2	21±0.4
11		11	0.008:1	478±7.6	243±10.2	39±1.2
12	50	20	0.008:1	453±23.9	233±7.3	37±1.0

*****COD concentrations in Table 3.3 were the sum of measured COD and the stoichiometrically calculated phenol COD.

On the other hand, CSTR was operated under only 2 SRTs. i.e. 65,000 and 6,000 d (Table 3.4) because of membrane clogging. To solve the problem, membrane was soaked in NaClO solution before being treated using backwash cleaning. However, the membrane filtration was not improved and the filtration pressure was still more than 15 kPa.

Table 3.4 Experimental conditions for CSTR

Experiment	SRT (d)	Experimental period (d)	Embalming fluid : Domestic wastewater Ratio (v:v)	Influent concentration (mg/l)		
				COD*	FA	Phenol
Start-up	65,000	28	0:1	185±29.1	-	-
1.1**		42	0.002:1	282± 16.6	59.5±1.9	3.7±0.6
1.2		18	0.002:1	353± 17.3	58.3±1.7	11.2±0.4
2		14	0.004:1	454± 34.6	106.8±6.2	20.9±1.8
3		16	0.008:1	586± 14.1	226.0±19.2	36.8±1.7
4		12	0.013:1	777± 32.3	426.2±15.3	62.9±1.1
5***		28	0.008:1	445± 37.8	-	40.3± 2.6
6	6,000	14	0.0007:1	255± 21.5	25.4 ±3.4	5.0± 0.8
7		9	0.002:1	294± 22.1	60.8± 4.4	10.6± 0.5
8****		10	0.008:1	573± 44.6	239.3± 11.1	39.1± 1.5

*****COD concentrations in Table 3.4 were the sum of measured COD and the stoichiometrically calculated phenol COD.

** To allow the microorganisms to acclimatise for phenol degradation, lower phenol concentration was first applied in the preparation of synthetic embalming fluid (Experiment 1.1)
*** Only phenol was spiked into the domestic wastewater to verify the assumption that low phenol removal efficiency was caused by the present of FA in the influent (Experiment 5)

**** Operated at HRT of 25.6 h because of membrane clogging (Experiment 8)

3.6 Physical and chemical analysis

3.6.1 Wastewater sampling and analysis

Samples were taken for analysis during each experiment from both reactors. Inlet and outlet samples were required for both Plug-flow and CSTR reactors. Additionally, for plug-flow reactor, samples taken from the port at the end (6th port) of the reaction part were also collected. Details of sampling point, sampling frequency, and analytical method used is presented in Table 3.5.

Table3.5 Parameters for measurement in the study

Parameter	Inlet	Outlet (Membrane effluent)	Sample at 6th port for plug-flow reactor	Frequency	Analytical Method
TCOD	√			3 times per week	Dichromate Open Reflux
FCOD		√	√	3 times per week	Dichromate Open Reflux
SS	√	√	√	2 times per week	Gravimetric method
VSS	√	√	√	2 times per week	Gravimetric method
Alkalinity	√	√	√	2 times per week	Titration method
VFA	√	√	√	2 times per week	Titration method
pH	√	√		Every day	pH meter
Temperature	√	√		Every day	Thermo meter
FA	√	√	√	3 times per week	Direct Photometric Method
Phenol	√	√	√	3 times per week	Direct Photometric Method

Analysis of COD, alkalinity, VFAs and solids was performed according to the Standard Methods for the Examination of Water and Wastewater (APHA, AWWA and WEF 1992).

3.6.2 Formaldehyde analysis

The concentrations of FA were measured according to the standard method for Formaldehyde in water (ASTM, 2005) and can be explained as following ;

3.6.2.1 Preparation of calibration curve of FA

To prepare FA solutions for the calibration curve, the FA standard concentration of 10 mg/l was diluted to 5 different concentrations, i.e. 0, 0.1, 0.5, 1 and 2 mg/l, respectively.

3.6.2.2 Sample measurement

The sample was filtered through glass microfiber filter paper GF/C having diameter of 47 mm (Whatman). The 5 ml of sample and 5 ml of 1 N sulfuric acid and sodium dioxide were then added in a 100 ml volumetric flask. Distilled water was added (10 ml) and acyetyl acetone was added to 50 ml. Then, the sample was incubated 60 C in water bath for 10 min. After the incubation, the sample was transferred to the cuvette and measured for the absorbance at the wave length of 425 nm. The absorbance of the FA from that of the standards and samples were compared to the calibration curve obtained from Topic 3.5.3.1

3.6.3 Phenol analysis

The colorimetric method was used to determine phenol concentration (APHA, AWWA, WEF 1992), which can be explained as following ;

3.6.3.1 Preparation of calibration curve of phenol

To prepare the stock 100 mg/l phenol solution, 10 mg of phenol was dissolved in deionization water. This stock phenol solutions were used further to prepare the calibration curve of phenol at 5 different concentrations (0, 0.25, 0.5, 1, and 2.5 mg/l, respectively).

3.6.3.2 Sample measurement

The sample was filtered through glass microfiber filter paper GF/C having diameter of 47 mm (Whatman). The 100 ml of the sample and 2.5 ml of 0.5N ammonium hydroxide were then added in a 250 ml flask. The phosphate buffer was added immediately to adjust the pH to 7.9. After that 1 ml of 4-aminoantipyrine solution was added in the flask and shaken for 10 sec. Potassium ferric cyanide solution (1 ml) was added to form the red color. After 15 min, the sample was transferred to the cuvette and measured the absorbent at the wave length of 500 nm.

3.6.4 SRT calculation

SRT of each studied reactor was controlled by varying amounts of sludge wasted from each reactor and calculated according to Equation 3.1.

$$SRT = VX_{inside}/Q_wX_w \qquad \text{(Eq.3.1)}$$

Where; V is volume of reaction tank, X_{inside} is VSS inside reactor, Q_w is wasted sludge flow and X_w is wasted VSS, respectively.

For CSTR, as X_{inside} was equal to X_w, equation for SRT calculation can be simplify as equal to the ratio of reactor volume to wasted sludge flow. However, X_{inside} for the plug-flow reactor (Figure 3.8) was approximated to be equal to $VX_{(inside, floated)} + VX_{(inside, settled)}$. Both $X_{(inside, floated)}$ and $X_{(inside, settled)}$ are collected from the reactor's middle length representing average MLVSS concentration inside the reaction part.

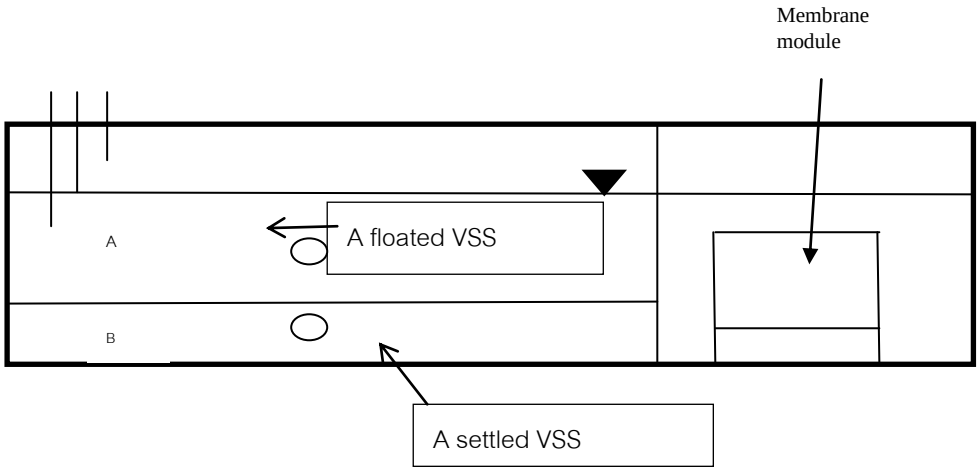

Figure3.8 Different VSS parts of plug-flow anaerobic membrane bioreactor; VSS was divided into 2 parts, i.e. the floated VSS (A) and the settled VSS (B). Samples were collected from the middle port to represent VSS from both parts of the reactor.

CHAPTER IV

RESULTS AND DISSCUSSION

As stated in Chapter 1, the objectives of this work were to; (1) investigate effects of sludge ages on removal efficiencies of formaldehyde and phenol using both CSTR and plug-flow anaerobic membrane bioreactors, (2) study effects of embalming fluid to wastewater ratios on removal efficiencies of FA and phenol, and (3) compare performance for FA and phenol removal between the plug-flow and CSTR anaerobic membrane bioreactors. Results and the corresponding discussion of each experiment conducted to fulfill each objective are presented in this chapter.

4.1 Performance of the CSTR

4.1.1 Physical and chemical analysis during start-up period of CSTR

CSTR anaerobic membrane bioreactor was started up at 12 h of HRT until the steady state was reached (considering from the stability of COD removal efficiency, in which the relative standard deviation was not higher than 10%). The sludge from a sludge digester of Chiang Mai University wastewater treatment plant was used as inoculum. Wastewater from the same source was selected for rapid start-up.

The CSTR required only 28 d to reach the steady state. Profiles of temperature, pH, alkalinity, VFA, SS, VSS, and COD were analysed by time to monitor the reactor performances and can be shown as following;

4.1.1.1 Temperature

The efficiency of anaerobic reactor is affected when temperature changes and the temperature should be monitored to check if decrease in specific microorganism activity has occurred. The temperature ranges of influent and effluent samples were 21 – 26℃ and 23-27℃, respectively. These temperatures were within the proper mesophilic range for anaerobic degradation (20 - 35℃) implying that the anaerobic microorganisms inside CSTR were functioning at optimum temperature.

Influent and effluent had slight temperature variations because of variations of ambient air temperature (Figure 4.1). Higher temperatures of some effluent samples compared to those of the influent could be observed because influent and effluent sample were collected at the different times of a day.

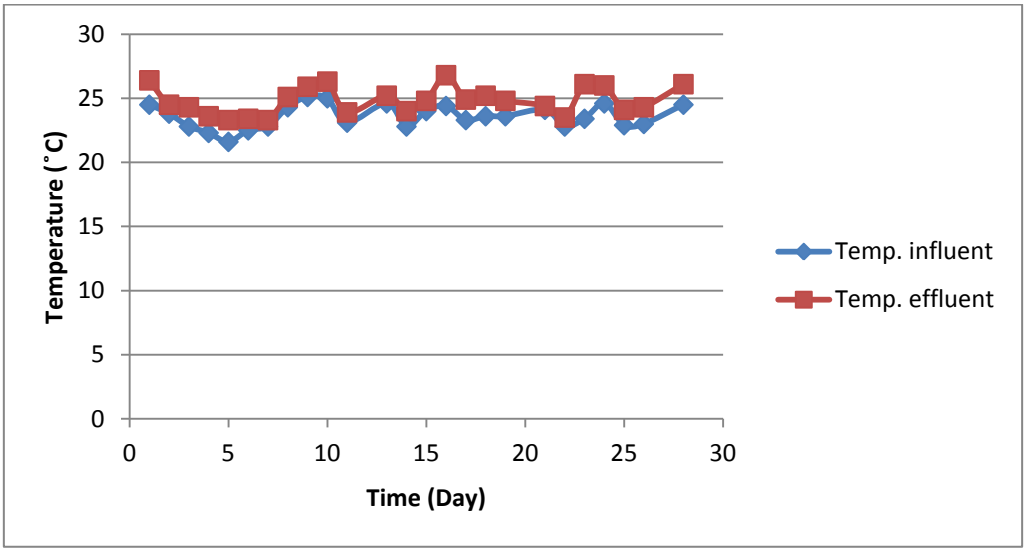

Figure 4.1 Temperature during the start up period of CSTR

4.1.1.2 pH

pH values can be significantly used as an indicator for anaerobic reactor stability. Methanogens prefer nearly neutral pH in the range of 6.5 to 8.2 (Speece, 1996). Results from this study showed that the pH values were in the optimum ranges, 7.0-8.2, for the effluent samples (

Figure 4.) without any chemical addition.

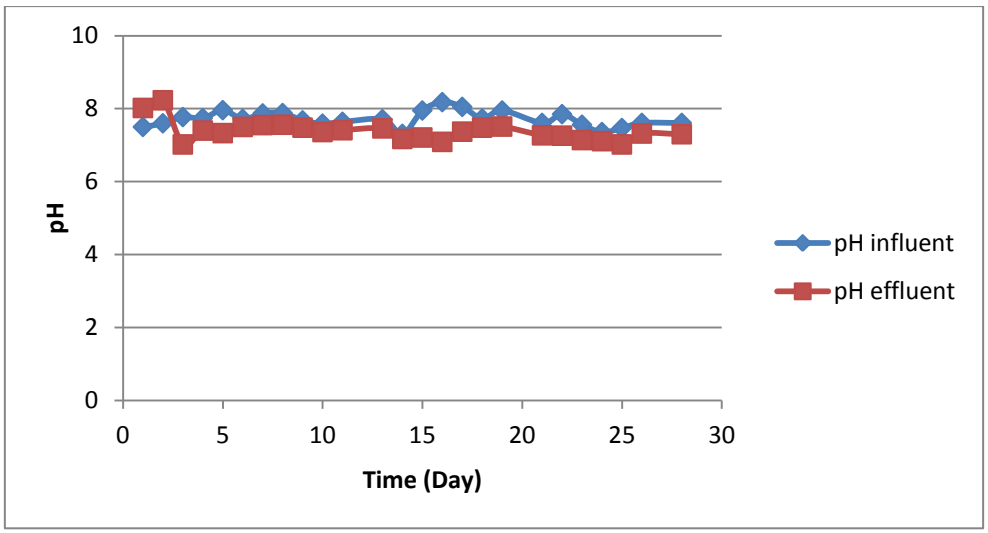

Figure 4.2 pH during the start up period of CSTR

4.1.1.3 Alkalinity and Volatile Fatty Acid (VFA)

The alkalinity helps opposing the change of pH. Domestic wastewater is normally alkaline, receiving its alkalinity concentrations from the materials added during domestic used. The alkalinity is known in the bicarbonate (HCO_3^-) form (Metcalf&Eddy, 2004). The alkalinity concentrations investigated in this study were in the ranges of 118-140 and 100-170 mg/l for influent and effluent samples, respectively (Figure 4.).

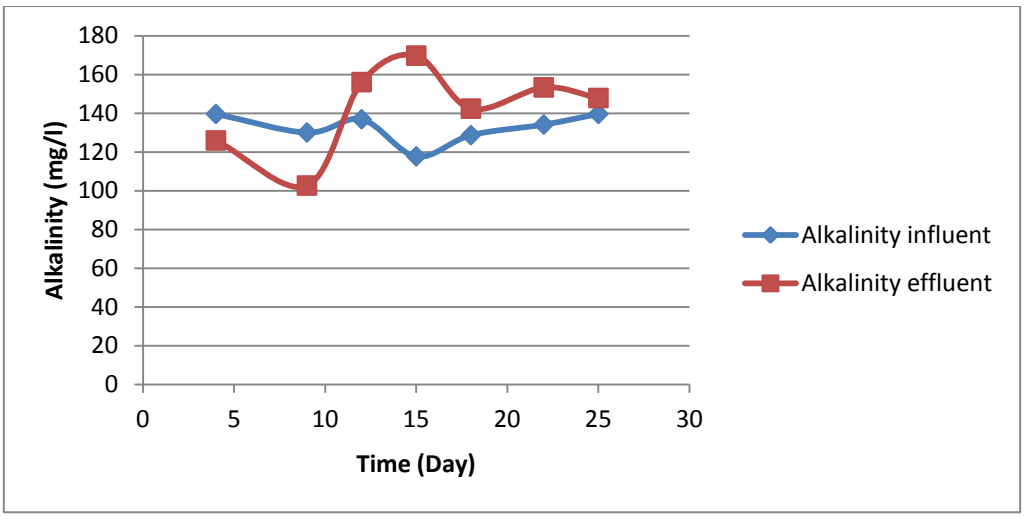

Figure 4.3 Alkalinity during the start up period of CSTR

The VFA is an important factor indicating the stability of acidogens and methanogens population. Accumulation of VFA affects the performance of methanogens in generating methane. The VFA concentration of the influent was in the range of 13-24 mg/l, while that of the effluent was in the range of 12-40 mg/l (Figure 4.). No significant VFA accumulation was found throughout the start-up period with maximum VFA concentration of only 40 mg/l was detected. This result was corresponded with the pH profile which was within the optimum value for methanogens, suggesting that alkalinity was adequate for both VFA and H_2CO_3 neutralization.

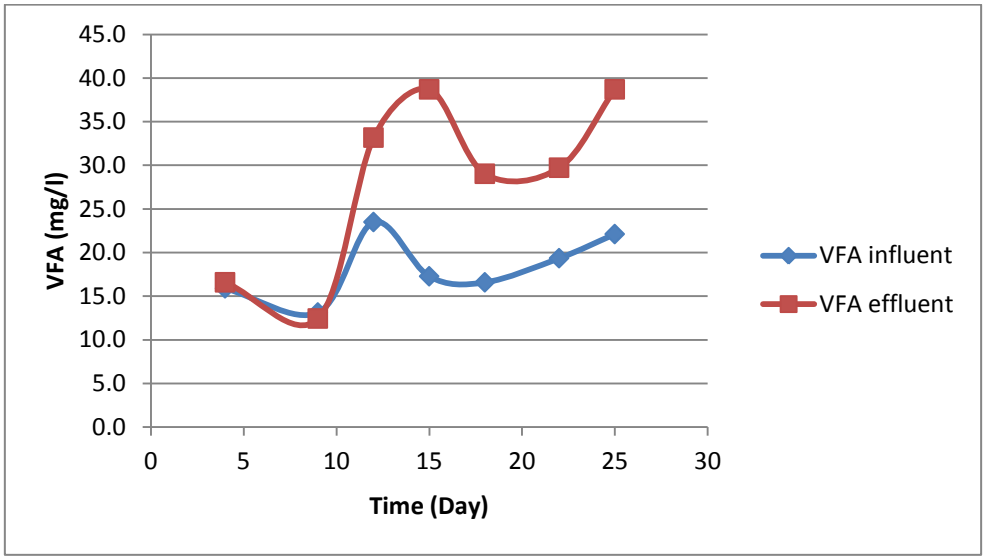

Figure 4.4 VFA during the start up period of CSTR

The appropriate ratio of VFA to alkalinity for the anaerobic process activity should be less than 0.4 (Speece, 1996). The ratio of VFA to alkalinity in the effluent (0.2±0.05)was estimated to be within the suitable range.

4.1.1.4 Suspended Solid (SS) and Volatile Suspended Solid (VSS)

Wastewater contains a variety of solid materials. The fact that the difference between colloidal particles and dissolved material has not been made routinely has led to confusion in the analysis of treatment plant operation. Generally, SS and VSS are

supposed to be organic material in the water (Metcalf&Eddy, 2004). The difference is SS contain more complex material than VSS. Therefore, the SS and VSS results are routinely utilised to evaluate the performance of the conventional treatment process.

The average influent SS and VSS concentration (Figure 4.5) during the start up period were 90±24.3 mg/l and 55±13.8 mg/l, respectively. Both SS and VSS were not detected in the effluent because the samples were filtered through the PVDF membrane having the pore size of 0.4 µm. It could be concluded that solid materials were completely removed by CSTR membrane bioreactor.

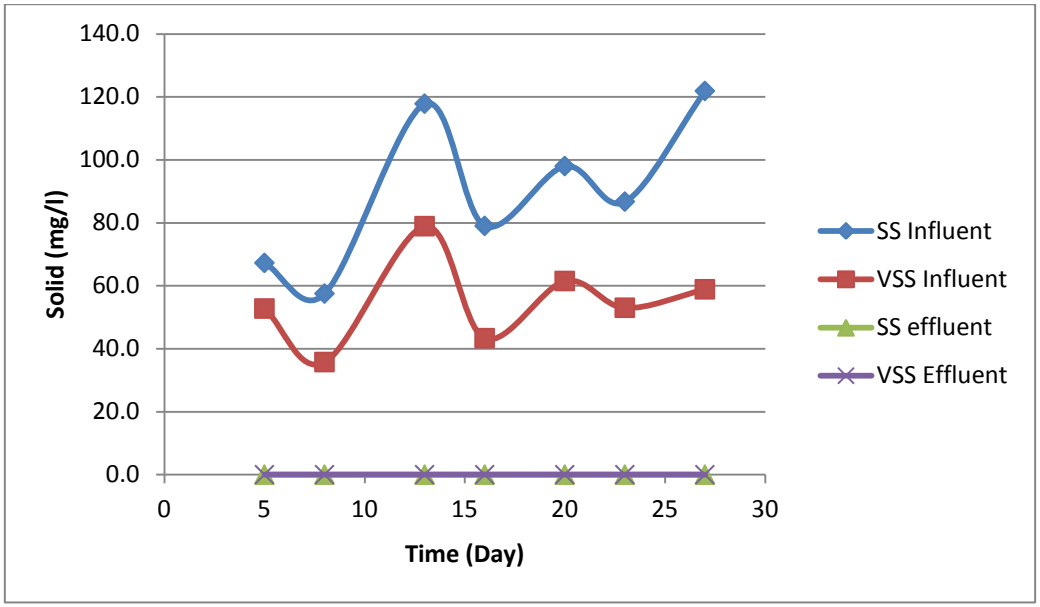

Figure 4.5 SS and VSS concentration during the start up period of CSTR

Relatively low concentrations of SS and VSS found in the influent were attributed to the fact that the wastewater used in this study was collected from the equalization tank of the separate sewer system. The SS and VSS concentrations measured in this study were slightly less than those reported by Metcalf&Eddy (2004), who reported that the typical concentrations of SS and VSS in the low strength domestic wastewater were 120 and 95 mg/l, respectively.

4.1.1.5 COD

The removal of organic substances by anaerobic microorganisms in the CSTR membrane bioreactor can be determined using the COD concentration and its removal efficiency. The influent COD concentration was in the range of 106-246 mg/l. The average effluent COD concentration during steady state was 40±3.9 mg/l (Figure 4.6). During this period, COD removal efficiency was 78±2.5%.

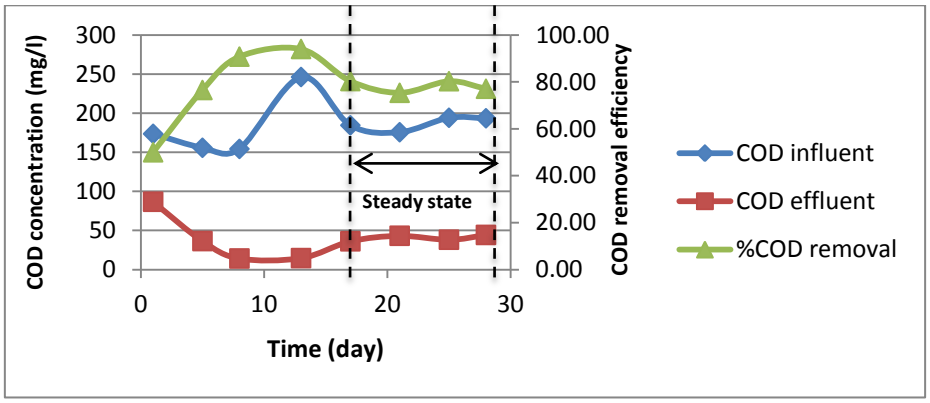

Figure 4.6 COD concentration and removal efficiency during the start up period of CSTR

During the first 7 d of the start-up period, the influent tank was not continuously mixed leading to the SS being settled at the bottom of the tank. As about 75% of the suspended solid are organic in nature (Metcalf&Eddy, 2004), the COD concentrations measured during this time were relatively lower.

After the overhead mixer had been installed, less variation of influent COD was found. The influent COD concentration measured in this study was similar to the normal COD concentration for the low strength domestic wastewater reported in Metcalf&Eddy (2004).

4.1.2 CSTR performance after FA and phenol addition

4.1.2.1 Temperature

The temperature during the experimental period fluctuated in the range of 18 – 32℃ (Figure 4.7). The temperatures of some effluent samples were slightly increased due to deviation of ambient air temperature during the sampling times. However, the operating temperatures of this study were still in the appropriate range for mesophilic anaerobic degradation (20-35℃).

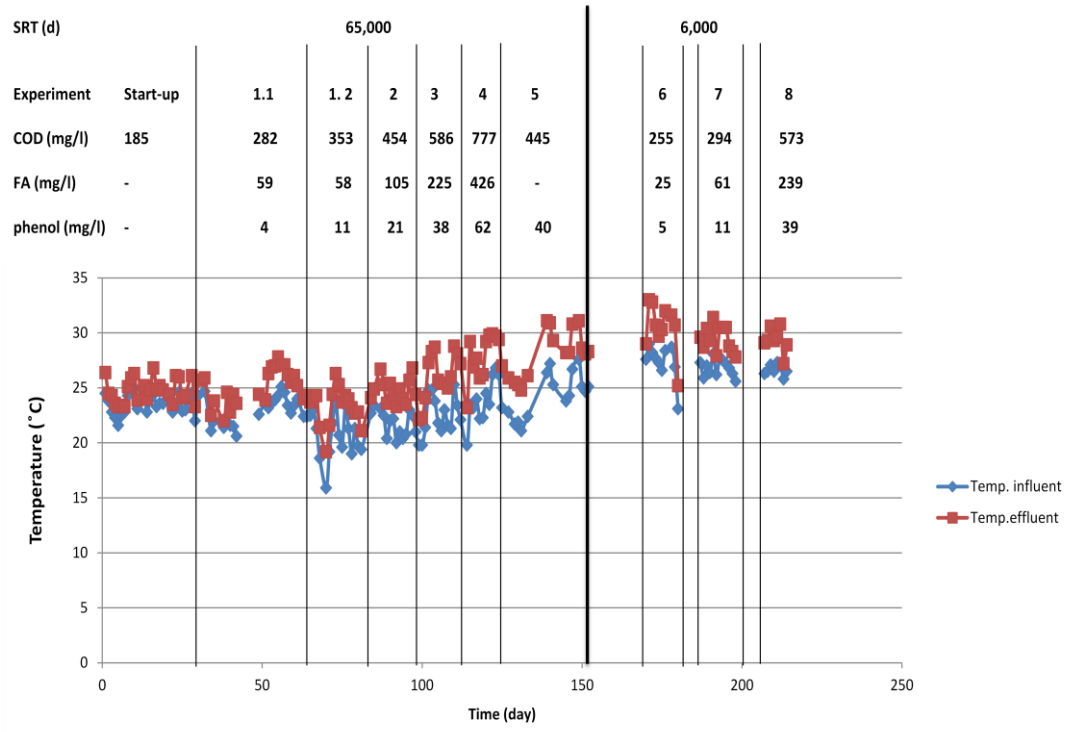

Figure 4.7 Temperature during the whole experimental period of CSTR

4.1.2.2 pH, VFA and alkalinity

The values of pH, alkalinity and VFA throughout the whole experimental period of this study are shown in the Figure 4.8, 4.9 and 4.10

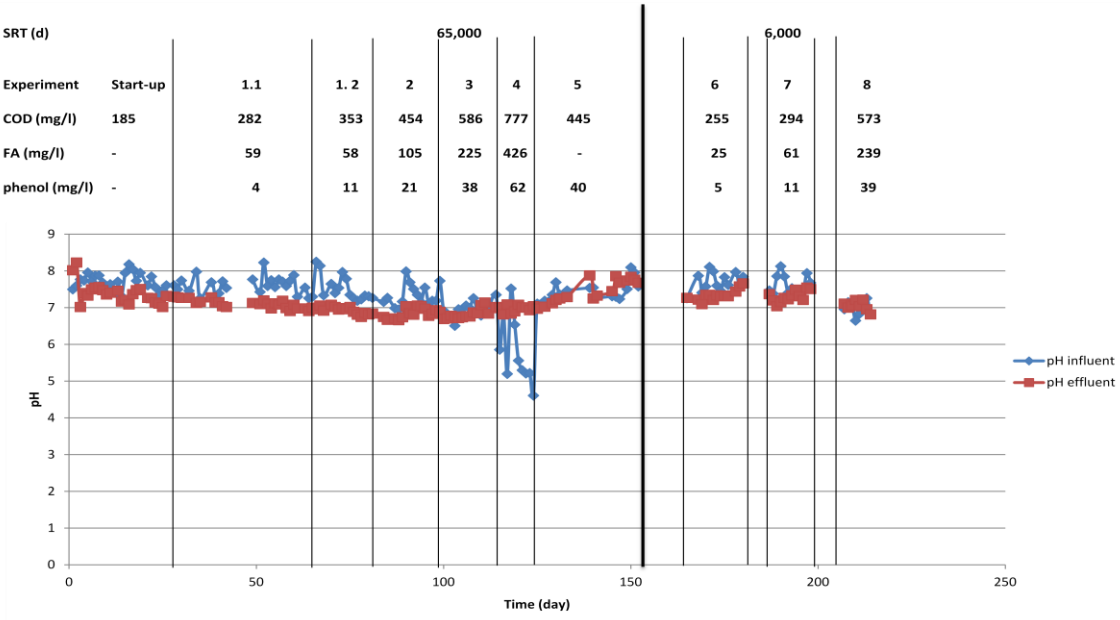

Figure 4.8 pH during the whole experimental period of CSTR

At the SRT of 65,000 d, pH in the influent samples decreased when ratio of embalming fluid to domestic wastewater was stepwise increased. In Experiment 4, pH of in the influent was suddenly dropped from 6.9±0.2 in Experiment 3 to as low as 5.8±0.9 in Experiment 4, along with the observed decrease of alkalinity and increase of VFA. This could be the result of the influent alkalinity being not enough to buffer the acidic embalming fluid at the amount used in Experiment 4.

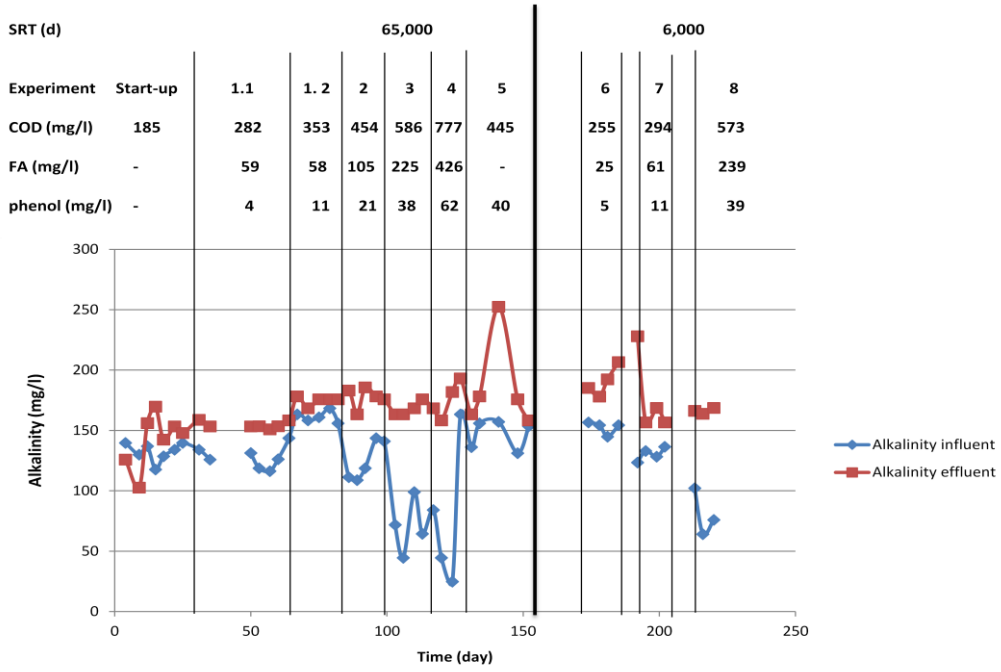

Figure 4.9 Alkalinity during the whole experimental period of CSTR

However, pH of the effluent samples was still in the anaerobic workable range of 6.8-7.1 and the average VFA concentration was 42.6±14.9 mg/l. Moreover, ratio of VFA to alkalinity was less than 0.40 (0.13-0.39) throughout the experimental period.

This result suggested that VFA in the influent was efficiently degraded by methanogens resulting in the alkalinity being produced. Consequently, pH of the reactor content could be maintained at the suitable range even when VFA of the influent increased.

The same trend was observed when the CSTR was operated at the SRT of 6,000 d. The average of pH in effluent sample was 7.3±0.2 and ratio of VFA to alkalinity was less than 0.4 (0.12-0.39) throughout all of the experiments (Experiment 6 to 8) which was within the suitable range for anaerobic process.

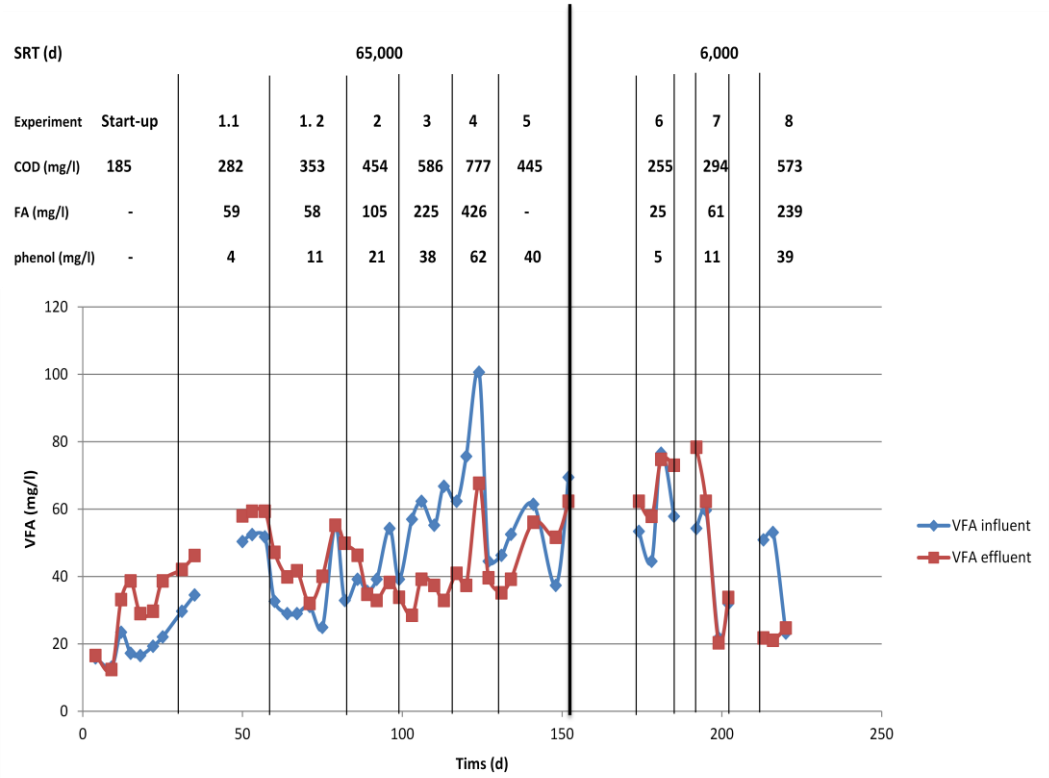

Figure 4.10 VFA during the whole experimental period of CSTR

4.1.2.3 Suspended Solid (SS) and Volatile Suspended Solid (VSS)

The influent average SS and VSS concentrations during the whole experimental period (Figure 4.11) were 127±37.7 mg/l and 61±18.1 mg/l, respectively. These concentrations were very close to those detected during the start-up step. As embalming fluid did not contain any suspended solids, its present in the influent did not significantly affect both SS and VSS concentrations.

Similarly, both SS and VSS were not detected in the effluent. This was due to the fact that the effluent was filtered through PVDF membrane. This reason could also explain the complete SS and VSS removal by the studied CSTR membrane bioreactor.

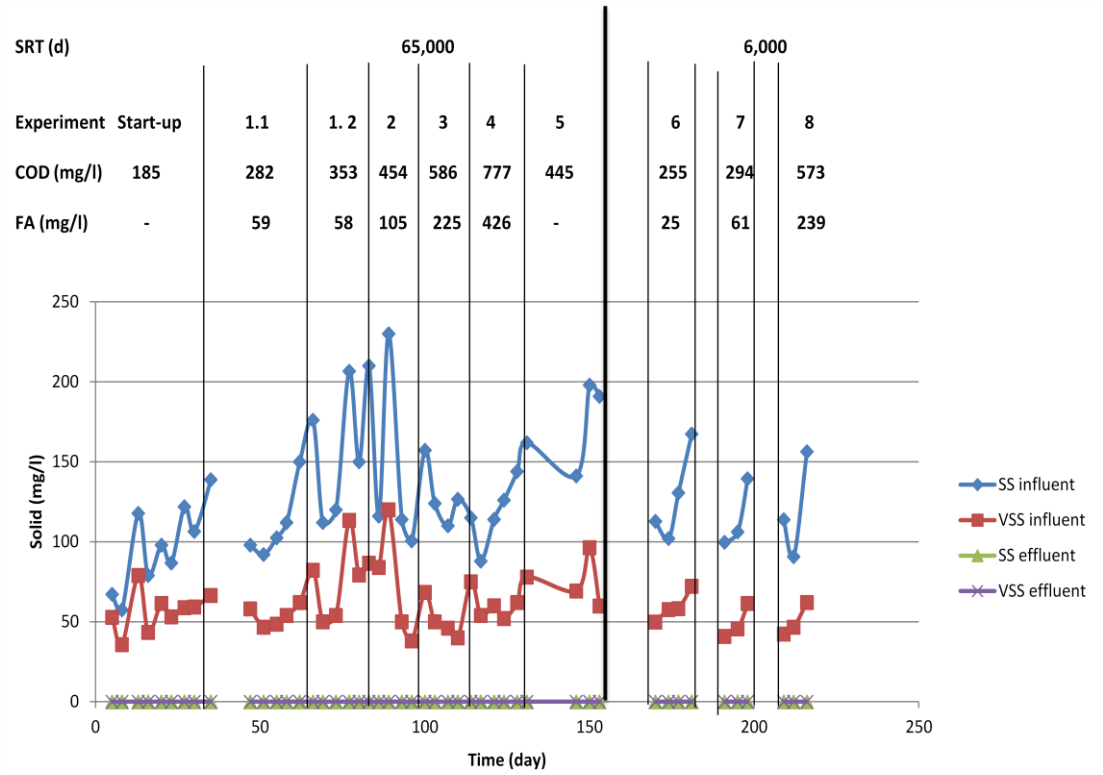

Figure 4.11 SS and VSS during the whole experimental period of CSTR

4.1.2.4 COD

The COD concentration and removal efficiency during the whole experimental period are shown in Figure 4.12.

Embalming fluid contains formaldehyde and phenol, which is an organic compound containing aromatic ring and bonds with the hydroxyl group. Aromatic hydrocarbons and pyridine are not oxidized under any circumstances in potassium dichromate (Sawyer, 2003). Therefore, COD in Table 4.1 was the sum of measured COD and the calculated phenol COD (Equation 4.1). Stoichiometrical equation provides that each gram of phenol is equal to 2.38 gCOD.

$$C_6H_5OH + 7O_2 \longrightarrow 6CO_2 + 3H_2O \qquad \text{(Eq. 4.1)}$$

M.W.	94	224
gram	1	2.38

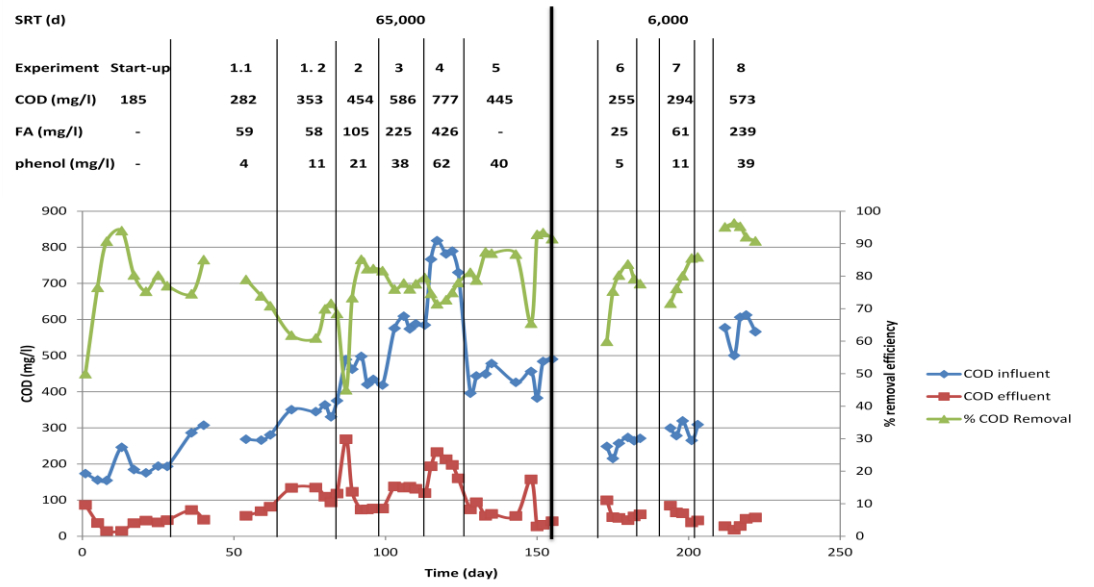

Figure4. 12 The COD concentration and removal efficiency during the whole experimental period of CSTR

When embalming fluid was spiked to domestic wastewater in Experiment 1.1, COD removal efficiency was not significantly affected (Figure 4.12). COD removal efficiency was slightly decreased in Experiment 1.2 when phenol concentration was increased to 11±0.4 mg/l. However, the sudden drop of COD removal efficiency was found at the beginning of Experiment 2 before recovering to 83±1.6% during the steady state. These results implied the restraint effects and the acclimatisation of microbial activity when feeding with higher concentration of the toxic substances. Moreover, high COD removal efficiency was observed in Experiment 3 and 4. This showed adaptation of anaerobic reactor for treating COD resulting in higher removal efficiencies achieved during all experiments. When only phenol was spiked to domestic wastewater in Experiment 5, COD removal efficiency was increased from 75±2.7% in Experiment 4 to 93±1.0%.

Anaerobic Membrane Bioreactor has the complete retention of biomass and suspended solids. This helps in improving the effluent quality, hence high COD elimination rates can be achieved (Fuchs et al., 2003). Though decrease of phenol removal was observed when phenol concentration reached 38 mg/l in Experiment 4

(Topic 4.1.2.6), the remained phenol concentrations in effluent calculated stoichiometrically contributed up to very low concentration in form of COD. Therefore, these explained high COD removal efficiency observed at ratio of embalming fluid to domestic wastewater of 0.008 : 1 and 0.013 : 1 (Experiment 3 and 4), when less phenol was found to be removed.

At SRT of 6,000 d, COD removal efficiencies achieved in Experiment 6 and 7 were still high (80±3.1% and 84±3.3%, respectively). When ratio of embalming fluid to domestic wastewater was 0.002: 1 in Experiment 1.2 and 7, significantly higher COD removal efficiencies were observed at SRT of 6,000 d compared to that at SRT of 65,000 d ($P \leq 0.05$). These results suggested that the acclimatisation of microbial activity might have more important role than the range of studied SRT on the reactor performance.

In Experiment 8, membrane used inside CSTR was found to be permanently clogged leading to the flow rate of effluent being reduced. Increase of COD removal efficiency found at this Experiment was likely to be the result of HRT being increase from 12 h to 25.6 h (93±2.3%). This was attributed to the advantage of longer HRT in removing toxic substances (Speece, 1996). Moreover, significantly higher COD removal efficiencies were observed at SRT of 6,000 d compared to that at SRT of 65,000 d in the same ratio of embalming fluid to domestic wastewater ($P \leq 0.05$), confirming the assumption that microbial acclimatisation had greater effect on CSTR performance when operated at the SRT in the range of 6,000-65,000 d.

4.1.2.5 FA

The FA concentration and removal efficiency during the whole experimental period are shown in Figure 4.13.

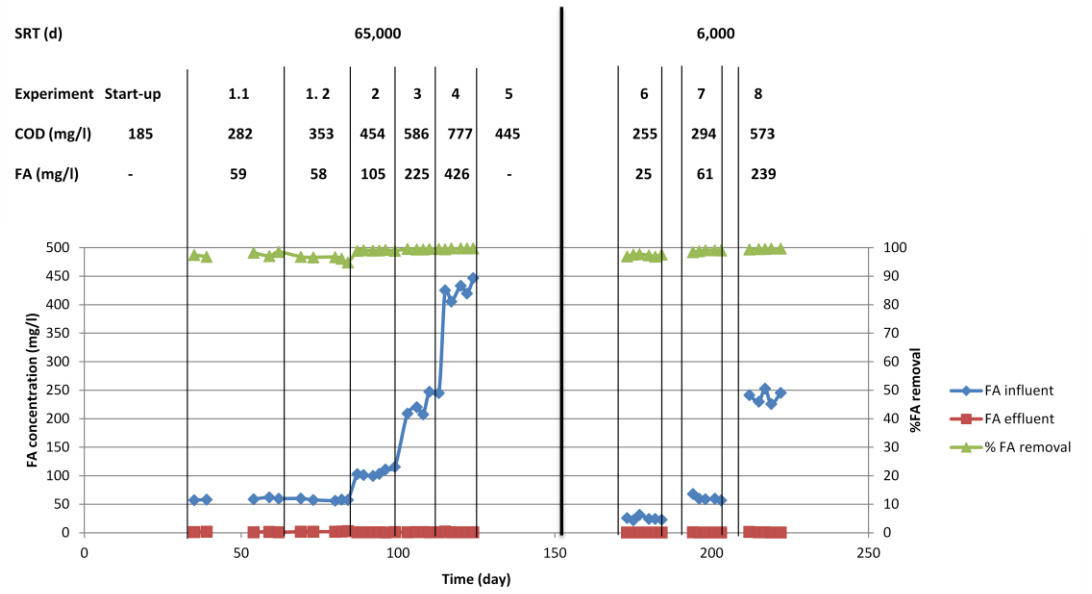

Figure 4.13 FA concentration and removal efficiency during the whole experimental period of CSTR

Figure 4.13 shows FA concentration and removal efficiency measured during 222 d of CSTR anaerobic membrane bioreactor operation. The reactor presented excellent performance for formaldehyde removal at all experiments when operated at SRT of 65,000 d and 6,000 d. At SRT of 65,000 d, the average effluent formaldehyde concentration was as low as 1.4 mg/l for influent concentrations ranging from 59±1.9 to 426±15.3 mg/l. FA removal efficiencies higher than 96% were achieved throughout the study period.

FA was also completely removed in all experiment at SRT of 6,000 d at the influent concentrations ranging from 25±3.4 to 239±11.1 mg/l. The FA removal efficiencies obtained at ratio of embalming fluid to domestic wastewater of 0.0007:1 and 0.002:1 (Experiment 6 and 7, respectively) were found to be statistically different ($P \leq 0.05$) in which higher FA removal efficiency was observed when higher ratio of embalming fluid was utilized. These results implied the restraint effects of acclimatisation of microbial activity when feeding with higher concentration of the toxic substances.

Wanawan and Patiroop (2010) reported that FA was not found to be substantially lost from the vigorously stirred open tank during the period of 8 h. Therefore, FA degradation in this current study was assumed to occur mainly by biological activity. However, it needs to be mentioned that the purging effect by N_2 gas used for membrane scouring could probably also bring about some FA volatilization. Extent of this volatilization could not be quantified in this current study.

4.1.2.6 Phenol

The phenol concentration and removal efficiency during the whole experimental period are presented in Figure 4.14 and 4.15.

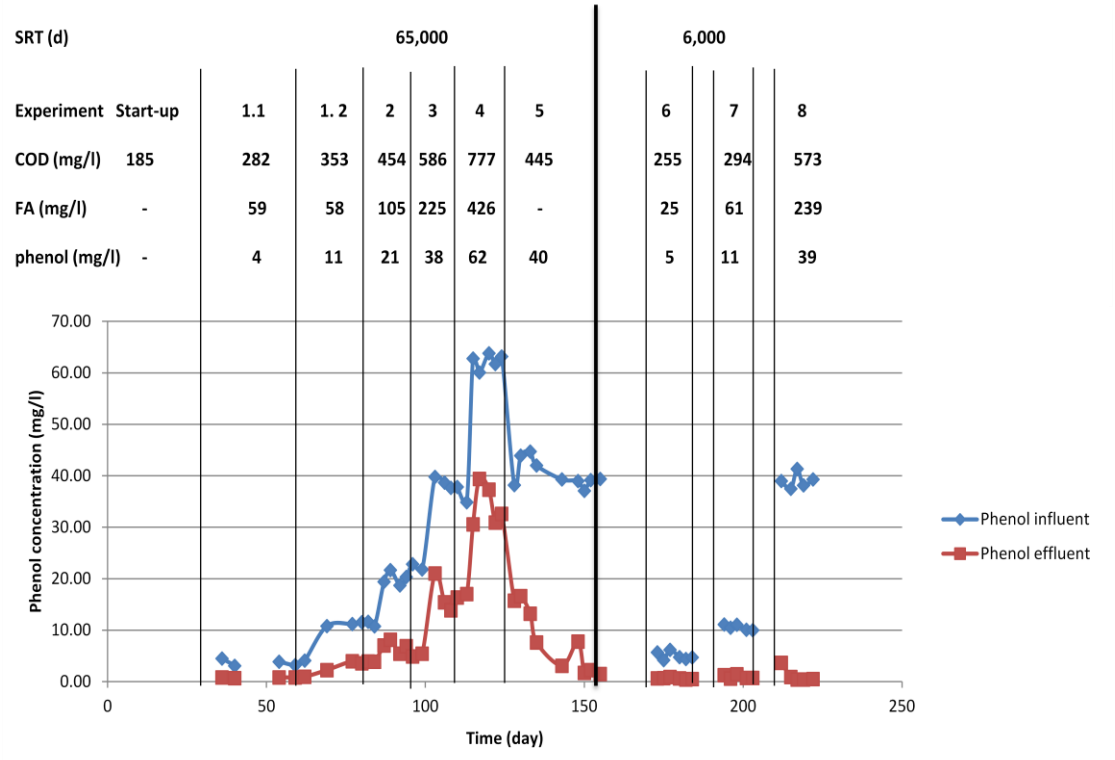

Figure 4.14 Phenol concentrations during the whole experimental period of CSTR

Fig.4.14 and 4.15 shows phenol concentration and removal efficiency measured during the experimental period. High removal efficiency (77±1.9%) was observed when low phenol concentration (3.8±0.6 mg/l) was fed into the reactor. Phenol removal efficiency, however, was slightly decreased in Experiment 1.2 and 2. Only 57±6.0% removal efficiency was found in Experiment 3 when phenol concentration was increased to 38±1.8 mg/l. Increase of phenol concentration to 62±1.4 mg/l in the Experimental 4 subsequently resulted in phenol removal efficiencies being sharply reduced to 46±4.5 %.

Deterioration of phenol removal found in this current study when its concentration was as low as 38 mg/l might be caused by presence of FA. Eiroa, et al. (2005) found that at the fixed initial concentration of 260 mgFA/l, the maximum phenol concentration that could be efficiently degraded was 180 mg/l. In addition, some previous studies also reported inhibition of phenol degradation in the presence of FA (Eiroa, et al., 2005 and Wanawan and Patiroop, 2010).

To prove that low phenol removal efficiency attained in this study was really the result of FA existence, only phenol was spiked in the domestic wastewater at the concentration of 40 mg/l in Experiment 5. Results obtained were obviously in agreement with those reported in previous studies (Bolanos et al., 2001 and Scully et al., 2006). Phenol removal efficiency was sharply increased and stabilised during steady state at 95±1.0%, the level observed in some previous studies when phenol, as the sole substrate in the range of 50 to 1,200 mg/l, was found to be efficiently removed under anaerobic condition (Bolanos et al. 2001; Fang et al., 2006; Scully et al. 2006 and Eioa et al., 2005)

At SRT of 6,000 d for CSTR anaerobic membrane bioreactor operation, the reactor presented high performance (>89%) for phenol removal in Experiment 6 and 7.

Compared to results reported at the ratio of embalming fluid to domestic wastewater of 0.002:1 (Experiment 1.2 and 7), significantly higher phenol removal efficiency was observed in Experiment 7 compared to those in Experiment 1.2 ($P \leq 0.05$). This showed that the acclimatisation was more important for phenol anaerobic degradation even when SRT was more than 10 times reduced in Experiment 7.

When only phenol was spiked to the domestic wastewater in Experiment 5 at the previous concentration that adversely affected the reactor performance, phenol removal efficiency was sharply increased to 95±1.0%. While the reactor presented high performance (>89%) for phenol removal in Experiment 6 and 7 that lower phenol was spiked with FA into domestic wastewater, significantly higher phenol removal efficiency was observed in Experiment 5 compared to those in Experiment 6 and 7 ($P \leq 0.05$). This implied that the absence of FA was more responsible than the microbial acclimatisation in phenol anaerobic degradation.

Membrane clogging was later observed resulting in the HRT being increased from 12 to 25.6 h in Experiment 8. Soaking membrane in NaClO solution and backwashing were due to avail. However, phenol was completely removed in Experiment 8. These results also implied that the advantage of longer HRT in removing toxic substances (Speece, 1996) and the acclimatisation of microbial activity.

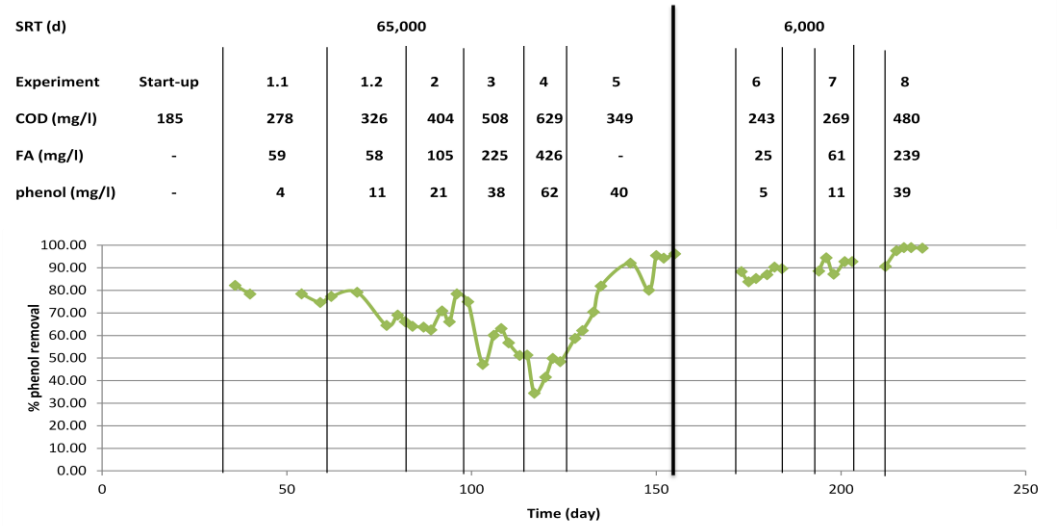

Figure 4.15 Phenol removal efficiency during the whole experimental period of CSTR

4.2 Performance of plug-flow reactor

4.2.1 Physical and chemical analysis during start-up period of plug-flow reactor

To start up the reactor, inoculum was added up to 30% of the working volume and the domestic wastewater was fed into reactor at 35 l/d corresponding to the HRT of 12 h until the steady state was reached (considering from COD removal efficiency fluctuation not more than 10% (RSD≤10%)). Inoculum was collected from a sludge digester of Chiang Mai University wastewater treatment plant. Wastewater from the same source was selected for rapid start-up. The PF reactor required only 16 d to reach the steady state. Profiles of temperature, pH, alkalinity, VFA, SS, VSS, and COD were analysed by time to monitor the reactor performances.

4.2.1.1 Temperature

The efficiency of anaerobic reactor may be affected when temperature changes. The temperature should be regularly monitored because decrease in specific microbial activity can happen if temperature drops below the suitable range. The temperature ranges of influent and effluent samples were 19 – 24℃ and 21-25℃, respectively. These temperatures were within the proper range for mesophilic anaerobic degradation (20 - 35℃) indicating that the anaerobic microorganisms inside plug-flow reactor were functioning at the suitable temperature.

Temperature of both influent and effluent slightly changed due to variations of ambient air temperature (Figure 4.16). This reason could also explain the higher temperatures of some effluent samples compared to those of the influent ones as influent and effluent sample were collected at the different times of a day.

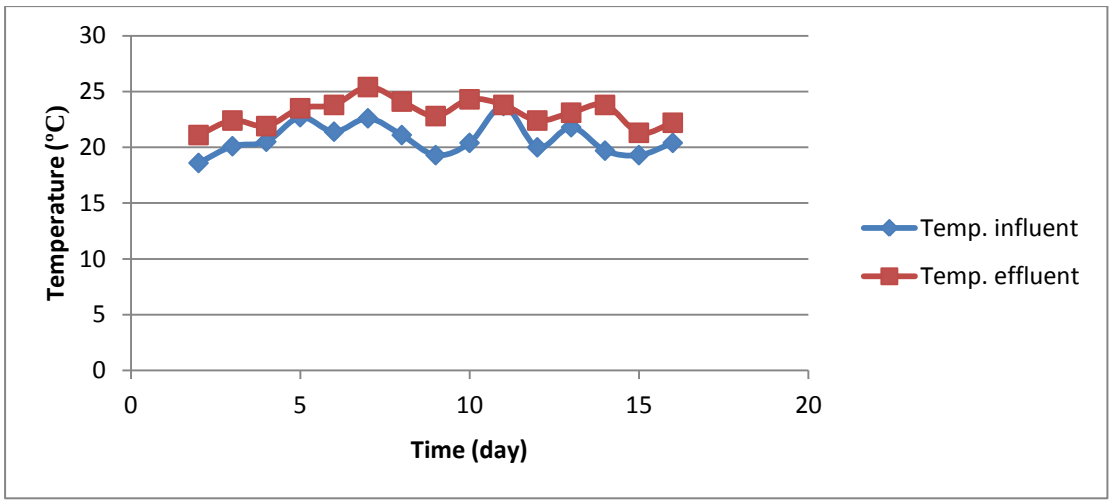

Figure 4.16 Temperature during the start up period of plug-flow reactor

4.2.1.2 pH

pH values can be significantly used as an indicator for anaerobic reactor's stability. Methanogens prefer nearly neutral pH in the range of 6.5 to 8.2 (Speece, 1996). Results from this current study showed that the pH values during were within the optimum ranges; 7.0-7.9, for the effluent samples (Figure 4.17).

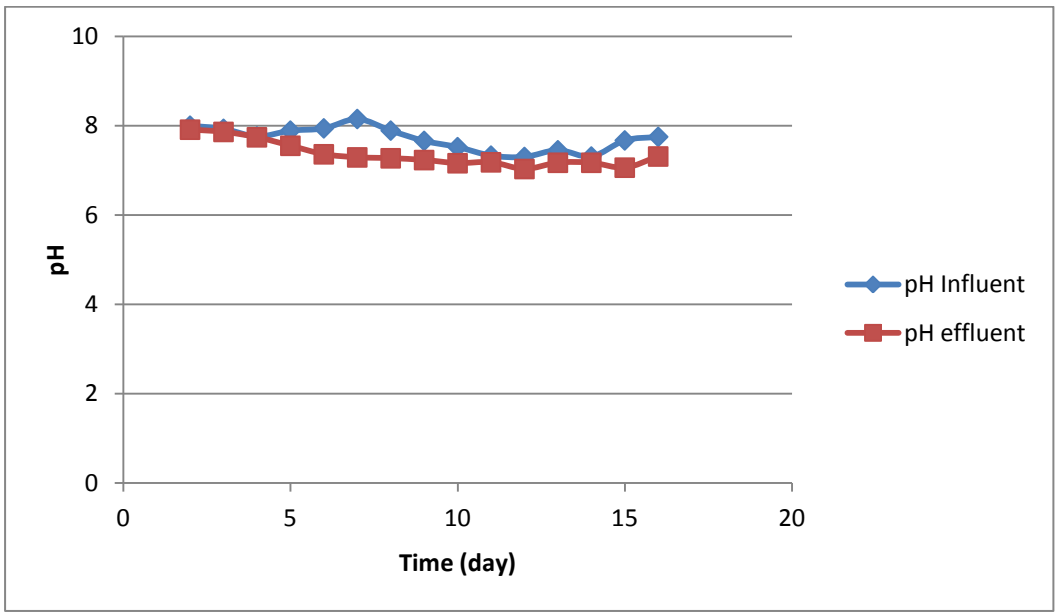

Figure 4.17 pH during the start up period of plug-flow reactor

4.2.1.3 Alkalinity and Volatile Fatty Acid (VFA)

The average alkalinity concentrations of samples (Figure 4.18) observed in this study were in the average of 150±18.2, 167±21.5 and 166±21.6 mg/l for influent, 6th port and effluent samples, respectively.

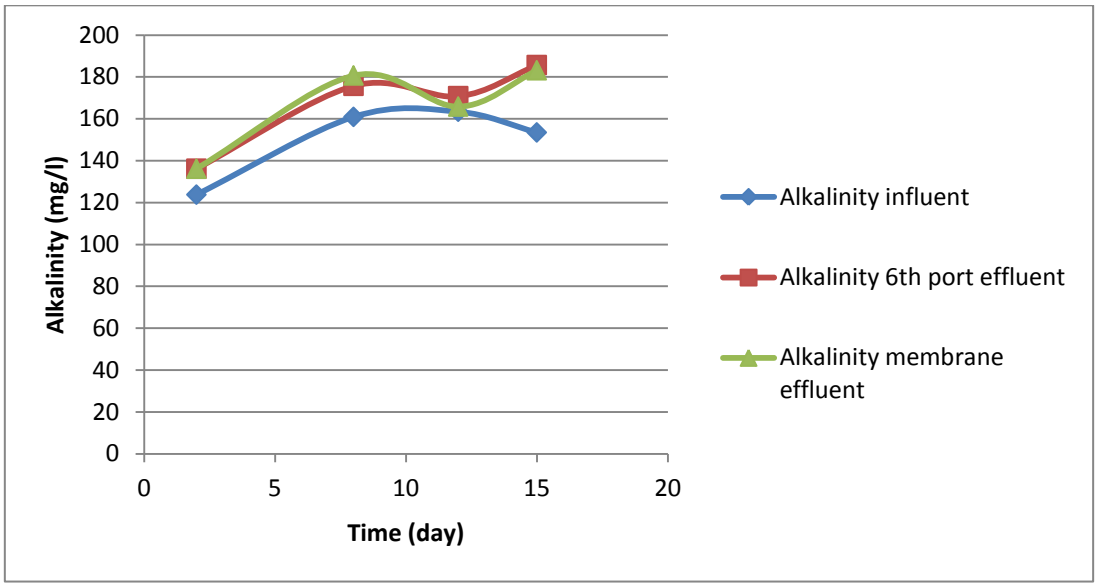

Figure 4.18 Alkalinity during the start up period of plug-flow reactor

The VFA is a considerable factor for the stability of acidogens and methanogens population. Furthermore, accumulation of VFA affects the performance of methanogens in generating methane. The VFA concentration of the influent was in the average of 22±4.1mg/l, while those of the 6th port and effluent samples were in the average of 28±5.7 and 27±7.0 mg/l, respectively (Figure 4.19).

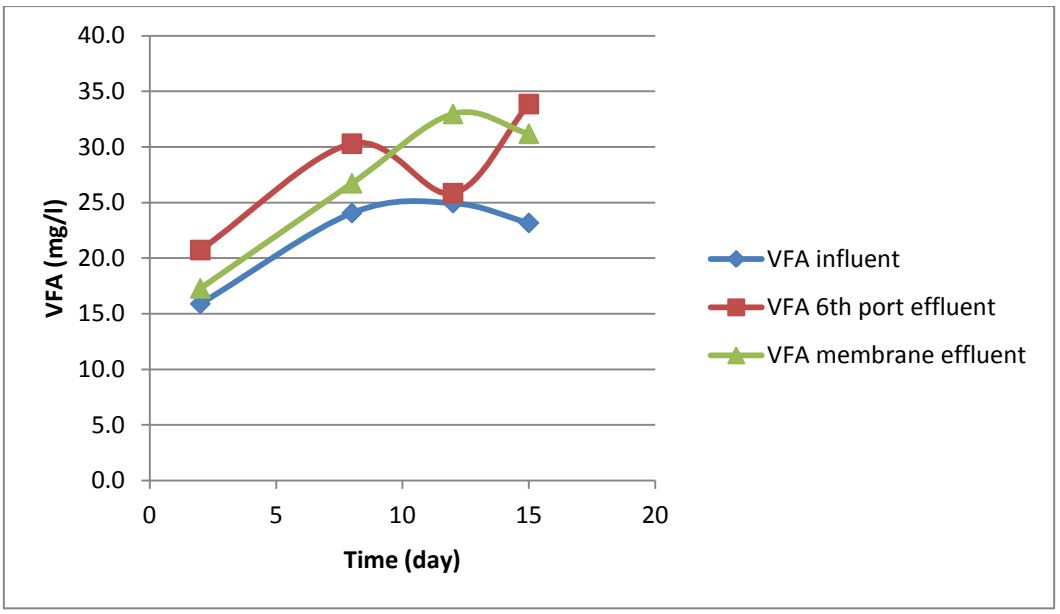

Figure 4.19 VFA during the start up period of plug-flow reactor

The ratios of VFA to alkalinity in the effluent were 0.12 to 0.22, less than 0.4 the suitable ratio of VFA to alkalinity for the anaerobic process activity (Speece, 1996). Furthermore, the alkalinity variation and VFA accumulation were not discovered during the start up period, showing the stability of anaerobic process.

4.2.1.4 Suspended Solid (SS) and Volatile Suspended Solid (VSS)

Figure 4.20 and 4.21 show SS and VSS concentration during the start up period of plug-flow reactor. The influent SS and VSS average concentrations during the start up period were 140±24.9 mg/l and 85±11.7 mg/l, respectively. SS and VSS were undetectable in effluent samples because the samples were filtered through the 0.4 µm of PVDF membrane.

SS and VSS concentrations in samples collected from the 6th port were found to be increased during steady-state. This showed that microorganisms could normally grow inside the reactor and suggested that these were no inhibiting compounds in the domestic wastewater utilised.

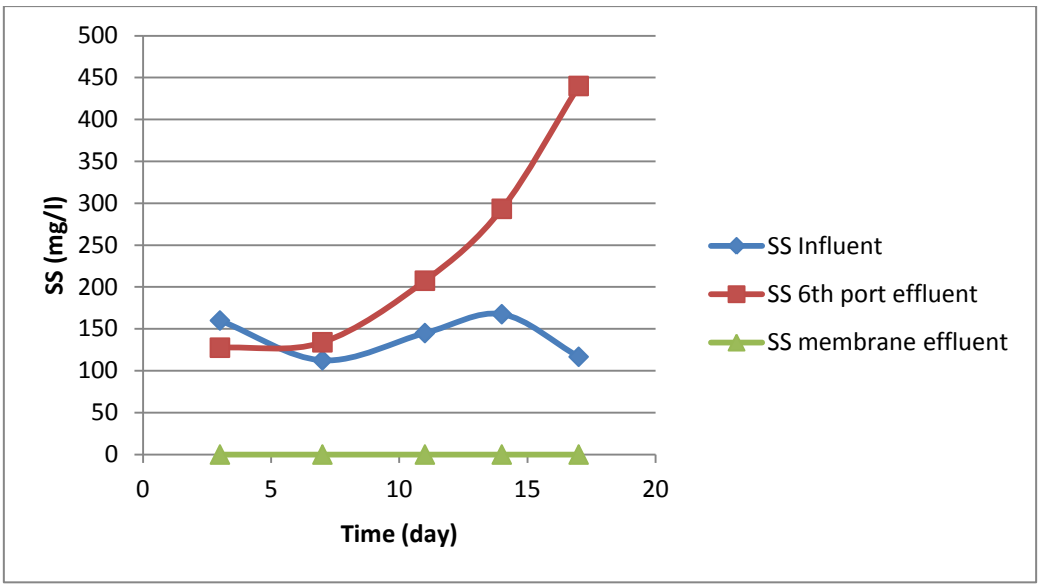

Figure 4.20 SS during the start up period of plug-flow reactor

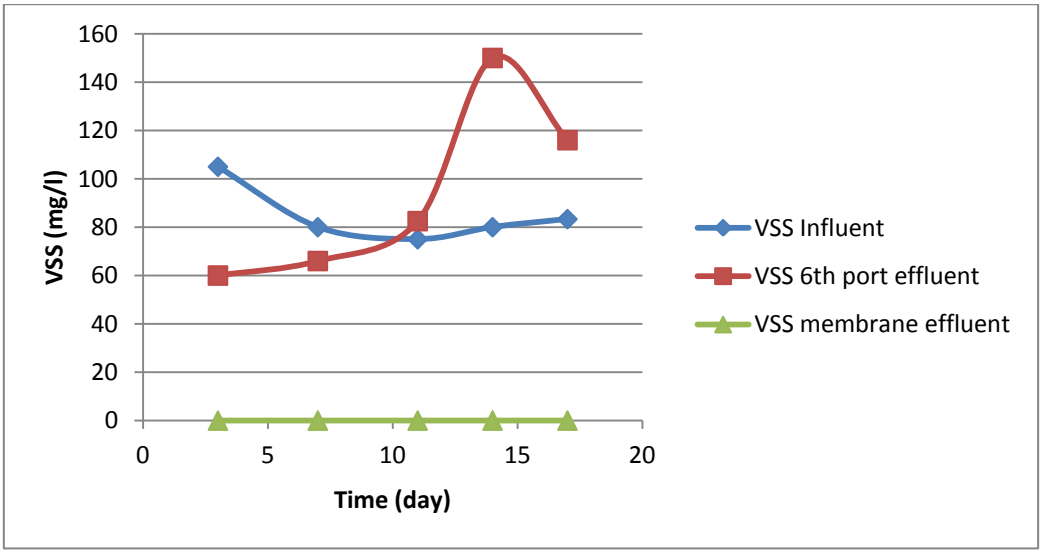

Figure 4.21 VSS during the start up period of plug-flow reactor

4.2.1.5 COD

The removal of organic substances by anaerobic process in the plug-flow membrane bioreactor can be determined using the COD concentration (Figure 4.22)

and removal efficiency (Figure 4.23). The influent COD concentration was in the range of 226-247 mg/l. The average influent and effluent COD concentrations at steady state were 236±9.4 and 51±8.6 mg/l, respectively. During this period, COD removal efficiency was 79±3.6 %.

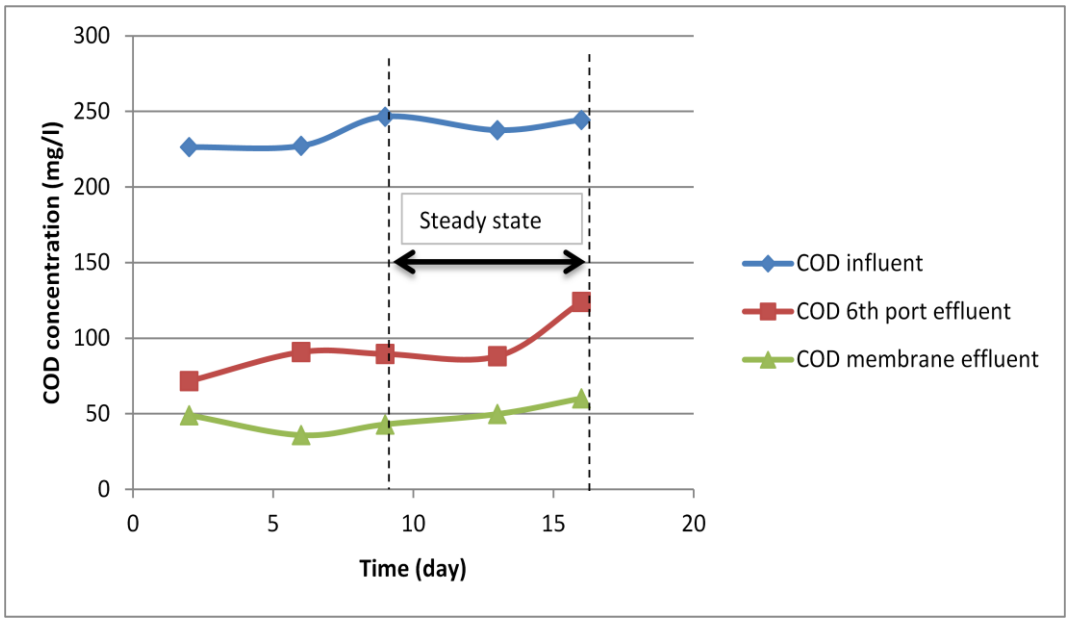

Figure 4.22 COD during the start up period of plug-flow reactor

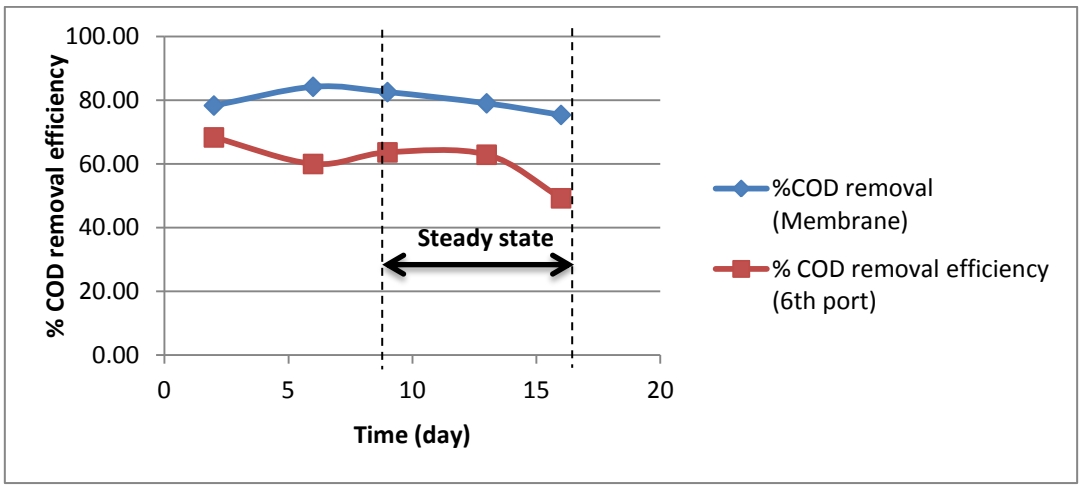

Figure 4.23 COD removal efficiency during the start up period of plug-flow reactor

Slight variation of influent COD was found because real wastewater was used. The influent COD concentration measured in this study was similar to the normal

COD concentration in the low strength domestic wastewater reported in Metcalf&Eddy (2004).

4.2.2 Reactor performance after FA and phenol addition of plug-flow reactor

4.2.2.1 Temperature

The temperatures for the whole experimental period (Figure 4.24) somewhat fluctuated in the range of 18 – 30℃. The temperatures of some effluent samples were slightly increased due to variation in ambient air temperature (21-32℃) during the sampling times. However, the operating temperatures of this study were still within the appropriate range for anaerobic degradation (20-35℃).

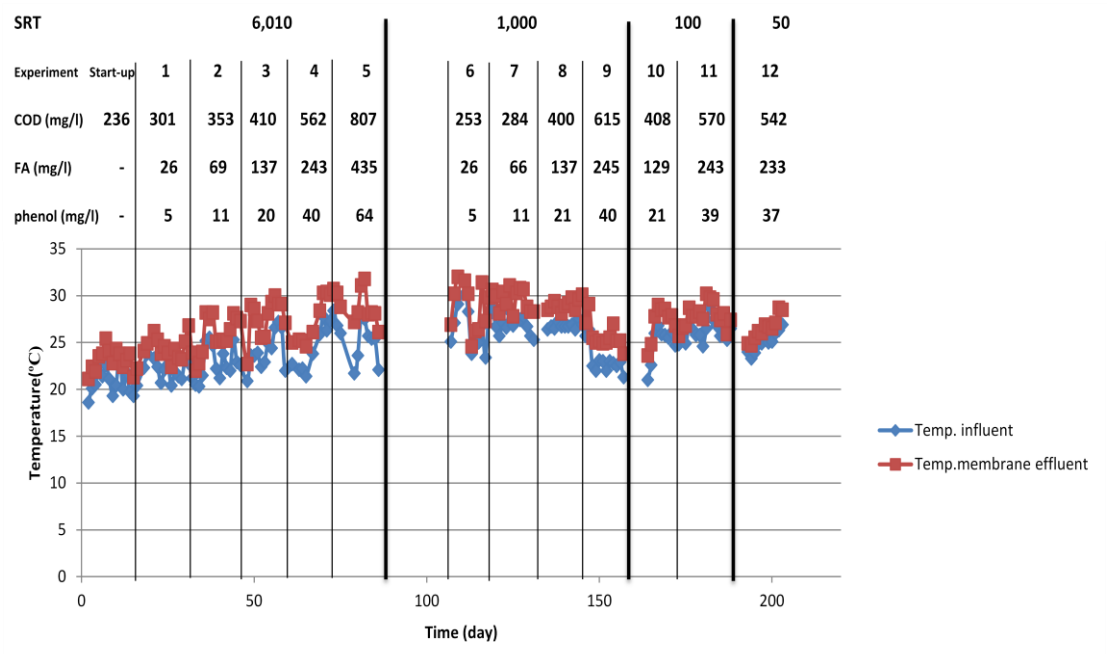

Figure 4.24 Temperature during the whole experimental period of plug-flow reactor

4.2.2.2 pH ,Alkalinity and VFA

Results in Figure 4.25, 4.26 and 4.27 show pH, alkalinity and VFA during the whole experimental period of plug-flow reactor**.**

At the SRT of 6,010 d, pH in the influent samples was decreased when ratio of embalming fluid to domestic wastewater was stepwise increased (Figure 4.25). The pH of influent samples was in the range 6.7-8.2 in Experiment 1 to 4. The pH in the influent samples was obviously dropped in the range of 5.3-6.5 in Experiment 5, corresponding to the decrease of alkalinity and increase of VFA in the influent samples. The alkalinities of influent samples were in the range of 74-113 mg/l in Experiment 5 (Figure 4.26). Additionally, the VFAs of influent and effluent samples were suddenly increased to the range of 61-93 and 44-87 mg/l, respectively (Figure 4.27). It was possible that alkalinity contained in the domestic wastewater was not enough at this FA and phenol concentration. This assumption was supported by the lower alkalinity concentrations in the effluent in Experiment 5 compared to those in the previous experiments.

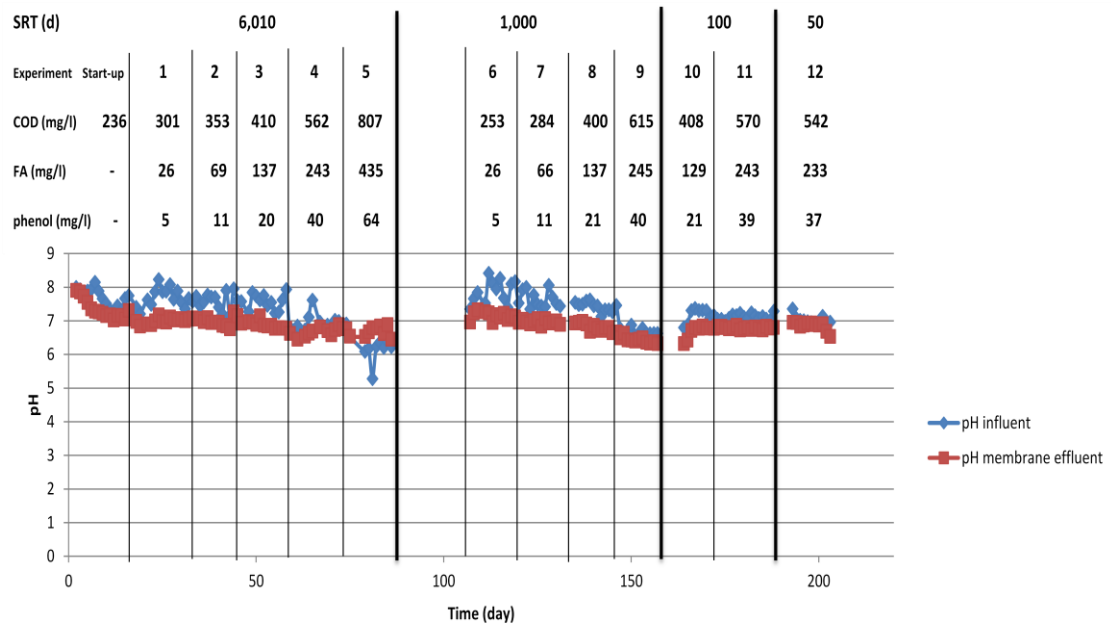

Figure 4.25 pH during the whole experimental period of plug-flow reactor

In Experiment 6 to 12, pH of the influent samples was also decreased (the range was 6.6-7.4) when ratio of embalming fluid to domestic wastewater was stepwise increased. The alkalinities and VFAs of influent samples were in the range of 136 -210 mg/l and 48-89 mg/l, respectively.

Speece (1995) explained that the plug-flow reactor will have VFA build-up in the inlet region because the VFA is produced faster than it can be consumed by the methanogens. For high COD wastewaters, the bicarbonate alkalinity required to temporarily neutralize the VFA in the inlet region can be extensive. Subsequently the VFA will be converted to CH_4 and the VFA alkalinity will be generated to bicarbonate alkalinity. Plug-flow reactor configurations increase the reverse alkalinity requirement to maintain an acceptable pH in the inlet zone. These reasons could be used to explain increase of the 6^{th} port alkalinities and effluent samples compared to that of the influent samples. Average pH in the effluent samples of the whole experiments was 6.9±0.3. Results from this study showed that the pH values at the latter part of the reactor were in the optimum ranges for methanogens, the microorganisms responsible in converting VFAs to CH_4 functioning at this part of the plug-flow reactor (6.5-8.2).

The alkalinities for the 6^{th} port of some samples were slightly higher than that of the effluent. This could be attributed to the fact that the flow regime of the membrane installing part was closer to the CSTR than plug-flow owing to the membrane scouring gas. Some amounts of alkalinity were required for both VFA and H_2CO_3 neutralisation. Unlike plug-flow reactor, alkalinity build was not occurred in CSTR resulting in alkalinity concentration in the effluent being slightly reduced.

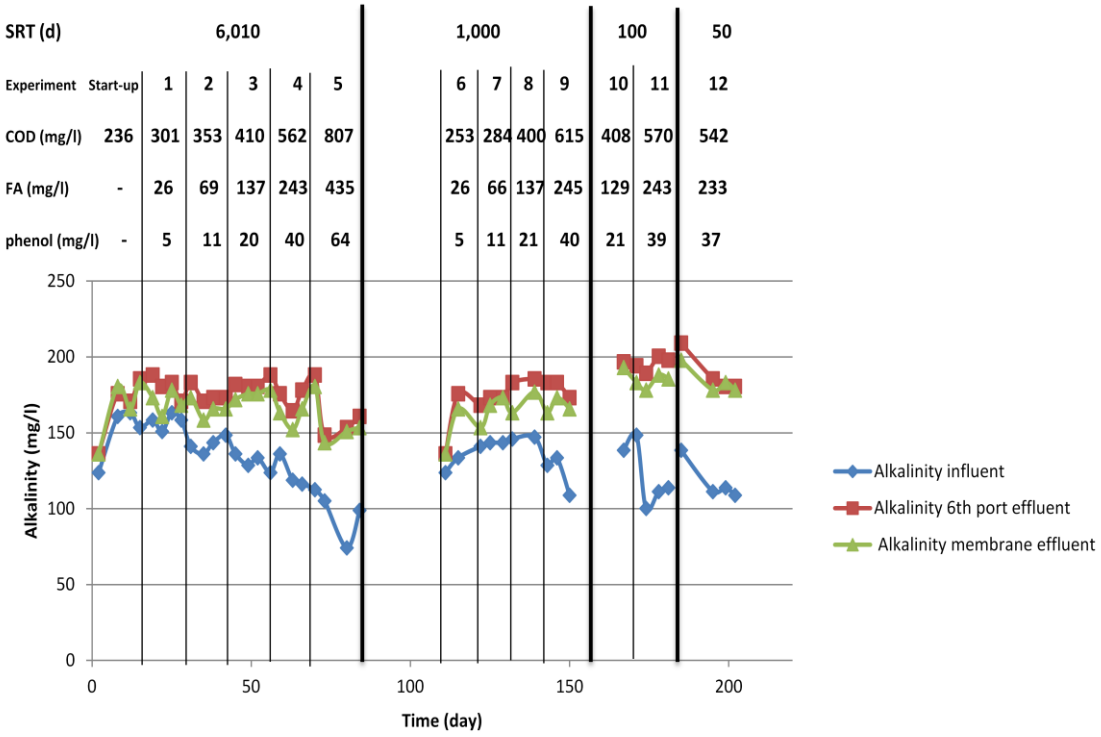

Figure 4.26 Alkalinity during the whole experimental period of plug-flow reactor

Unbalanced metabolism can occur at lower SRT when the acidogens produce volatile acid faster than the methanogen convert them to methane (Speece, 1996). This occurrence was supported by the fact that yield of acid forming bacteria is higher than yield of methanogen (Table4.1)

VFA accumulation or signs of deterioration of balance between acidogenic bacteria and methanogen could be seen when the SRT was reduce from 1,000 to 100d. The same trend could also be observed when SRT decreased from 100 to 50 d, when VFA of effluent was found be increased sharply from the beginning (Figure 4.27).

Table 4.1 Values of yield for substrates utilized in anaerobic process (Speece, 1996)

Substrate	Process	Yield (gVSS/gCOD)
Carbohydrate	Acidogenesis	0.14-0.17
Long-chain fatty acids	Anaerobic oxidation	0.04-0.11
Short-chain fatty acids	Anaerobic oxidation	0.025-0.047
Acetate	Aceticlastic methanogenesis	0.01-0.054
Hydrogen/carbon dioxide	Methanogenesis	0.017-0.045

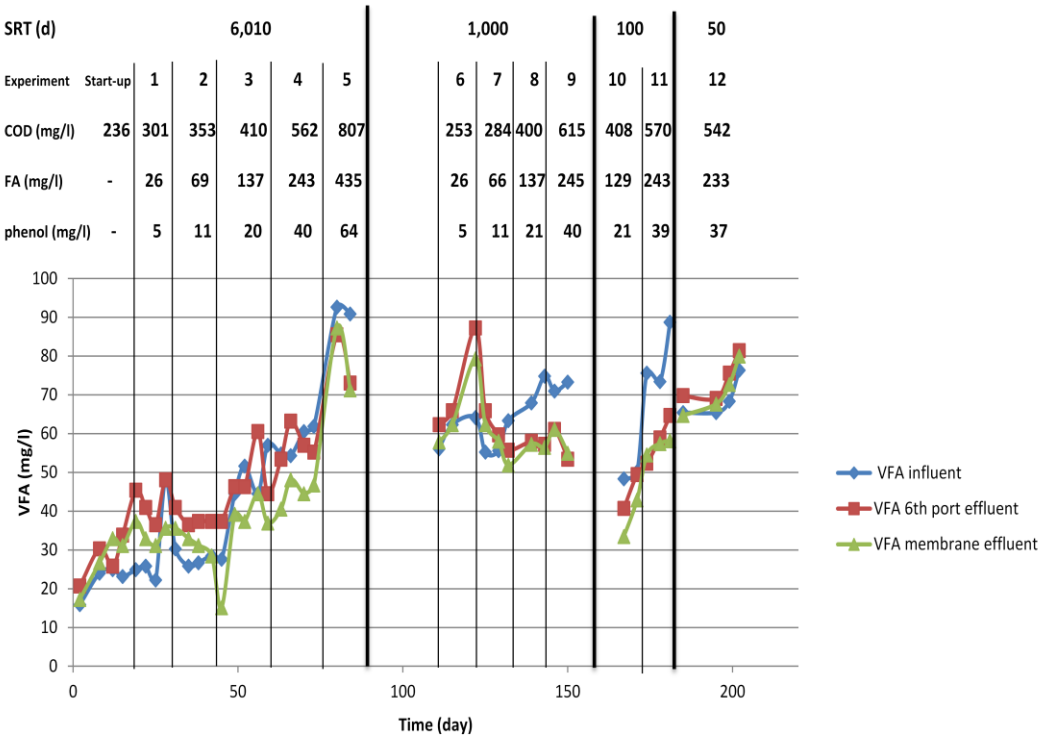

Figure 4.27 VFA during the whole experimental period of plug-flow reactor

4.2.2.4 Suspended solid (SS) and Volatile suspended solid (VSS)

The SS and VSS concentrations throughout the experimental period are shown in Figure 4.28 and 4.29.

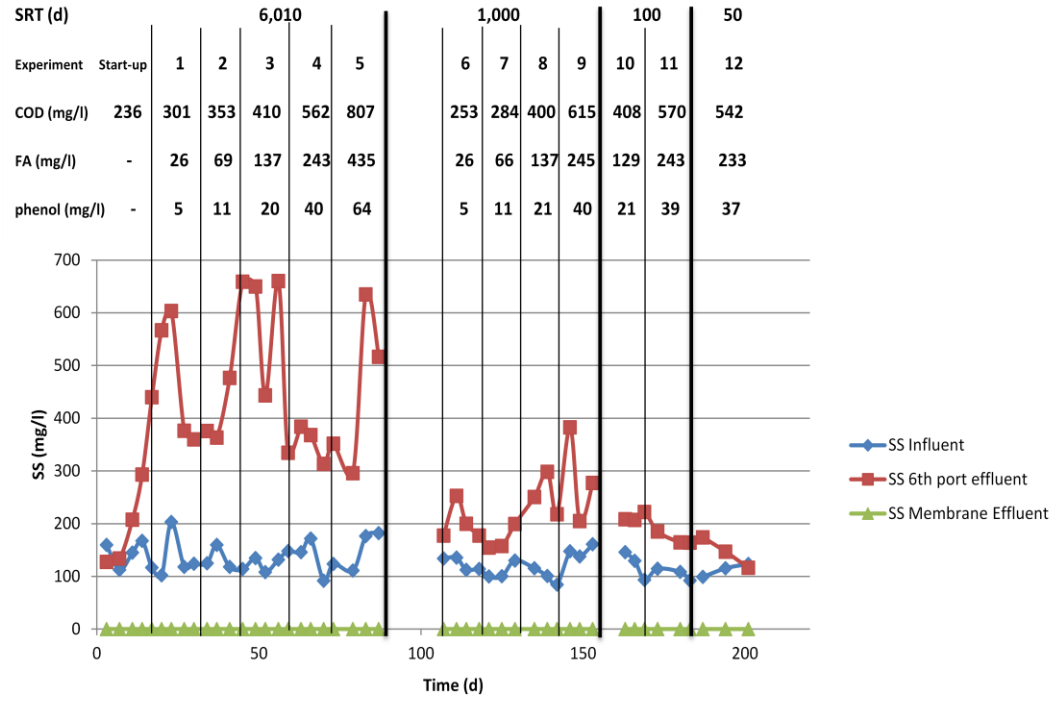

Figure 4.28 SS during the whole experimental period of plug-flow reactor

SS and VSS concentrations of influent samples during the whole experimental period were greatly fluctuated in the range of 84-203 and 33-62 mg/l, respectively. Variation of wastewater from treatment plant was likely to be the reason of this finding.

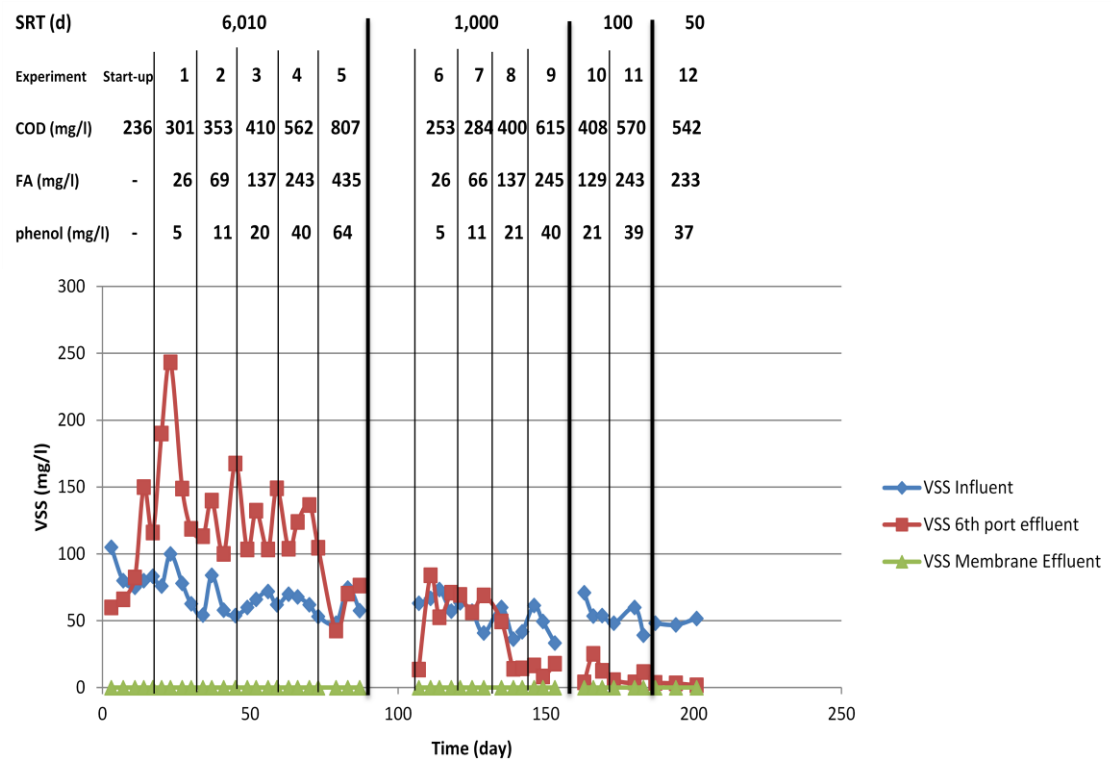

Figure 4.29 VSS during the whole experimental period of plug-flow reactor

For the plug-flow reactor, the microorganism responsible in suspended growth process is maintained in liquid suspension. Generally, microbial suspension is referred to as the mixed liquor suspended solid (MLSS) or mixed liquor volatile suspended solid (MLVSS). VSS is commonly used to follow biomass growth in biological wastewater treatment system. Moreover, the VSS measurement is used as appearance indicator of biomass production and also provides a useful measurement of reactor solids in general (Metcalf&Eddy, 2004). Therefore, suspended solid (SS) and volatile suspended solid (VSS) collected from 6th port referred to microorganism concentrations at the end port of the reactor.

SS and VSS of 6th port decreased when the SRTs were decreased. For the SRT of 6,010 d, the range of SS and VSS of 6th port were 127-660 mg/l and 42-243 mg/l, respectively. The SS and VSS of port 6 at the SRT of 1,000 d were drastically decreased to the range of 154-383 mg/l and 8.4-84 mg/l, respectively. In experiment 10 to 12, the range of SS and VSS were of 116-223 mg/l and 1.8-25 mg/l,

respectively. These results indicated that the microbial populations inside the plug-flow reactor were decreased by the decrease of SRT.

Table 4.2 shows SS and VSS collected from the middle of reaction part of plug-flow reactor (the 3rd port). The average SS and VSS was decreased when SRTs were decreased. However, it was later found that the acclimatisation was superior to the size of microbial population in anaerobic degradation to remove toxic substances. This finding is explained in the next topics. Nevertheless, values of SS and VSS in Table 4.2 show that most of the suspended solids inside plug flow reactor were in the forms of fixed solids. This result did not reasonably conform with ratio of VSS to SS of the seed which was quite high. High amounts of fixed solids found could be the result of samples being collected from the port located at the bottom of the reactor. As solids tended to accumulate at the reactor bottom, ratio of fixed solids could be higher for the samples at the lower layer where samples were taken.

Table 4.2 The average SS and VSS in each SRT of plug-flow reactor

SRT (d)	SS (mg/l)	VSS (mg/l)
6,010	16,252	3,978
1,000	15,258	3,552
100	10,094	2,271
50	6,157	1,730

Equation 4.2 shows the mass concentration of microorganisms (X) in the reactor. When SRT decreased, mass concentration of microorganisms decreased. Therefore, the results of SS and VSS in Figure 4.28 and 4.29 were consistent with Equation 4.2, including SS and VSS collected in Table 4.2

$$X = Y\Theta_S (S_0-S)/ \Theta_H (1+k_d\Theta_S) \qquad (Eq\ 4.2)$$

Where; S_0= substrate concentration in influent, S= substrate concentration in influent Θ_S = sludge retention time, Θ_H = hydraulic retention time, k_d = decay coefficient, Y = maximum yield coefficient and X = microorganism concentration

4.2.2.5 COD

The COD concentration and removal efficiency from every conducted experiment are shown in Figure 4.30 and 4.32 present COD concentrations and removal efficiency during the experimental period.

Effect of SRT on the plug-flow reactor was firstly studied at the SRT of 6,010 d. When embalming fluid was spiked to domestic wastewater in Experiment 1, COD removal efficiency (83±3.0%) was not significantly affected (Figure 4.32). When FA and phenol concentrations were increased in Experiment 2 and 3, 87±2.8% and 88±1.3% of COD removal efficiencies were observed. However, the COD removal efficiencies of these three experiments were not statistically different (P>0.05). Nevertheless, COD removal efficiency was dropped to 81±3.9% when FA and phenol concentrations were 243±22.3 and 40±2.4 mg/l (Figure 4.30), respectively in Experiment 4. At the ratio of embalming fluid to wastewater ratio of 0.013:1 in Experiment 5, COD removal efficiencies were sharply reduced to 72±3.4 %. It was possible that the inhibition effects of microbial activity when feeding with higher concentration of the FA and phenol was the cause of this reduction.

When the SRT of plug-flow reactor was decreased to 1,000 d COD removal efficiencies in Experiment 6 and 7 were 82±4.7% and 83±3.3%, respectively. When FA and phenol concentrations were increased in Experiment 8 and 9, the COD removal efficiencies was slightly increased to 88±1.3% and 86±2.8%, respectively. The COD removal efficiencies achieved from both ratios of embalming fluid to domestic wastewater for Experiment 8 and 9 were not found to be significantly different (P>0.05).

At SRT of 100 d, embalming fluid was spiked to domestic wastewater in Experiment 10 and 11. The COD removal efficiencies were 86±3.6% and 83±1.6 %, respectively.

The COD removal efficiencies for both Experiment 10 and 11 were not found to be significantly different (P>0.05). The last experiment was operated at SRT of 50 d, with only spiked embalming fluid to domestic wastewater at the ratio of 0.008: 1. The COD removal efficiency was slightly decreased to 80±1.5%.

In Experiment 6 to 12, high COD removal efficiency (about ≥ 80%) could be achieved, regardless of the SRT values. These could be the result of the acclimatisation of microbial activity.

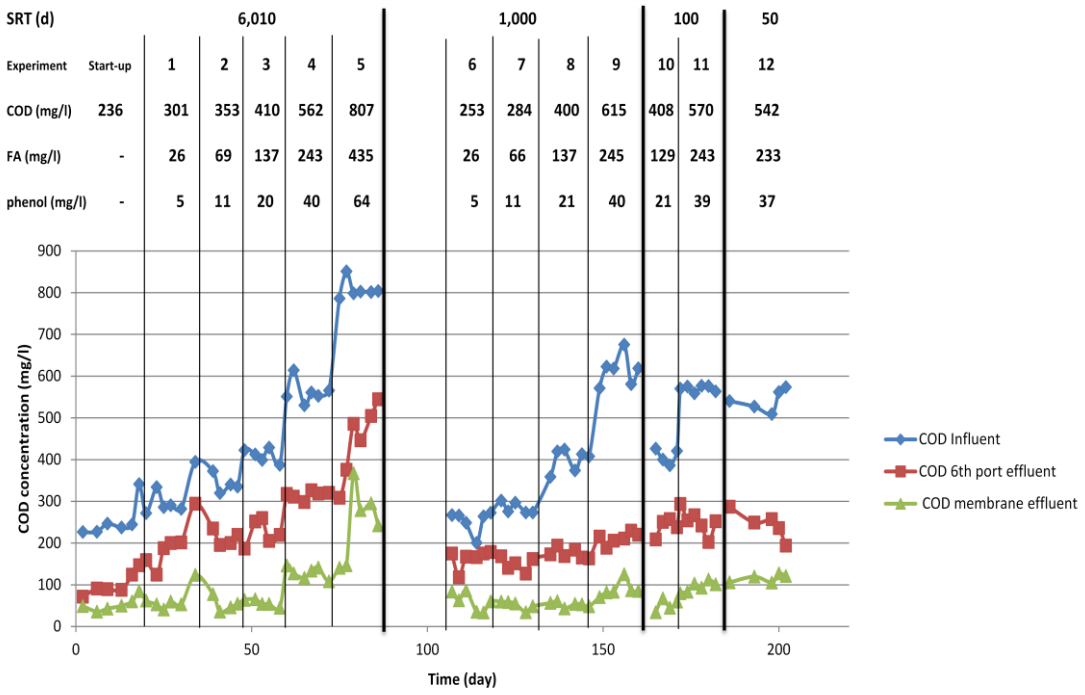

Figure 4.30 COD concentration during the whole experimental period of plug-flow reactor

Figure 4.30 obviously shows that significant amounts of COD were removed in the membrane installed part of the reactor.

There were two possible reasons that the COD removal efficiencies of 6th port effluent were obviously lower than the COD removal efficiencies of membrane effluent (Figure 4.32).

Firstly, a glass-fiber filter (Whatman GF/C) with a normal pore size of 1.2 µm was used for suspended solid separation. The size of bacteria generally found is in the range of about 0.2 to 10 µm (Figure 4.31). From this range, when compared to the pore of glass-fiber filter used to remove suspended solid, it means that some amount of bacteria could get through the of glass fiber filter, leading to high concentration of COD being measured in samples from the 6th port.

Additionally, in AnMBRs, diverse size of microorganisms could be retained in the reactor because pore size of the membrane used in this current study was as small as 0.4 µm. Therefore, some small-size microorganisms could be collected with the sample from 6th port, and subsequently got pass the GF/C used for sample filtration.

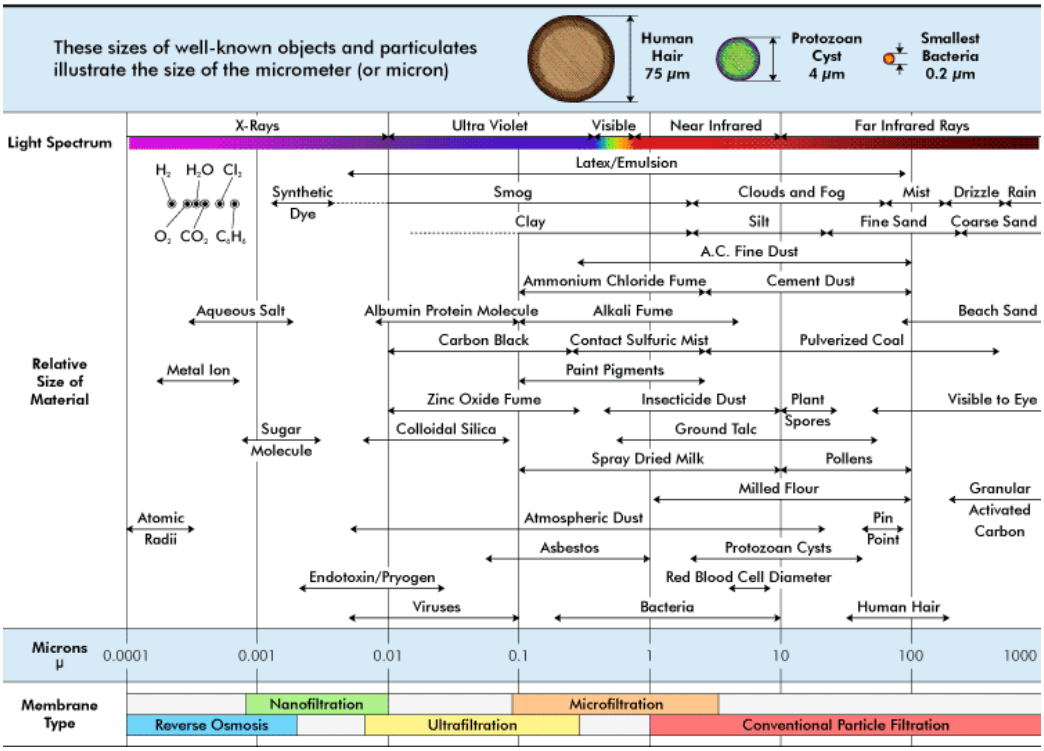

Figure 4.31 The particle size of wastewater composition

(Source: http://www.fmt-houston.com/technical_data.htm**)**

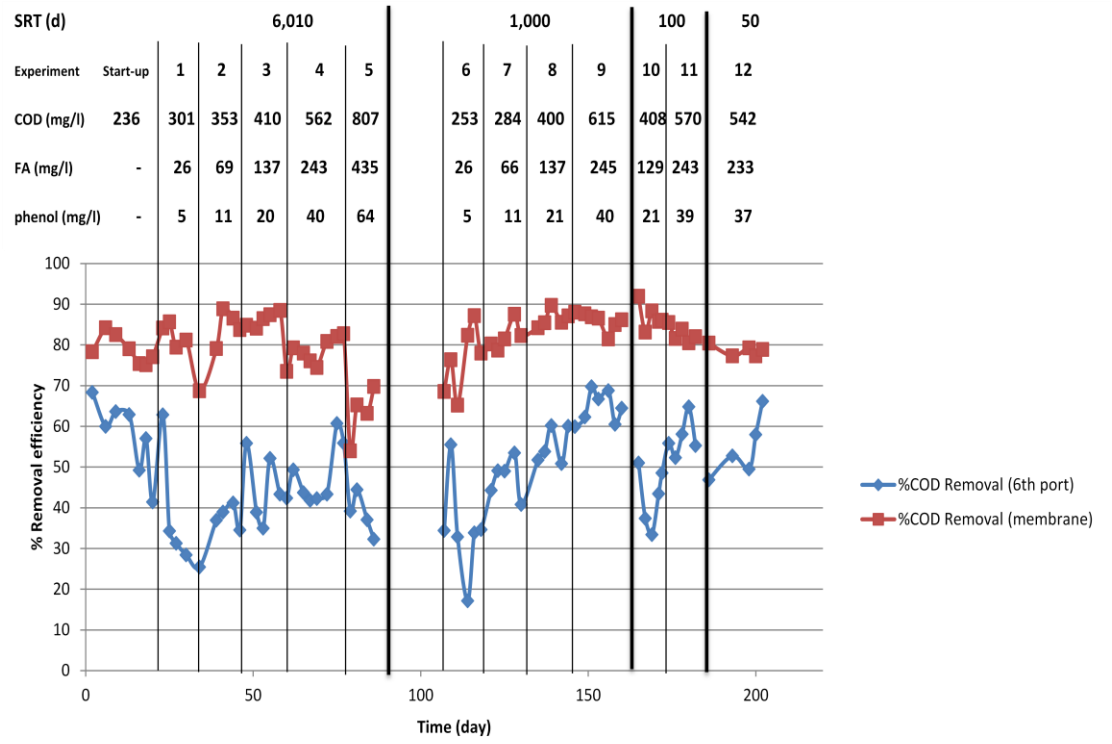

Figure 4.32 COD removal efficiency during the whole experimental period of plug-flow reactor

4.2.2.6 FA

The FA concentration and removal efficiency from every conducted experiment are shown in Figure 4.33 and 4.34 present FA concentrations and removal efficiency during the experimental period.

The reactor presented excellent performance for formaldehyde removal at all experiments when plug flow anaerobic membrane bioreactor was utilised. The average effluent formaldehyde concentration was very low (lower than 2 mg/l). FA removal efficiencies higher than 95% were achieved throughout the study period. Lag phases were observed after embalming fluid addition in Experiment 1 and 6 with the initial ratio of embalming fluid to domestic wastewater of 0.0007:1 (Figure 4.34). After these lag phase, high FA removal efficiencies were achieved in both SRTs (6,010 and 1,000 d).

Very low FA concentrations were found in the effluent samples during the steady state of Experimental 10 to 12 (SRT of 100 and 50 d), indicating complete FA removal from the wastewater. Almost complete FA removal was found in all these experiments without the lag phase that it especially occurred in Experiment 1 and 6. These results indicated that anaerobic degradation of FA in anaerobic membrane bioreactor was efficient for the studied SRTs and range of FA concentration.

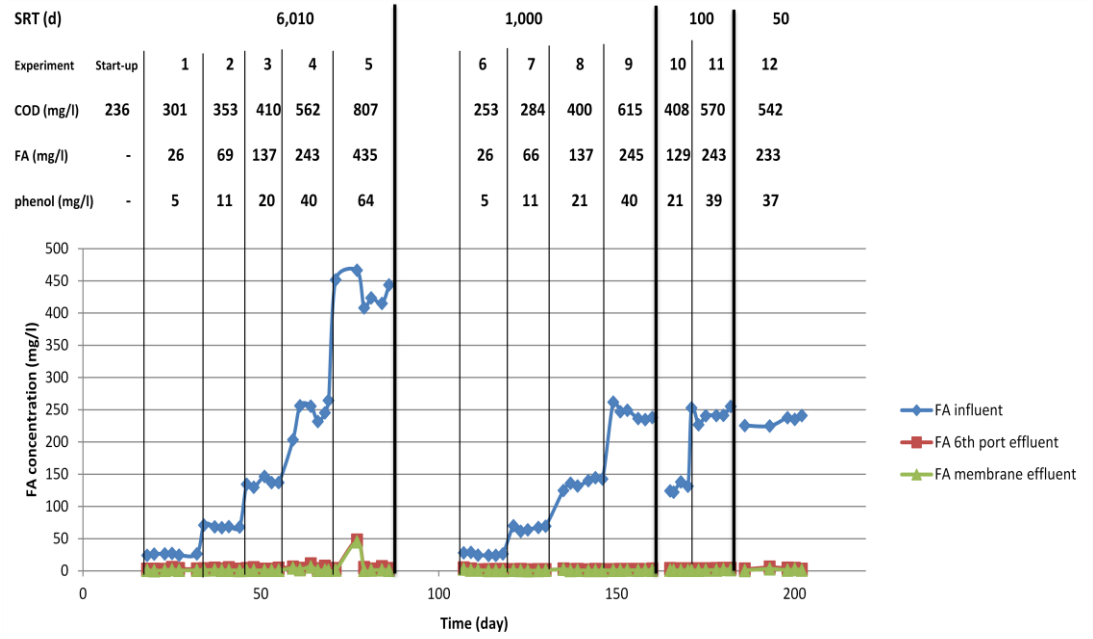

Figure 4.33 FA concentrations during the whole experimental period of plug-flow reactor

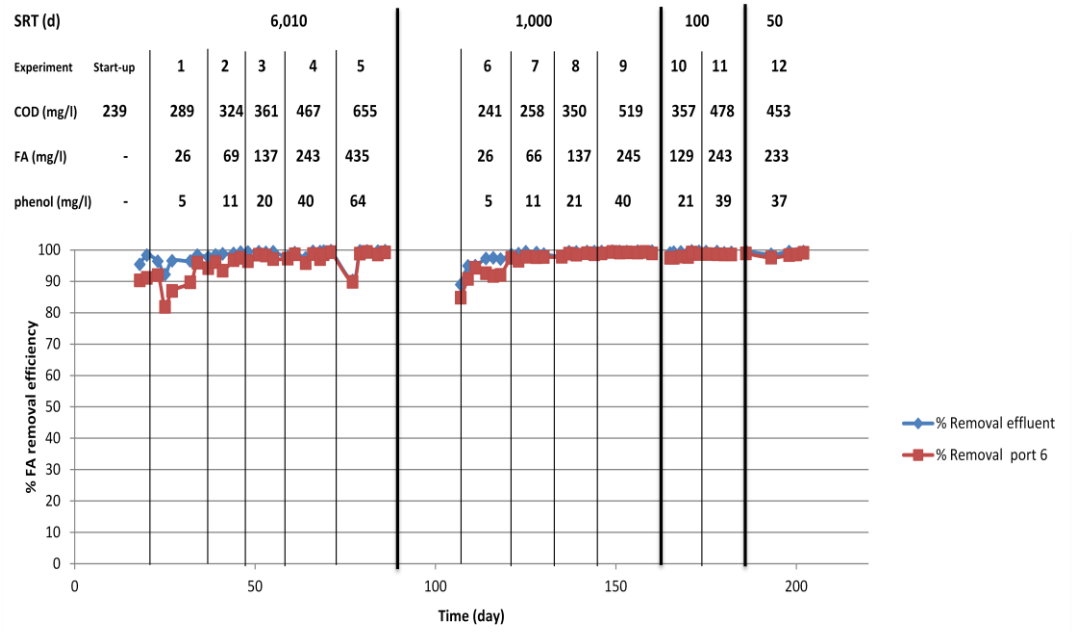

Figure 4.34 FA removal efficiency during the whole experimental period of plug-flow reactor

FA degradation in this current study was assumed to occur mainly by biological activity even though the purging effect by N_2 gas used for membrane scouring could also bring about the FA volatilisation. This volatilisation of FA was supposed to be insignificant, as the purge gas was recirculated within the system. This assumption was supported by Wanawan and Patiroop (2010), who reported that FA was not found to be substantially lost from the vigorously stirred open tank during the period of 8 h. Moreover, Omil et al. (1999) reported that only 10-11% of abiotic formaldehyde removal occurred in the anaerobic bioreactor and small percentage of abiotic FA removal particularly via absorption, hence removal of FA by adsorption and volatilisation in the bioreactor was considered negligible. These tentatively ensured that volatilisation was also not the main removal pathway of FA in this current study.

4.2.2.7 Phenol

The phenol concentration and removal efficiency from every conducted experiment are shown Figure 4.35 and 4.36 present phenol concentrations and removal efficiency during the experimental period.

When initial phenol concentration (5.0±0.1 mg/l) in Experiment 1 was fed into the reactor, high removal efficiency (75±0.3%) was found. Phenol removal efficiencies were slightly increased to 81±1.4% and 84±3.8% in Experiment 2 and 3. The phenol removal efficiencies achieved from both Experiment 2 and 3, however, were not found to be significantly different ($P>0.05$). However, phenol removal efficiency was reduced to only 62±5.4% in Experiment 4 when phenol concentration was increased to 40±2.4 mg/l. Increase of embalming fluid to wastewater ratio to 0.013:1 in Experiment 5, corresponding to phenol concentration of 64±2.8 mg/l, resulted in phenol removal efficiencies being sharply dropped to 41±3.8 %.

Deterioration of phenol removal found in this current study when phenol concentration was as low as 40±2.4 mg/l and 64±2.8 mg/l in Experiment 4 and 5, respectively, might be caused by the presence of FA. Eiroa, et al. (2005) found that at the fixed initial concentration of 260 mgFA/l, the maximum phenol concentration that could be efficiently degraded was 180 mg/l. In addition, previous studies also reported inhibition of phenol degradation in the presence of FA (Wanawan and Patiroop, 2010 and Eiroa, et al., 2005).

Surprisingly, when SRT was reduced to 1,000 d, phenol removal efficiency was found to increase to 88±0.4 % in Experiment 6. Then, phenol concentration was increased to 11±0.1 mg/l, phenol removal efficiencies were increased to 94±2.8%. However, phenol removal efficiencies were dropped to 81±1.4% and 76± 1.4% in Experiment 8 and 9, respectively.

At SRT of 100 d, phenol concentration initially utilised was 21±0.4 mg/l in Experiment 10. Phenol removal efficiency was found to be increased from76±1.4% in Experiment 9 to 85±4.0% in Experiment 10. When phenol concentration was increased to 39±1.2 mg/l, phenol removal efficiencies were slightly decreased to 74±0.9% in Experiment 11. Finally, Experiment 12 was operated under SRT of 50 d. Phenol concentration was 37±1.0mg/l and phenol removal efficiency was 73± 2.0 %.

At ratio of embalming fluid and domestic wastewater of 0.008: 1, the deterioration of phenol removal was found under the SRT of 6,010 d. However, phenol removal efficiencies at this ratio were increased at the next experiments of shorter SRTs (SRTs

= 1,000, 100 and 50 d in Experiment 9 to 12). Phenol removal efficiencies obtained from these three experiments were not found to be significantly different ($P>0.05$). These results showed that the acclimatisation was more important for phenol anaerobic degradation and was in agree with the finding of Bolanos et al (2001) who found that phenol degradation at very high concentrations could be achieved in the reactor containing adapted microorganism. Moreover, Scully et al. (2006) found that acclimation period was a significant consideration and period of between 20 and 100 d had previously been reported during treatment of phenolic wastewaters.

Wanawan and Patiroop (2010) suggested that lower phenol removal efficiency could be explained by the presence of FA in the influent which even found when the plug flow anaerobic reactor was utilised. However, phenol influent was efficiently removed at the lower SRT (1,000, 100 and 50 d, respectively) in the ratio of embalming fluid to domestic wastewater of 0.008:1 after the deterioration of phenol removal in Experiment 4. This was possible that the inhibition of phenol in the presence of FA was occurred when anaerobic microorganism responsible in phenol degradation had not acclimatised to FA existence.

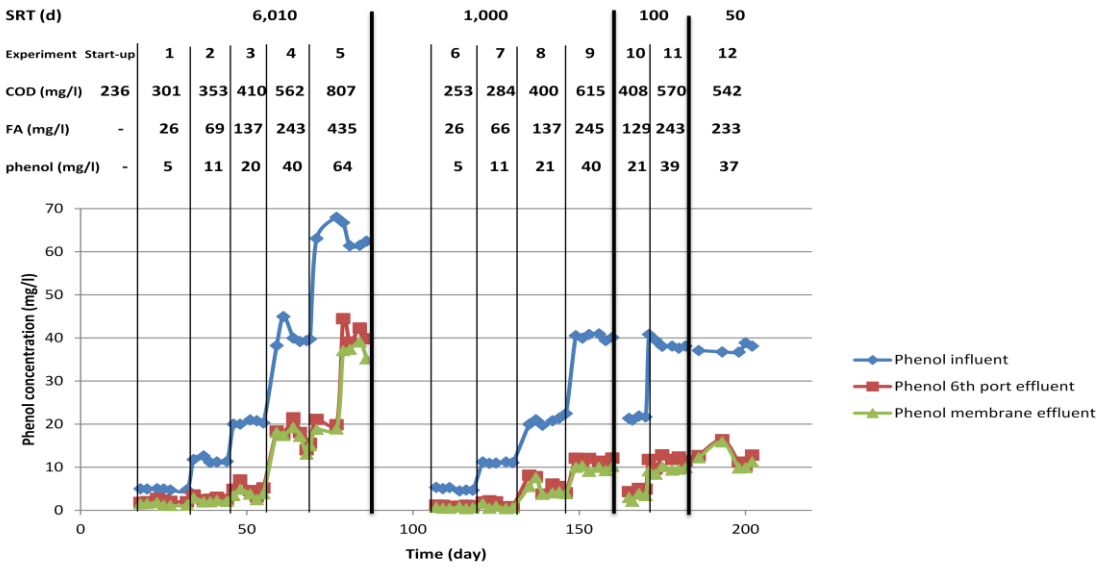

Figure 4.35 Phenol concentrations during the whole experimental period of plug-flow reactor

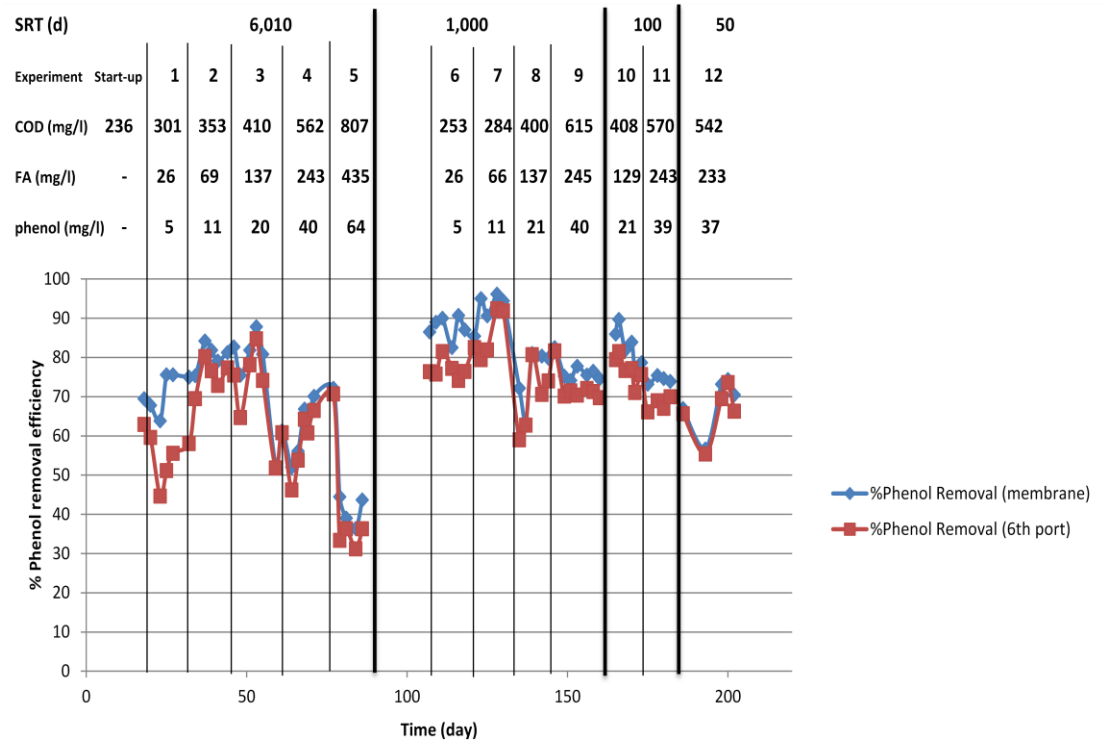

Figure4.36 Phenol removal efficiency during the whole experimental period of plug-flow reactor

From the results in Figure 4.33 and 4.35, FA and phenol concentrations were not found to be different between that from 6th port and the membrane effluent. This finding confirmed the assumption made in Topic 4.2.2.5 that high COD observed in samples collected from the 6th port was attributed by small VSS which got through the GF/C. Moreover, results of this study revealed that the utilized PVDF membrane did not help in both FA and phenol removal.

Apart from the degradation process, higher phenol removal found at shorter SRTs (Figure 4.36) could also be attributed to the absorption process. As more new cells were produced at shorter SRT compared to that at longer SRT, specific surface for absorption was more available.

4.2.2.8 Microorganism performance of plug-flow reactor

Figure 4.37 and 4.38 show the specific FA and phenol removal rate at the ratio of embalming fluid to domestic wastewater of 0.008:1, when deterioration of phenol removal was observed. When SRTs decreased, specific FA and phenol removal rate increased, in which the highest removal rates were found at the shortest studied SRT of each compound. This revealed that microorganisms inside both CSTR and plug-flow anaerobic membrane bioreactors could still efficiently function even when their amounts (measured in form of VSS) were reduced at short SRT to less than or equal to 25 mg/l. Moreover, it could be conducted from these specific removal rates that lower phenol removal efficiencies detected at shorter SRT (especially at SRT of 50 d) was the results of lesser amount of microorganisms present inside the reactor and not from the kinetic inferiority of the microorganisms.

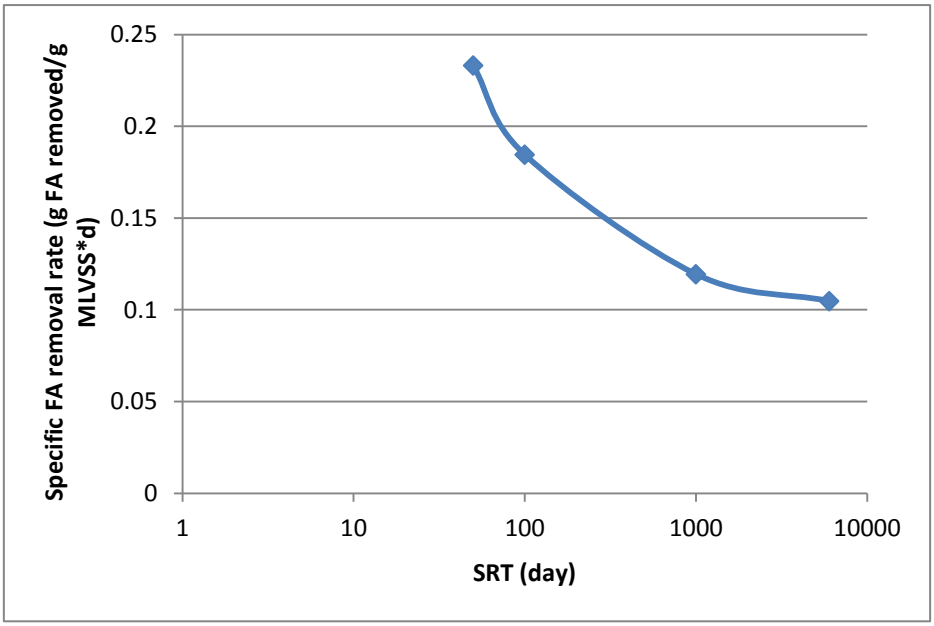

Figure 4.37 Specific FA removal rate at the ratio of embalming fluid to domestic wastewater of 0.008:1

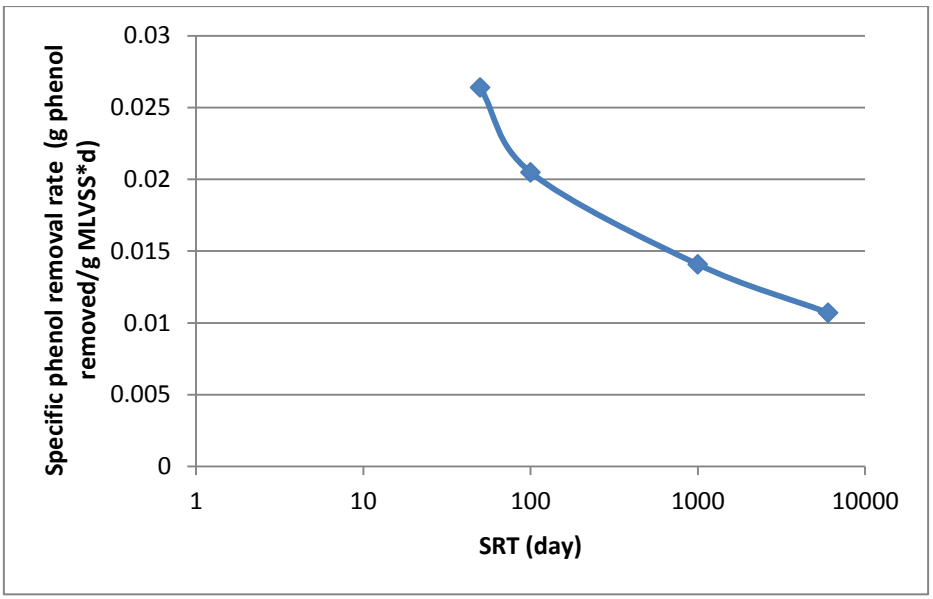

Figure4.38 Specific phenol removal rate at the ratio of embalming fluid to domestic wastewater of 0.008:1

4.3 Comparison of the plug-flow and CSTR anaerobic membrane reactor performance

At the ratio of 0.002:1, the phenol removal efficiencies of the plug flow reactor (Experiment 2) and CSTR (Experiment 1.2) were 75±0.3 %and 66 ±2.3 %, respectively. Additionally, COD removal efficiency of the plug flow and CSTR reactor at this ratio were 87±2.8% and 70±1.6%. From these results, significantly higher COD and phenol removal efficiencies were observed in plug-flow reactor compared to those in CSTR ($P \leq 0.05$).

At the ratio of 0.004:1, the phenol removal efficiencies of the plug flow reactor (Experiment 3) and CSTR (Experiment 2) were found to be 84±3.8%and 73±5.4%, respectively. Again, significantly higher phenol removal efficiencies were found in plug flow reactor compared to those in CSTR ($P \leq 0.05$). However, COD removal efficiency of the plug flow and CSTR reactor at this ratio were 88±1.3% and 83±1.6%. Even though COD removal efficiencies obtained from plug-flow and CSTR

were not statistically different (P>0.05), obviously higher average value was gained from the plug-flow reactor.

At the ratio of 0.008:1, deterioration of phenol removal was found. This might be caused by presence of FA for the plug-flow (Experiment 4) and CSTR (Experiment 3). Nevertheless, the phenol removal efficiencies of the plug flow and CSTR reactors at this ratio were 62±5.4% and 58±5.1%, respectively, which obviously showed the superiority of the plug-flow reactor to the CSTR even when microorganisms were suffered by a compound toxicity.

Grandhi et al, (2011) studied the value of dispersion number of the completely mixed flow regime of UASB and plug-flow pattern of hybrid reactor for anaerobic treatment of distillery spent wash. The value of dispersion number of plug-flow regime was obviously less than completely mixed flow regime. The plug-flow regime of hybrid reactor was more efficient than the UASB reactor having completely mixed flow regime. This revealed that the dispersion was important effect for removing substance. Correspondingly, the plug-flow reactor was more efficient than the CSTR in those ratios of embalming fluid to domestic wastewater (0.002:1, 0.004:1 and 0.008:1) in this current study.

4.4 Comparison of results obtained in this current study with those of some previous studies

Compared to results reported in the literature (Table 4.3), FA removal efficiencies were very high especially when the continuously fed plug flow reactors were utilized. On the other hand, Pereira & Zaiat (2009) observed that completely mixed reactor was less appropriate for formaldehyde degradation than the continuous immobilized-cell reactor. They suggested that in the batch reactor, the entire microbial community was subjected to primary substrates, byproducts and end products, increasing the possibility of activity inhibition. Whereas, in continuous-flow reactors especially those with flow pattern close to plug flow, specific biomass can grow along the reactor's length. Wanawan and Patiroop (2010) claimed that a group of microorganisms could be adapted to specific compounds optimizing the

degradation of primary substrates and byproducts .Nonetheless, FA was found to be successfully degraded by many types of anaerobic reactor (Table 4.3) if the biomass was allowed to acclimatise.

Table 4.3 Comparison of FA removal efficiency found in this current study and that reported in some previous studies

Type of reactor	Loading rate	Initial FA concentration (mg/l)	HRT	Efficiency (%)		References
				COD	FA	
AF	1.28 kg COD/m^3.d 1.37 kg FA/m^3.d	1373	12 h	77	99	Wanawan and Patiroop (2010)
AF	5.78 kgFA/ m^3.d	26.2–1158.6	4.8 h	92	95	Oliveira et al. (2004)
UASB	6.0 kg COD/m^3.d	50-2000	14.4h	90-95	>95	Vidal et al. (1999)
UASB	0.37 -2.96 kg COD/ m^3.d	625–5000	1.8 d.		99.5	Eiroa et al. (2006)
Fluidized bed	5.1 kg COD/m^3.d	20-1100	8-16 h		97.34	Moteleb et al. (2002)
ASBBR	0.08-2.78 kg FA/ m^3.d	36.1-1104.4	8 h	70.8	99	Pereira and Zaiat (2009)
CSTR AnMBRs		60-420	12 h	75-80	>97	This current study
PF AnMBRs		26-435	12 h	72-88	>95	This current study

AF= Anaerobic filter, UASB= Upflow Anaerobic Sludge Blanket, ASBBR= Anaerobic sequencing biofilm batch reactor, EGSB = expanded granular sludge bed and AnMBRs = Anaerobic membrane bioreact

Domestic wastewater used as co-substrate in this experiment might also have a significant role in the degradation of FA. As shown previously, Vidal et al. (1999)

showed that co-substrate is an important factor for improving yield of anaerobic degradation, higher FA concentrations were tolerated when added continuously to glucose enrichment systems rather than when slug doses were used. This also indicated that the continuous operation was more favorable for bacterial acclimation. Therefore, the domestic wastewater used as the co-substrate in this current study could possibly be contributed to high FA removal gained throughout the experimental period. On the other hand, relatively lower phenol concentrations (Table 4.4) were found to be removed under anaerobic condition compared to FA concentrations (Table 4.3)

Table 4.4 also shows that high phenol removal efficiency tended to be attained using anaerobic reactor with the plug flow regime. In this current study, the plug-flow and CSTR membrane bioreactors could maintain the sludge age as long as 65,000 d and 6,010 d, respectively. However, at this long SRT, both reactors still failed to remove phenol at higher concentration. Moreover, Wanawan and Patiroop (2010) suggested that lower phenol removal efficiency could be explained by the presence of FA in the influent which even found when the plug flow anaerobic reactor was utilised. They found that FA was efficiently removed by anaerobic filter at all studied initial concentrations (19.6-1,412.9 mg/l), while phenol was almost completely removed only when initial concentrations lower than 15.3 mg/l and 32.6 mg/l in 6h- and 12h-HRT reactors, respectively.

However, when operated under shorter SRTs, the plug-flow and CSTR anaerobic membrane bioreactor in this current study could remove both FA and phenol more efficiently than the values obtained at longer SRTs (6,010 and 65,000 d in plug-flow reactor and CSTR, respectively). These indicated that bacterial acclimation was more important for FA and phenol degradation than SRT in the ranges used in this current study.

Table 4.4 Comparison of phenol removal efficiency found in this current study and in some previous studies

Type of reactor	Loading rate	Initial phenol concentration (mg/l)	HRT	Efficiency (%)		References
				COD	Phenol	
AF	0.28 kgCOD/m^3.d 0.066 kgPhenol/m^3.d	33	12h	95	98	Wanawan and Patiroop (2010)
AF	2.03kgCOD/m^3.d	50-1200	12 h	98	99	Bolanos et al. (2001)
UASB	0.9kgCOD/m^3.d	630	40h	96	99	Fang et al. (2006)
EGSB	1.2kgPhenol/m^3.d	500		90	99	Scully et al. (2006)
Batch*	0.89 kgCOD /m^3.d	30-580			33.7-96	Eioa et al. (2005)
CSTR AnMBRs		3-120	12 h	75-80	40-80	This current study
PF AnMBRs		5-64	12 h	72-88	41-83	This current study

*FA concentration of 260 mg/l was used

CHAPTER V

CONCLUSION

Based on the obtained results from the study of effects of sludge retention time on plug-flow and CSTR anaerobic membrane bioreactors performance in removing formaldehyde and phenol, the main ingredients of embalming fluid, the following conclusions could be drawn.

1. Both the plug-flow and CSTR anaerobic membrane bioreactors could completely remove FA at all studied initial FA concentrations (25 to 435 mg/l).

2. Inhibition of phenol anaerobic degradation was observed in the presence of FA. Reduction of phenol removal was at phenol and FA concentrations of 40 and 240 mg/l, respectively in both the plug-flow and CSTR reactors.

3. The plug-flow reactor (SRT of 6,010 d) was significantly more efficient than the CSTR (SRT of 65,000 d) in removing phenol at the ratios of embalming fluid to domestic wastewater of 0.002:1 and 0.004:1, corresponding initial phenol concentration of 20 and 40 mg/l, respectively.

4. It was found that microbial acclimatization had greater effect on both CSTR and plug-flow reactor compared to the SRT in simultaneous removing phenol and FA.

5. Shorter studied STRs did not affect FA and phenol removal in the plug-flow reactor. However, VFA accumulation was occurred at SRT of 100 and 50 d, signaling the imbalance between the acid formers and methanogens inside the reactor.

6. PVDF membrane did not help in removing both FA and phenol, but some amounts of COD were removed by this membrane installed inside the reactor.

CHAPTER VI

RECOMMENDATIONS FOR FUTURE WORK

The following statements are recommended for future studies.

1. It is interesting to study the FA and phenol volatilisation from the purging effect. Although volatilisation of FA and phenol was supposed to be insignificant in some previous studies, purging effect could, to some extent, have a part in both FA and phenol removal in the vigorously purged anaerobic MBR.

2. To be able to design and construct the full-scale anaerobic membrane bioreactor for removing FA and phenol with domestic wastewater, experiments using the pilot-scale reactor will give some beneficial information.

3. It is interesting to investigate the phenol degradation pathway when initial phenol concentration could be efficiently degraded at the presence of FA.

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APPENDICES

APPENDIX A

EXPERIMENTAL DATA

Table A-1 pH and temperature data throughout the operation period of CSTR

Date	Time (day)	SRT (day)	pH		Temp (ºC)	
			Influent	Effluent	Influent	Effluent
9/11/2011	1	65,000	7.5	8.02	24.5	26.4
10/11/2011	2		7.6	8.23	23.8	24.5
11/11/2011	3		7.77	7.02	22.8	24.3
12/11/2011	4		7.74	7.4	22.3	23.6
13/11/2011	5		7.96	7.33	21.6	23.3
14/11/2011	6		7.72	7.5	22.5	23.4
15/11/2011	7		7.87	7.55	22.8	23.3
16/11/2011	8		7.88	7.56	24.3	25.1
17/11/2011	9		7.68	7.48	25.1	25.9
18/11/2011	10		7.59	7.36	25	26.3
19/11/2011	11		7.64	7.41	23.1	23.9
21/11/2011	13		7.71	7.46	24.6	25.2
22/11/2011	14		7.31	7.17	22.8	24
23/11/2011	15		7.95	7.21	24	24.8
24/11/2011	16		8.18	7.09	24.4	26.8
25/11/2011	17		8.05	7.37	23.3	24.9
26/11/2011	18		7.73	7.48	23.6	25.2
27/11/2011	19		7.95	7.51	23.6	24.8
29/11/2011	21		7.61	7.27	24.1	24.4
30/11/2011	22		7.85	7.26	22.8	23.5
1/12/2011	23		7.56	7.14	23.4	26.1
2/12/2011	24		7.36	7.11	24.6	26
3/12/2011	25		7.47	7.02	22.9	24.1
4/12/2011	26		7.61	7.32	23	24.3
6/12/2011	28		7.61	7.3	24.5	26.1
7/12/2011	29		7.5	7.28	22	23.3
8/12/2011	30		7.74	7.27	24.3	25.7
10/12/2011	32		7.46	7.27	24.7	25.9
12/12/2011	34		7.98	7.13	21.1	22.5
13/12/2011	35		7.26	7.16	22	23.8
16/12/2011	38		7.69	7.28	21.4	22
17/12/2011	39		7.33	7.14	22.4	24.6
18/12/2011	40		7.39	7.15	21.6	22.8
19/12/2011	41		7.72	7.04	21.5	24.4
21/12/2011	42		7.54	7.02	20.6	23.6
28/12/2011	49		7.77	7.13	22.6	24.4
30/12/2011	51		7.43	7.1	23.7	23.9
31/12/2011	52		8.23	7.2	23.2	26.3

Table A-1 pH and temperature data throughout the operation period of CSTR (cont.)

Date	Time (day)	SRT (day)	pH		Temp (ºC)	
			Influent	Effluent	Influent	Effluent
1/1/2012	53		7.59	7.11	23.7	26.9
2/1/2012	54		7.75	6.98	23.9	27
3/1/2012	55		7.56	7.12	24.3	27.8
4/1/2012	56		7.77	7.09	25.1	27.1
5/1/2012	57		7.71	7.19	24.6	27.1
6/1/2012	58		7.59	6.99	23.4	26.2
7/1/2012	59		7.73	6.91	22.7	25.5
8/1/2012	60		7.89	7.08	23.4	26.1
9/1/2012	61		7.3	6.98	24	25.2
11/1/2012	63		7.55	6.98	22.4	24
12/1/2012	64		7.26	6.91	22.4	24.3
13/1/2012	65		7.3	7	22.5	23.7
14/1/2012	66		8.25	6.96	23	24
15/1/2012	67		8.14	7.06	21.3	24.3
16/1/2012	68		7.34	6.92	18.6	21.4
18/1/2012	70		7.65	7.08	15.9	19.2
19/1/2012	71		7.4	7.02	19.2	21.6
20/1/2012	72		7.54	6.95	21.8	24.4
21/1/2012	73		7.97	6.99	23.8	26.3
22/1/2012	74		7.79	6.96	20.7	25.3
23/1/2012	75	65,000	7.35	7.02	19.6	23.7
24/1/2012	76		7.26	6.89	23.4	24.3
25/1/2012	77		7.19	6.81	21.3	24
26/1/2012	78		7.23	6.75	19	23.2
27/1/2012	79		7.33	6.86	21.3	22.7
28/1/2012	80		7.31	6.82	19.7	22.8
29/1/2012	81		7.27	6.84	19.4	21.1
1/2/2012	84		7.16	6.75	22.7	24.1
2/2/2012	85		7.27	6.67	23.4	24.9
4/2/2012	87		6.99	6.71	23.1	26.7
5/2/2012	88		6.95	6.66	22.5	25.3
6/2/2012	89		7.17	6.74	20.4	23.6
7/2/2012	90		7.99	7.04	22	25.4
8/2/2012	91		7.69	6.85	22.2	24.4
9/2/2012	92		7.51	6.81	20	23.3
10/2/2012	93		7.35	7.06	21	24.9
11/2/2012	94		7.15	7.04	20.4	24
12/2/2012	95		7.55	6.97	20.8	23.5
13/2/2012	96		7.13	6.78	23	25.7
14/2/2012	97		7.19	6.83	22.5	26.8
15/2/2012	98		7.19	6.93	21	24.4

Table A-1 pH and temperature data throughout the operation period of CSTR (cont.)

Date	Time (day)	SRT (day)	pH		Temp (ºC)	
			Influent	Effluent	Influent	Effluent
16/2/2012	99		7.73	6.89	19.8	22.1
17/2/2012	100		6.92	6.69	19.8	22.3
18/2/2012	101		6.83	6.71	21.4	24.1
19/2/2012	102		6.71	6.78	24.8	27.3
20/2/2012	103		6.51	6.76	24.8	28.3
21/2/2012	104		6.96	6.72	23.8	28.7
22/2/2012	105		6.86	6.74	21.8	25.7
23/2/2012	106		7.06	6.77	21.1	25.4
24/2/2012	107		6.99	6.76	23	25.4
25/2/2012	108		7.26	6.87	21.6	25
26/2/2012	109		6.91	6.85	21.3	26
27/2/2012	110		6.79	7.07	25.3	28.8
28/2/2012	111		7.09	7.14	23.4	28.1
29/2/2012	112		6.99	6.84	22.1	27.2
2/3/2012	114		7.35	7.02	19.8	23.2
3/3/2012	115		5.86	6.99	23.4	29.2
4/3/2012	116		6.83	6.82	23.2	26.9
5/3/2012	117		5.2	7.09	24	27.7
6/3/2012	118		7.52	6.84	22.2	25.9
7/3/2012	119		6.54	6.9	22.3	26.2
8/3/2012	120	65,000	5.56	7.08	24.5	29.2
9/3/2012	121		5.3	7.01	23.5	29.8
10/3/2012	122		5.21	7	26.2	29.9
11/3/2012	123		5.22	6.93	26.8	29.7
12/3/2012	124		4.61	7.04	26.2	29.4
13/3/2012	125		7.11	6.97	23.2	27
15/3/2012	127		7.19	7.03	22.8	25.9
17/3/2012	129		7.35	7.12	21.7	25.5
18/3/2012	130		7.69	7.21	21.9	25.3
19/3/2012	131		7.36	7.25	21.1	24.8
21/3/2012	133		7.47	7.29	22.4	26.1
27/3/2012	139		7.54	7.88	26.4	31.1
28/3/2012	140		7.55	7.25	27.2	30.9
29/3/2012	141		7.29	7.33	25.3	29.3
2/4/2012	145		7.31	7.45	23.8	28.2
3/4/2012	146		7.3	7.86	24.3	28.2
4/4/2012	147		7.24	7.68	26.7	30.8
6/4/2012	149		7.51	7.74	27.6	31.1
7/4/2012	150		8.1	7.84	25.1	28.6
8/4/2012	151		7.96	7.76	24.7	28.1
9/4/2012	152		7.58	7.68	25.1	28.3

Table A-1 pH and temperature data throughout the operation period of CSTR (cont.)

Date	Time (day)	SRT (day)	pH		Temp (ºC)	
			Influent	Effluent	Influent	Effluent
21/4/2012	165		7.26	7.27	-	-
24/4/2012	168		7.87	7.22	-	-
25/4/2012	169		7.41	7.1	-	-
26/4/2012	170		7.58	7.35	27.6	29
27/4/2012	171		8.11	7.35	29	33
28/4/2012	172		7.99	7.21	28.2	32.8
29/4/2012	173		7.6	7.34	27.7	30.7
30/4/2012	174		7.46	7.31	27.3	29.7
1/5/2012	175		7.83	7.33	26.6	30.3
2/5/2012	176		7.62	7.31	28.4	32
4/5/2012	178		7.97	7.44	28.7	31.6
5/5/2012	179		7.6	7.58	26.9	30.7
6/5/2012	180		7.84	7.66	23.1	25.2
13/5/2012	187		7.47	7.37	27.3	29.6
14/5/2012	188		7.38	7.2	25.9	28.7
15/2/2012	189		7.86	7.04	27	30.4
16/5/2012	190	6,000	8.13	7.15	26.4	29.3
17/5/2012	191		7.85	7.27	28.1	31.4
18/5/2012	192		7.41	7.23	26.2	27.9
19/5/2012	193		7.53	7.34	27.8	30.5
20/5/2012	194		7.43	7.49	27.5	30.5
21/5/2012	195		7.49	7.31	27.2	30.5
22/5/2012	196		7.44	7.21	26.8	28.8
23/5/2012	197		7.94	7.55	26.3	28.3
24/5/2012	198		7.68	7.51	25.6	27.8
2/6/2012	207		6.96	7.11	26.3	29.1
3/6/2012	208		7.15	7	26.5	29.3
4/6/2012	209		7.1	7.06	27.1	30.6
5/6/2012	210		6.65	7.21	26.5	29.3
6/6/2012	211		6.83	7.04	27.3	29.6
7/6/2012	212		7.01	7.22	27.1	30.8
8/6/2012	213		7.26	6.96	25.8	27.2
9/6/2012	214		6.84	6.82	26.5	28.9

Table A-2 pH and temperature data throughout the operation period of plug-flow reactor

Date	Time (day)	SRT (day)	pH		Temp (ºC)	
			Influent	Effluent	Influent	Effluent
16/1/2012	2		8	7.91	18.6	21.1
17/1/2012	3		7.93	7.86	20.1	22.4
18/1/2012	4		7.76	7.74	20.5	21.9
19/1/2012	5		7.89	7.55	22.7	23.5
20/1/2012	6		7.94	7.36	21.4	23.8
21/1/2012	7		8.15	7.29	22.6	25.4
22/1/2012	8		7.89	7.27	21.1	24.1
23/1/2012	9		7.66	7.23	19.3	22.8
24/1/2012	10		7.52	7.16	20.4	24.3
25/1/2012	11		7.33	7.18	23.7	23.8
26/1/2012	12		7.3	7.03	20	22.4
27/1/2012	13		7.45	7.17	21.8	23.1
28/1/2012	14		7.31	7.17	19.7	23.8
29/1/2012	15		7.67	7.06	19.3	21.3
30/1/2012	16		7.75	7.31	20.4	22.2
1/2/2012	18		7.41	6.99	22.3	24.1
2/2/2012	19		7.21	6.85	23.8	24.9
4/2/2012	21		7.63	6.91	23.3	26.2
5/2/2012	22		7.49	6.89	22.4	25.3
6/2/2012	23		7.87	7	20.7	23.8
7/2/2012	24	6,010	8.23	7.18	22.1	24.6
8/2/2012	25		7.87	6.98	22.7	23.9
9/2/2012	26		7.88	6.97	20.4	22.4
10/2/2012	27		8.08	7.12	21.9	24.3
11/2/2012	28		7.64	7.05	21.4	23.4
12/2/2012	29		7.89	7.03	21.1	23.2
13/2/2012	30		7.56	7.07	23.2	25.1
14/2/2012	31		7.36	7.01	22.8	26.8
15/2/2012	32		7.67	7.05	21.2	23.9
16/2/2012	33		7.58	7.09	20.5	22
17/2/2012	34		7.73	7.06	20.3	22.8
18/2/2012	35		7.45	7.07	21.5	24
19/2/2012	36		7.56	6.98	25.2	28.2
20/2/2012	37		7.77	7.1	25.5	27.5
22/2/2012	39		7.7	6.97	22.2	25.1
23/2/2012	40		7.41	6.96	21.2	25.1
24/2/2012	41		7.2	6.87	23.8	25.3
25/2/2012	42		7.91	6.85	22.3	25.2
26/2/2012	43		7.17	6.77	22	26.4
27/2/2012	44		7.96	7.27	25.3	28.1
28/2/2012	45		7.6	7.16	22.9	27.6

Table A-2 pH and temperature data throughout the operation period of plug-flow reactor (cont.)

Date	Time (day)	SRT (day)	pH		Temp (ºC)	
			Influent	Effluent	Influent	Effluent
29/2/2012	46	6,010	7.58	6.93	22.6	27.3
2/3/2012	48		7.28	6.98	20.9	22.7
3/3/2012	49		7.85	6.96	23.6	29
4/3/2012	50		7.74	6.9	23.6	28.6
5/3/2012	51		7.62	7.15	23.9	27.3
6/3/2012	52		7.76	6.87	22.4	25.5
7/3/2012	53		7.46	6.85	22.9	25.6
8/3/2012	54		7.55	6.87	24.9	28.1
9/3/2012	55		7.23	6.78	24.4	29.3
10/3/2012	56		7.26	6.8	26.6	30
11/3/2012	57		7.63	6.79	27.2	29.1
12/3/2012	58		7.94	6.78	26.6	29.1
13/3/2012	59		6.81	6.63	22	27.1
15/3/2012	61		6.85	6.46	22.7	25
17/3/2012	63		6.73	6.55	22.1	25.3
18/3/2012	64		7.11	6.64	22.2	25.2
19/3/2012	65		7.62	6.7	21.4	24.6
21/3/2012	67		6.97	6.82	23.8	26.1
23/3/2012	69		6.88	6.71	25.9	28.4
24/3/2012	70		6.65	6.59	27.8	30.3
25/3/2012	71		7.02	6.75	26.3	30.4
27/3/2012	73		6.88	6.78	28.4	30.7
28/3/2012	74		6.91	6.77	26.8	30.3
29/3/2012	75		6.55	6.55	26	28.8
2/4/2012	79		6.09	6.54	21.7	27.2
3/4/2012	80		6.18	6.68	23.6	28.2
4/4/2012	81		5.28	6.8	27.9	31.1
6/4/2012	82		6.24	6.79	27.5	31.8
7/4/2012	83		6.37	6.85	25.7	28
9/4/2012	85		6.39	6.89	25.4	28.1
10/4/2012	86		6.23	6.46	22.1	26.1
30/4/2012	107	1,000	7.35	6.97	25.1	26.9
1/5/2012	108		7.66	7.24	27.1	30.2
2/5/2012	109		7.85	7.33	29.1	32
4/5/2012	111		7.53	7.28	30.2	31.6
5/5/2012	112		8.42	7.24	28.3	30.2
6/5/2012	113		8.13	6.95	23.8	24.6
7/5/2012	114		7.95	7.19	24.8	26.2
8/5/2012	115		8.27	7.11	25	26.4
9/5/2012	116		7.68	7.23	26.8	31.4
10/5/2012	117		7.4	7.04	23.4	27.3

Table A-2 pH and temperature data throughout the operation period of plug-flow reactor (cont.)

Date	Time (day)	SRT (day)	pH		Temp (ºC)	
			Influent	Effluent	Influent	Effluent
11/5/2012	118		8.1	7.15	27.9	29.8
12/5/2012	119		8.17	7.12	28.6	30.6
13/5/2012	120		7.53	6.96	26.7	30
14/5/2012	121		7.93	7.05	25.7	28.1
15/5/2012	122		8	6.97	27.1	30.4
16/5/2012	123		7.35	6.91	26.6	29.1
17/5/2012	124		7.77	7.01	28.3	31.1
18/5/2012	125		7.49	7.07	26.8	27.8
19/5/2012	126		7.44	6.84	27.8	30.3
20/5/2012	127		7.42	7.07	27.4	30.8
21/5/2012	128		8.06	6.94	27.8	30.7
22/5/2012	129		7.7	6.95	26.7	28.8
24/5/2012	131		7.44	6.9	25.3	28.3
28/5/2012	135		7.55	6.94	26.4	28.5
29/5/2012	136		7.48	6.96	26.7	28.8
30/5/2012	137		7.5	6.99	26.5	29.4
31/5/2012	138		7.59	6.91	27.3	28.8
1/6/2012	139	1,000	7.63	6.69	26.7	28.1
2/6/2012	140		7.45	6.87	26.7	28.9
4/6/2012	142		7.13	6.72	26.9	29.8
5/6/2012	143		7.33	6.81	26.4	28.5
6/6/2012	144		7.33	6.81	27.6	29.6
7/6/2012	145		7.27	6.65	26.9	30.1
8/6/2012	146		7.46	6.67	25.7	27.1
9/6/2012	147		6.78	6.5	26.4	29.1
10/6/2012	148		6.62	6.64	22.5	25.5
11/6/2012	149		6.56	6.44	22	25
12/6/2012	150		6.88	6.43	23.1	25.2
13/6/2012	151		6.57	6.4	23	24.9
14/6/2012	152		6.63	6.46	22	25
15/6/2012	153		6.78	6.5	23	25.5
16/6/2012	154		6.64	6.37	22.8	27
17/6/2012	155		6.62	6.34	22.5	25.2
18/6/2012	156		6.63	6.38	22.9	25.2
19/6/2012	157		6.63	6.33	21.3	23.8
25/6/2012	164		6.8	6.33	21	23.6
26/6/2012	165		6.88	6.43	22.6	24.8
27/6/2012	166	100	7.31	6.72	26	27.8
28/6/2012	167		7.37	6.81	26.8	29
29/6/2012	168		7.31	6.78	25.9	28.5
30/6/2012	169		7.32	6.85	25.8	28.6

Table A-2 pH and temperature data throughout the operation period of plug-flow reactor (cont.)

Date	Time (day)	SRT (day)	pH		Temp (ºC)	
			Influent	Effluent	Influent	Effluent
1/7/2012	170	100	7.31	6.79	25.5	27.7
2/7/2012	171		7.09	6.79	26.1	27.9
3/7/2012	172		7.16	6.78	24.7	26.8
4/7/2012	173		7.05	6.84	24.8	25.7
5/7/2012	174		7.05	6.84	25.5	26.6
6/7/2012	175		6.99	6.8	24.9	26.8
7/7/2012	176		7.08	6.77	26.7	28.7
8/7/2012	177		7.18	6.81	26.4	27.8
9/7/2012	178		7.16	6.87	25.8	27.8
10/7/2012	179		7.23	6.73	25.8	28.3
11/7/2012	180		7.11	6.78	24.6	27.5
12/7/2012	181		7.09	6.81	26.5	30.2
13/7/2012	182		7.24	6.75	28.7	29.8
14/7/2012	183		7.15	6.82	27.4	29.6
15/7/2012	184	50	7.08	6.77	26.8	28
16/7/2012	185		7.13	6.73	25.7	27.4
17/7/2012	186		7.06	6.84	25.8	28.1
18/7/2012	187		7.01	6.79	25.3	25.9
19/7/2012	188		7.29	6.81	26.5	27.4
24/7/2012	193		7.36	6.96	24	24.9
25/7/2012	194		7.08	6.95	23.3	24.7
26/7/2012	195		7.02	6.84	23.9	25.5
27/7/2012	196		7.01	6.88	24.8	26.2
28/7/2012	197		6.98	6.94	24.9	26
29/7/2012	198		6.95	6.94	25.6	26.9
30/7/2012	199		6.94	6.89	25	26.7
31/7/2012	200		6.97	6.88	25.1	26.5
1/8/2012	201		7.14	6.92	26	27.1
2/8/2012	202		6.84	6.69	26.3	28.7
3/8/2012	203		6.97	6.54	26.9	28.5

Table A-3 Alkalinity and VFA data throughout the operation period of CSTR

Date	Time (day)	SRT (day)	Alkalinity (mg/l)		VFA (mg/l)	
			Influent	Effluent	Influent	Effluent
12/11/2011	4	65,000	140	126	16	17
17/11/2011	9	65,000	130	103	13	12
20/11/2011	12	65,000	137	156	23	33
23/11/2011	15	65,000	118	170	17	39
26/11/2011	18	65,000	129	142	17	29
30/11/2011	22	65,000	134	153	19	30
3/12/2011	25	65,000	140	148	22	39
9/12/2011	31	65,000	134	159	30	42
13/12/2011	35	65,000	126	153	35	46
28/12/2011	50	65,000	131	153	50	58
31/12/2011	53	65,000	119	153	53	59
4/1/2011	57	65,000	116	151	52	59
7/1/2011	60	65,000	126	153	33	47
11/1/2011	64	65,000	144	158	29	40
14/1/2011	67	65,000	163	178	29	42
18/1/2012	71	65,000	158	168	31	32
22/1/2012	75	65,000	161	176	25	40
26/1/2012	79	65,000	168	176	55	55
29/1/2012	82	65,000	156	176	33	50
2/2/2012	86	65,000	111	183	39	46
5/2/2012	89	65,000	109	163	36	35
8/2/2012	92	65,000	119	186	39	33
12/2/2012	96	65,000	144	178	54	38
15/2/2012	99	65,000	141	176	39	34
19/2/2012	103	65,000	72	163	57	29
22/2/2012	106	65,000	45	163	62	39
26/2/2012	110	65,000	99	168	55	37
29/2/2012	113	65,000	64	176	67	33
4/3/2012	117	65,000	84	168	62	41
7/3/2012	120	65,000	45	158	76	37
11/3/2012	124	65,000	25	182	101	68
14/3/2012	127	65,000	163	193	45	40
18/3/2012	131	65,000	136	163	46	35
21/3/2012	134	65,000	156	178	53	39
28/3/2012	141	65,000	157	252	61	56
4/4/2012	148	65,000	131	176	37	52
8/4/2012	152	65,000	153	158	69	62
25/4/2012	174	6,000	157	185	53	62
29/4/2012	178	6,000	154	178	45	58
2/5/2012	181	6,000	145	192	77	75
6/5/2012	185	6,000	154	207	58	73
13/5/2012	192	6,000	124	228	54	78

Table A-3 Alkalinity and VFA data throughout the operation period of CSTR (cont.)

Date	Time (day)	SRT (day)	Alkalinity (mg/l)		VFA (mg/l)	
			Influent	Effluent	Influent	Effluent
16/5/2012	195	6,000	133	157	60	62
20/5/2012	199	6,000	128	169	22	20
23/5/2012	202	6,000	137	157	32	34
3/6/2012	213	6,000	102	166	51	22
6/6/2012	216	6,000	64	164	53	21
10/6/2012	220	6,000	76	169	23	25

Table A-4 Alkalinity and VFA data throughout the operation period of plug-flow reactor

Date	Time (day)	SRT (day)	Alkalinity (mg/l)			VFA (mg/l)		
			Influent	6^{th} port	Effluent	Influent	6^{th} port	Effluent
16/1/2012	2	6,010	124	136	136	16	21	17
22/1/2012	8	6,010	161	176	181	24	30	27
26/1/2012	12	6,010	163	171	166	25	26	33
29/1/2012	15	6,010	153	186	183	23	34	31
2/2/2012	19	6,010	158	188	173	25	45	37
5/2/2012	22	6,010	151	181	161	26	41	33
8/2/2012	25	6,010	163	183	178	22	37	31
12/2/2012	28	6,010	158	171	168	48	48	36
15/2/2012	31	6,010	141	183	173	30	41	36
19/2/2012	35	6,010	136	171	158	26	37	33
22/2/2012	38	6,010	144	173	166	27	37	31
26/2/2012	42	6,010	149	173	166	29	37	29
29/2/2012	45	6,010	136	182	172	28	37	15
4/3/2012	49	6,010	129	181	176	45	46	39
7/3/2012	52	6,010	134	181	176	52	46	37
11/3/2012	56	6,010	124	188	178	45	61	45
14/3/2012	59	6,010	136	176	163	57	45	37
18/3/2012	63	6,010	119	165	152	55	53	41
21/3/2012	66	6,010	116	178	166	54	63	48
25/3/2012	70	6,010	113	188	181	61	57	45
28/3/2012	73	6,010	105	149	144	62	55	47
4/4/2012	80	6,010	74	153	151	93	86	87
8/4/2012	84	6,010	99	161	153	91	73	71
2/5/2012	111	1,000	124	136	136	56	62	58
6/5/2012	115	1,000	134	176	166	62	66	62
13/5/2012	122	1,000	141	168	153	64	87	79
16/5/2012	125	1,000	144	173	168	55	66	62

Table A-5 SS and VSS data throughout the operation period of CSTR

Date	Time (day)	SRT (day)	SS (mg/l)		VSS (mg/l)	
			Influent	Effluent	Influent	Effluent
20/5/2012	129	1,000	144	173	173	56
23/5/2012	132	1,000	146	183	163	63
30/5/2012	139	1,000	147	186	177	68
3/6/2012	143	1,000	129	183	163	75
6/6/2012	146	1,000	134	183	173	71
10/6/2012	150	1,000	109	173	166	73
27/6/2012	167	100	139	197	193	48
1/7/2012	171	100	149	194	183	50
4/7/2012	174	100	100	189	178	76
8/7/2012	178	100	111	200	188	73
11/7/2012	181	100	114	198	186	89
16/7/2012	185	50	139	209	198	65
26/7/2012	195	50	111	186	178	65
30/7/2012	199	50	114	181	183	68
2/7/2012	202	50	109	181	178	76
13/11/2011	5	65,000	67	0	53	0
16/11/2011	8	65,000	57	0	36	0
21/11/2011	13	65,000	118	0	79	0
24/11/2011	16	65,000	79	0	43	0
28/11/2011	20	65,000	98	0	62	0
1/12/2011	23	65,000	87	0	53	0
5/12/2011	27	65,000	122	0	59	0
8/12/2011	30	65,000	107	0	59	0
13/12/2011	35	65,000	139	0	67	0
25/12/2011	47	65,000	98	0	58	0
29/12/2011	51	65,000	92	0	47	0
2/1/2012	55	65,000	103	0	48	0
5/1/2012	58	65,000	112	0	54	0
9/1/2012	62	65,000	150	0	62	0
13/1/2012	66	65,000	176	0	82	0
17/1/2012	69	65,000	112	0	50	0
21/1/2012	73	65,000	120	0	54	0
25/1/2012	77	65,000	207	0	113	0
28/1/2012	80	65,000	150	0	79	0
31/1/2012	83	65,000	210	0	87	0
3/2/2012	86	65,000	116	0	84	0
6/2/2012	89	65,000	230	0	120	0
10/2/2012	93	65,000	114	0	50	0
13/2/2012	96	65,000	101	0	38	0
17/2/2012	100	65,000	157	0	68	0
20/2/2012	103	65,000	124	0	50	0
24/2/2012	107	65,000	110	0	46	0

Table A-5 SS and VSS data throughout the operation period of CSTR (cont.)

Date	Time (day)	SRT (day)	SS (mg/l)		VSS (mg/l)	
			Influent	Effluent	Influent	Effluent
27/2/2012	110	65,000	127	0	40	0
2/3/2012	114	65,000	115	0	75	0
5/3/2012	117	65,000	88	0	54	0
9/3/2012	121	65,000	114	0	60	0
12/3/2012	124	65,000	126	0	52	0
16/3/2012	128	65,000	144	0	62	0
19/3/2012	131	65,000	162	0	78	0
2/4/2012	146	65,000	141	0	69	0
6/4/2012	150	65,000	198	0	96	0
9/4/2012	153	65,000	191	0	60	0
23/4/2012	170	6,000	113	0	50	0
27/4/2012	174	6,000	102	0	58	0
30/4/2012	177	6,000	131	0	58	0
4/5/2012	181	6,000	167	0	72	0
14/5/2012	191	6,000	100	0	41	0
1/6/2012	209	6,000	114	0	42	0
18/5/2012	195	6,000	106	0	45	0
21/5/2012	198	6,000	140	0	62	0
4/6/2012	212	6,000	91	0	47	0
8/6/2012	216	6,000	156	0	62	0

Table A-6 SS and VSS data throughout the operation period of plug-flow reactor

Date	Time (day)	SRT (day)	SS (mg/l)			VSS (mg/l)		
			Influent	6th port	Effluent	Influent	6th port	Effluent
17/1/2012	3	6,010	160	128	0	105	60	0
21/1/2012	7	6,010	113	134	0	80	66	0
25/1/2012	11	6,010	145	208	0	75	82	0
28/1/2012	14	6,010	168	293	0	80	150	0
31/1/2012	17	6,010	117	440	0	83	116	0
3/2/2012	20	6,010	102	567	0	76	190	0
6/2/2012	23	6,010	203	603	0	100	243	0
10/2/2012	27	6,010	118	376	0	78	149	0
13/2/2012	30	6,010	124	360	0	63	119	0
17/2/2012	34	6,010	125	376	0	54	113	0
20/2/2012	37	6,010	160	363	0	84	140	0
24/2/2012	41	6,010	118	477	0	58	100	0
27/2/2012	45	6,010	114	659	0	54	168	0
2/3/2012	49	6,010	135	650	0	60	103	0
5/3/2012	52	6,010	108	443	0	66	132	0
9/3/2012	56	6,010	132	660	0	72	103	0
12/3/2012	59	6,010	148	335	0	62	149	0
16/3/2012	63	6,010	146	384	0	70	104	0
19/3/2012	66	6,010	172	368	0	68	124	0
23/3/2012	70	6,010	92	313	0	62	137	0
26/3/2012	73	6,010	124	352	0	53	105	0
2/4/2012	79	6,010	111	296	0	48	43	0
6/4/2012	83	6,010	177	635	0	74	70	0
9/4/2012	87	6,010	182	517	0	58	76	0
30/4/2012	107	1,000	134	178	0	63	14	0
4/5/2012	111	1,000	136	253	0	67	84	0
7/5/2012	114	1,000	113	200	0	74	53	0
11/5/2012	118	1,000	114	178	0	57	71	0
14/5/2012	121	1,000	100	155	0	64	69	0
18/5/2012	125	1,000	100	158	0	57	56	0
22/5/2012	129	1,000	130	199	0	41	69	0
28/5/2012	135	1,000	116	250	0	60	50	0
1/6/2012	139	1,000	101	298	0	36	14	0
4/6/2012	142	1,000	84	218	0	42	15	0
8/6/2012	146	1,000	148	383	0	61	17	0
11/6/2012	149	1,000	138	205	0	50	8	0
15/6/2012	153	1,000	161	277	0	33	18	0
25/6/2012	163	100	146	208	0	71	4	0
29/6/2012	166	100	130	207	0	54	25	0
2/7/2012	169	100	94	222	0	54	13	0
6/7/2012	173	100	115	185	0	48	6	0

Table A-6 SS and VSS data throughout the operation period of plug-flow reactor (cont.)

Date	Time (day)	SRT (day)	SS (mg/l)			VSS (mg/l)		
			Influent	6^{th} port	Effluent	Influent	6^{th} port	Effluent
13/7/2012	180	100	109	165	0	60	4	0
17/7/2012	183	100	92	164	0	39	12	0
18/7/2012	187	50	99	174	0	48	4	0
25/7/2012	194	50	116	147	0	47	3	0
1/8/2012	201	50	124	116	0	52	2	0

Table A-7 COD data throughout the operation period of CSTR

Date	Time (day)	SRT (day)	COD (mg/l)		
			Influent	Effluent	%Removal
9/11/2011	1	65,000	174	87	50
13/11/2011	5	65,000	156	37	77
16/11/2011	8	65,000	154	14	91
21/11/2011	13	65,000	246	15	94
24/11/2011	17	65,000	185	36	80
28/11/2011	21	65,000	176	43	75
2/12/2011	25	65,000	194	38	80
5/12/2011	28	65,000	193	44	77
28/12/2011	36	65,000	286	73	75
2/1/2012	40	65,000	308	46	85
5/1/2012	54	65,000	269	57	79
9/1/2012	59	65,000	266	69	74
12/1/2012	62	65,000	281	82	71
16/1/2012	69	65,000	350	134	62
20/1/2012	77	65,000	345	134	61
23/1/2012	80	65,000	364	109	70
27/1/2012	82	65,000	330	94	72
30/1/2012	84	65,000	375	118	68
1/2/2012	87	65,000	489	269	45
3/2/2012	89	65,000	462	123	73
6/2/2012	92	65,000	498	74	85
8/2/2012	94	65,000	420	74	82
10/2/2012	96	65,000	434	77	82
13/2/2012	99	65,000	419	77	82
20/2/2012	103	65,000	576	138	76
22/2/2012	106	65,000	609	135	78
24/2/2012	108	65,000	574	137	76
27/2/2012	110	65,000	588	131	78
29/2/2012	113	65,000	585	120	80
2/3/2012	115	65,000	767	194	75
5/3/2012	117	65,000	818	233	72
7/3/2012	120	65,000	782	213	73
9/3/2012	122	65,000	790	197	75
12/3/2012	124	65,000	730	160	78
14/3/2012	128	65,000	396	74	81
16/3/2012	130	65,000	444	94	79
19/3/2012	133	65,000	449	56	87
21/3/2012	135	65,000	478	62	87
29/3/2012	143	65,000	426	56	87
2/4/2012	148	65,000	456	157	66
4/4/2012	150	65,000	383	27	93
6/4/2012	152	65,000	484	32	93

Table A-7 COD data throughout the operation period of CSTR (cont.)

Date	Time (day)	SRT (day)	COD (mg/l)		
			Influent	Effluent	%Removal
9/4/2012	155	65,000	490	42	92
23/4/2012	173	6,000	249	100	60
25/4/2012	175	6,000	215	53	75
27/4/2012	177	6,000	257	51	80
30/4/2012	180	6,000	273	44	84
2/5/2012	182	6,000	264	55	79
4/5/2012	184	6,000	271	61	78
14/5/2012	194	6,000	300	85	72
16/5/2012	196	6,000	279	66	76
18/5/2012	198	6,000	320	64	80
21/5/2012	201	6,000	265	38	86
23/5/2012	203	6,000	309	44	86
1/6/2012	212	6,000	577	28	95
4/6/2012	215	6,000	501	18	96
6/6/2012	217	6,000	606	28	95
8/6/2012	219	6,000	612	48	92
11/6/2012	222	6,000	566	52	91

Table A-8 COD data throughout the operation period of plug-flow reactor

Date	Time	SRT	COD			%Removal	
			Influent	6^{th} port	Effluent	6^{th} port	Membrane
16/1/2012	2	6,010	226	72	49	68	78
20/1/2012	6	6,010	227	91	36	60	84
23/1/2012	9	6,010	247	90	43	64	83
27/1/2012	13	6,010	238	88	50	63	79
30/1/2012	16	6,010	244	124	60	49	75
1/2/2012	18	6,010	341	147	85	57	75
3/2/2012	20	6,010	272	159	62	41	77
6/2/2012	23	6,010	334	124	53	63	84
8/2/2012	25	6,010	286	188	41	34	86
10/2/2012	27	6,010	291	200	60	31	79
13/2/2012	30	6,010	282	202	53	28	81
17/2/2012	34	6,010	395	294	123	25	69
22/2/2012	39	6,010	372	235	78	37	79
24/2/2012	41	6,010	320	195	36	39	89
27/2/2012	44	6,010	340	200	46	41	87
29/2/2012	46	6,010	335	220	54	35	84
2/3/2012	48	6,010	423	187	64	56	85
5/3/2012	51	6,010	412	252	65	39	84
7/3/2012	53	6,010	399	260	54	35	86
9/3/2012	55	6,010	429	205	54	52	87
12/3/2012	58	6,010	388	220	45	43	88
14/3/2012	60	6,010	551	318	146	42	74
16/3/2012	62	6,010	614	311	127	49	79
19/3/2012	65	6,010	530	298	117	34	69
21/3/2012	67	6,010	561	326	134	56	76
23/3/2012	69	6,010	553	319	141	33	65
26/3/2012	72	6,010	565	320	108	17	82
29/3/2012	75	6,010	786	309	141	34	87
2/4/2012	77	6,010	851	376	147	35	78
4/4/2012	79	6,010	799	486	367	44	80
6/4/2012	81	6,010	803	446	279	49	79
9/4/2012	84	6,010	802	504	295	49	81
11/4/2012	86	6,010	804	544	243	53	88
30/4/2012	107	1,000	267	175	84	41	82
2/5/2012	109	1,000	266	118	63	52	84
4/5/2012	111	1,000	249	167	87	54	85
7/5/2012	114	1,000	200	166	35	60	90
9/5/2012	116	1,000	264	175	34	51	86
11/5/2012	118	1,000	273	178	60	60	87
14/5/2012	121	1,000	302	168	60	60	88
16/5/2012	123	1,000	276	141	59	62	88
18/5/2012	125	1,000	297	151	55	70	87

Table A-8 COD data throughout the operation period of plug-flow reactor (cont.)

Date	Time	SRT	COD			%Removal	
			Influent	6th port	Influent	6th port	Influent
21/5/2012	128	1,000	273	127	34	67	87
23/5/2012	130	1,000	273	162	48	69	81
28/5/2012	135	1,000	359	173	57	60	85
30/5/2012	137	1,000	420	194	61	64	86
1/6/2012	139	1,000	424	169	44	34	69
4/6/2012	142	1,000	374	184	54	56	76
6/6/2012	144	1,000	413	165	53	33	65
8/6/2012	146	1,000	408	163	49	17	82
11/6/2012	149	1,000	571	216	71	34	87
13/6/2012	151	1,000	623	189	82	35	78
15/6/2012	153	1,000	618	206	83	44	80
18/6/2012	156	1,000	676	211	125	49	79
20/6/2012	158	1,000	581	230	87	49	81
22/6/2012	160	1,000	618	220	85	53	88
25/6/2012	165	100	426	209	34	51	92
27/6/2012	167	100	400	250	67	37	83
29/6/2012	169	100	386	257	45	33	88
1/7/2012	171	100	421	238	60	43	86
2/7/2012	172	100	570	294	80	49	86
4/7/2012	174	100	575	254	83	56	85
6/7/2012	176	100	559	267	103	52	82
9/7/2012	178	100	577	242	93	58	84
11/7/2012	180	100	576	203	112	65	81
13/7/2012	182	100	564	252	101	55	82
18/7/2012	186	50	540	287	106	47	80
25/7/2012	193	50	527	249	120	53	77
30/7/2012	198	50	509	257	105	50	79
1/8/2012	200	50	562	236	128	58	77
3/1/2012	202	50	573	194	121	66	79

Table A-9 FA data throughout the operation period of CSTR

Date	Time	SRT	FA (mg/l)		
			Influent	Effluent	%Removal
12/12/2011	35	65,000	57	1	97
16/12/2011	39	65,000	58	2	97
31/12/2012	54	65,000	59	1	98
5/12/2012	59	65,000	62	2	97
8/1/2012	62	65,000	60	1	98
15/1/2012	69	65,000	60	2	97
18/1/2012	73	65,000	58	2	97
24/1/2012	80	65,000	56	2	97
27/1/2012	82	65,000	58	2	96
29/1/2012	84	65,000	58	3	95
2/2/2012	87	65,000	103	1	99
4/2/2012	89	65,000	101	1	99
7/2/2012	92	65,000	100	1	99
9/2/2012	94	65,000	103	1	99
11/2/2012	96	65,000	111	1	99
16/2/2012	99	65,000	116	1	99
18/2/2012	103	65,000	209	1	100
21/2/2012	106	65,000	220	1	99
23/2/2012	108	65,000	208	1	99
25/2/2012	110	65,000	247	1	100
28/2/2012	113	65,000	245	1	100
1/3/2012	115	65,000	425	2	99
3/2/2012	117	65,000	406	1	100
6/3/2012	120	65,000	433	1	100
8/3/2012	122	65,000	420	1	100
10/3/2012	124	65,000	447	1	100
23/4/2012	173	6,000	26	1	97
25/4/2012	175	6,000	22	1	98
27/4/2012	177	6,000	32	1	98
30/4/2012	180	6,000	24	1	97
2/5/2012	182	6,000	24	1	97
4/5/2012	184	6,000	23	1	98
14/5/2012	194	6,000	68	1	98
16/5/2012	196	6,000	60	1	99
18/5/2012	198	6,000	59	1	99
21/5/2012	201	6,000	60	1	99
23/5/2012	203	6,000	57	1	99
1/6/2012	212	6,000	242	2	99
4/6/2012	215	6,000	230	1	100
6/6/2012	217	6,000	253	1	100
8/6/2012	219	6,000	226	1	100
11/6/2012	222	6,000	245	1	100

Table A-10 FA data throughout the operation period of plug-flow reactor

Date	Time	SRT	FA			%Removal	
			Influent	6^{th} port	Effluent	6^{th} port	Membrane
2/2/2012	18	6,010	24	2	1	90	95
4/2/2012	20	6,010	26	2	0	91	98
7/2/2012	23	6,010	26	2	1	92	96
9/2/2012	25	6,010	27	5	2	82	92
11/2/2012	27	6,010	24	3	1	87	97
16/2/2012	32	6,010	26	3	1	90	96
18/2/2012	34	6,010	71	3	1	96	98
21/2/2012	37	6,010	68	4	2	94	98
23/2/2012	39	6,010	67	3	1	96	98
25/2/2012	41	6,010	69	5	1	93	99
28/2/2012	44	6,010	68	2	1	97	99
1/3/2012	46	6,010	134	3	1	98	99
3/3/2012	48	6,010	130	5	1	96	99
6/3/2012	51	6,010	147	2	1	98	99
8/3/2012	53	6,010	137	2	1	98	99
10/3/2012	55	6,010	137	4	1	97	99
14/3/2012	59	6,010	203	6	5	97	98
16/3/2012	61	6,010	256	4	2	99	99
19/3/2012	64	6,010	255	11	6	96	97
21/3/2012	66	6,010	232	3	1	99	100
23/3/2012	68	6,010	245	7	1	97	100
26/3/2012	69	6,010	264	4	1	99	100
28/3/2012	71	6,010	452	3	1	99	100
2/4/2012	77	6,010	467	47	45	90	90
4/4/2012	79	6,010	408	5	1	99	100
6/4/2012	81	6,010	424	3	1	99	100
9/4/2012	84	6,010	415	6	2	99	100
11/4/2012	86	6,010	444	3	1	99	100
30/4/2012	107	1,000	28	4	3	85	89
2/5/2012	109	1,000	29	3	1	91	95
4/5/2012	111	1,000	24	1	1	94	95
7/5/2012	114	1,000	24	2	1	93	97
9/5/2012	116	1,000	24	2	1	92	97
11/5/2012	118	1,000	26	2	1	92	97
14/5/2012	121	1,000	70	2	1	97	99
16/5/2012	123	1,000	61	2	1	97	99
18/5/2012	125	1,000	64	1	0	98	99
21/5/2012	128	1,000	67	2	1	98	99
23/5/2012	130	1,000	69	2	1	98	99
28/5/2012	135	1,000	125	3	3	98	98
30/5/2012	137	1,000	136	2	1	99	99
1/6/2012	139	1,000	132	2	1	98	99

Table A-10 FA data throughout the operation period of plug-flow reactor (cont.)

Date	Time	SRT	FA			%Removal	
			Influent	6^{th} port	Influent	6^{th} port	Influent
4/6/2012	142	1,000	140	1	1	99	100
6/6/2012	144	1,000	145	2	1	99	99
8/6/2012	146	1,000	142	2	1	99	99
11/6/2012	149	1,000	262	2	1	99	100
13/6/2012	151	1,000	247	2	1	99	100
15/6/2012	153	1,000	249	2	1	99	99
18/6/2012	156	1,000	236	2	1	99	100
20/6/2012	158	1,000	235	2	1	99	99
22/6/2012	160	1,000	238	3	1	99	100
25/6/2012	165	100	124	3	1	97	99
27/6/2012	166	100	122	3	1	97	99
29/6/2012	168	100	138	3	1	98	99
1/7/2012	170	100	131	3	1	98	99
2/7/2012	171	100	253	2	1	99	100
4/7/2012	173	100	227	3	1	99	100
6/7/2012	175	100	241	3	1	99	99
9/7/2012	178	100	241	3	1	99	99
11/7/2012	180	100	241	4	2	99	99
13/7/2012	182	100	255	4	2	99	99
18/7/2012	186	50	226	2	1	99	100
25/7/2012	193	50	225	5	3	98	99
30/7/2012	198	50	238	4	1	98	99
1/8/2012	200	50	235	3	3	99	99
3/8/2012	202	50	241	2	1	99	99

Table A-11 Phenol data throughout the operation period of CSTR

Date	Time	SRT	Phenol		
			Influent	Effluent	%Removal
13/12/2011	36	65,000	5	1	82
17/12/2011	40	65,000	3	1	78
31/12/2012	54	65,000	4	1	78
5/12/2012	59	65,000	3	1	75
8/1/2012	62	65,000	4	1	77
15/1/2012	69	65,000	11	2	79
23/1/2012	77	65,000	11	4	64
25/1/2012	80	65,000	12	4	69
27/1/2012	82	65,000	12	4	66
29/1/2012	84	65,000	11	4	64
2/2/2012	87	65,000	19	7	64
4/2/2012	89	65,000	22	8	62
7/2/2012	92	65,000	19	5	71
9/2/2012	94	65,000	20	7	66
11/2/2012	96	65,000	23	5	79
14/2/2012	99	65,000	22	5	75
18/2/2012	103	65,000	40	21	47
21/2/2012	106	65,000	39	15	60
23/2/2012	108	65,000	38	14	63
25/2/2012	110	65,000	38	16	57
28/2/2012	113	65,000	35	17	51
1/3/2012	115	65,000	63	31	51
3/2/2012	117	65,000	60	39	34
6/3/2012	120	65,000	64	37	42
8/3/2012	122	65,000	62	31	50
10/3/2012	124	65,000	63	33	48
14/3/2012	128	65,000	38	16	59
16/3/2012	130	65,000	44	17	62
19/3/2012	133	65,000	45	13	70
21/3/2012	135	65,000	42	8	82
28/3/2012	143	65,000	39	3	92
2/4/2012	148	65,000	39	8	80
4/4/2012	150	65,000	37	2	95
6/4/2012	152	65,000	39	2	94
9/4/2012	155	65,000	39	1	96
23/4/2012	173	6,010	6	1	88
25/4/2012	175	6,010	4	1	84
27/4/2012	177	6,010	6	1	85
30/4/2012	180	6,010	5	1	87
2/5/2012	182	6,010	4	0	90
4/5/2012	184	6,010	5	0	91
14/5/2012	194	6,010	11	1	89

Table A-11 Phenol data throughout the operation period of CSTR (cont.)

Date	Time	SRT	Phenol		
			Influent	Influent	Influent
16/5/2012	196	6,010	10	1	94
18/5/2012	198	6,010	11	1	87
21/5/2012	201	6,010	10	0	96
23/5/2012	203	6,010	10	0	96
1/6/2012	212	6,010	39	4	91
4/6/2012	215	6,010	38	1	98
6/6/2012	217	6,010	41	0	99
8/6/2012	219	6,010	38	0	99
11/6/2012	222	6,010	39	1	99

Table A-12 Phenol data throughout the operation period of plug-flow reactor

Date	Time	SRT	Phenol			%Removal	
			Influent	6^{th} port	Effluent	6^{th} port	Membrane
2/2/2012	18	6,010	5	2	2	63	70
4/2/2012	20	6,010	5	2	2	60	68
7/2/2012	23	6,010	5	3	2	45	64
9/2/2012	25	6,010	5	2	1	51	76
11/2/2012	27	6,010	5	2	1	56	76
16/2/2012	32	6,010	5	2	1	58	75
18/2/2012	34	6,010	12	4	3	70	75
21/2/2012	37	6,010	13	3	2	80	84
23/2/2012	39	6,010	11	3	2	77	82
25/2/2012	41	6,010	11	3	2	73	79
28/2/2012	44	6,010	11	3	2	77	81
1/3/2012	46	6,010	20	5	3	76	83
3/3/2012	48	6,010	20	7	5	65	75
6/3/2012	51	6,010	21	5	4	78	82
8/3/2012	53	6,010	21	3	3	85	88
10/3/2012	55	6,010	20	5	4	74	81
14/3/2012	59	6,010	38	18	18	52	53
16/3/2012	61	6,010	45	18	17	61	61
19/3/2012	64	6,010	40	22	19	46	52
21/3/2012	66	6,010	39	18	17	54	56
23/3/2012	68	6,010	39	14	13	64	67
26/3/2012	69	6,010	40	16	15	61	62
28/3/2012	71	6,010	63	21	19	66	70
2/4/2012	77	6,010	68	20	19	71	72
4/4/2012	79	6,010	67	45	37	33	44
6/4/2012	81	6,010	61	39	37	36	39
9/4/2012	84	6,010	62	42	39	31	36

Table A-12 Phenol data throughout the operation period of plug-flow reactor (cont.)

Date	Time	SRT	Phenol			%Removal	
			Influent	6th port	Effluent	6th port	Membrane
11/4/2012	86	6,010	63	40	35	36	44
30/4/2012	107	1,000	5	1	1	76	87
2/5/2012	109	1,000	5	1	1	76	89
4/5/2012	111	1,000	5	1	1	82	90
7/5/2012	114	1,000	5	1	1	77	83
9/5/2012	116	1,000	5	1	0	74	91
11/5/2012	118	1,000	5	1	1	76	87
14/5/2012	121	1,000	11	2	2	83	85
16/5/2012	123	1,000	11	2	1	79	95
18/5/2012	125	1,000	11	2	1	82	91
21/5/2012	128	1,000	11	1	0	92	96
23/5/2012	130	1,000	11	1	1	92	94
28/5/2012	135	1,000	20	8	6	59	72
30/5/2012	137	1,000	21	8	8	63	64
1/6/2012	139	1,000	20	4	4	81	81
4/6/2012	142	1,000	21	6	4	71	80
6/6/2012	144	1,000	21	6	4	74	80
8/6/2012	146	1,000	22	4	4	82	83
11/6/2012	149	1,000	41	12	10	70	75
13/6/2012	151	1,000	40	11	10	72	74
15/6/2012	153	1,000	41	12	9	70	78
18/6/2012	156	1,000	41	11	10	72	76
20/6/2012	158	1,000	39	11	9	71	77
22/6/2012	160	1,000	40	12	10	70	75
25/6/2012	165	100	21	4	3	79	86
27/6/2012	166	100	21	4	2	82	90
29/6/2012	168	100	22	5	4	77	82
1/7/2012	170	100	22	5	3	77	84
2/7/2012	171	100	41	12	9	71	77
4/7/2012	173	100	40	10	8	76	79
6/7/2012	175	100	38	13	10	66	73
9/7/2012	178	100	38	12	9	69	75
11/7/2012	180	100	38	12	10	67	75
13/7/2012	182	100	38	11	10	70	74
18/7/2012	186	50	37	13	12	66	67
25/7/2012	193	50	37	16	16	55	57
30/7/2012	198	50	37	11	10	70	73
1/8/2012	200	50	39	10	10	74	74
3/8/2012	202	50	38	13	11	66	70

Table A-13 SS, VSS and sludge wasted of CSTR

Date	SS (mg/l)	VSS (mg/l)	Sludge wasted (ml/d)
28/1/2012	2008	1608	-
19/2/2012	5000	2266.667	-
16/3/2012	12000	4600	-
7/5/2012	11824	3648	2
18/5/2012	8956	3324	2

Table A-14 SS, VSS and sludge wasted of plug-flow reactor

Date	SS (mg/l)	VSS (mg/l)	Sludge wasted(ml/d)
28/1/2012	20100	3000	-
19/2/2012	18229	3486	-
28/2/2012	14633	4533	-
16/3/2012	12200	4575	-
28/3/2012	16100	4300	-
30/4/2012	9757	3374	10
7/5/2012	13490	3552	10
18/5/2012	20100	4218	10
3/6/2012	17686	3066	10
14/6/2012	14938	3465	100
29/6/2012	6883	1448	100
5/7/2012	8462	1900	100
16/7/2012	5825	1573	200
23/7/2012	6490	1730	200

APPENDIX B

SRT CALCULATION

1. SRT of 65,000 d of CSTR

SRT = VX_{inside}/Q_wX_w

=14000 ml/(0.215 ml/d) ; Q_w=3ml/2w

= 65,000 d

2. SRT of 6,010 d of plug-flow reactor

SRT = VX_{inside}/Q_wX_w

=$VX_{(inside, floated)} + VX_{(inside, settled)}/Q_wX_w$ Q_w=3ml/2w

=[(0.12*0.97*0.125) m^3*1000 l/m^3*119mg/l]+[(0.12*0.97*0.075)m^3*1000 l/m^3*3978mg/l]/[(3978 mg/l*0.243 ml/d)+(119 mg/l*42.86 ml/d)]/(1,000 l/m^3)

= 6,010 d

BIOGRAPHY

Name	Krisadee Promtavee
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Education	
2006 – 2009	B. Eng. in Environmental Engineering, Chiang Mai University, Thailand.
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Thesis Presentation	Oral presentation at the 3rd International Conference on Green and Sustainable Innovation, 25 May 2012, Chiang Mai, Thailand