FILAMENTOUS FOAMING PROBLEM CONTROL IN ACTIVATED SLUDGE

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CERTIFICATE OF ORIGINALITY

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__________________ (Signed)

HUANGFU Yanchong (Name of student)

This thesis is dedicated to my parents.

For their endless love, support and encouragement

ABSTRACT

Filamentous foaming is a common problem happened in activated sludge treatment plants. It often deteriorates the quality of final effluent. It was previously identified as that the cause of foaming problem was the overgrowth of filamentous bacteria, like *Microthrix parvicella*. In this study, characteristics of filamentous and floc-forming bacteria were identified firstly. The maximum specific growth rate and the half-velocity constant(Ks) of the Monod kinetics model for filamentous and floc-forming bacteria, were obtained from the batch culture growth data, followed by processing with nonlinear regression method. It was discovered that the growth rate of *Microthrix parvicella* , under the condition of Food to Microorganism (F/M) ratio below 0.71 mg of BOD/(mg of MLSS•d), was higher than non-filamentous bacteria like, like *P.aeruginosa*.

Based on the theory of growth kinetics, “Revised Feast-Famine Operation (RFFO)” technology was developed in reducing the filamentous foaming problems. In the feast phase, with a high F/M ratio, activated sludge cultures consume nutrients and produce the stored polymers, like Polyhydroxyalkanoate (PHA), simultaneously. In the famine phase, with a low F/M ratio, activated sludge cultures consume stored polymers as a carbon and energy source. The sludge microbes underwent a repetitive switch between high and low F/M ratio during the course of wastewater treatment. In this dissertation, it will also discuss on the metabolic model for the

activated sludge cultures. The experimental results revealed that FFO strategy effectively suppressed overgrowth of filamentous germs in keeping with high biological oxygen demand (BOD) removal efficiency. The overall performance of degree of foaming also indicated that the RFFO strategy effectively and rapidly restrained the overgrowth of filamentous bacteria in the reactor system.

Finally, it was integrated with the mathematical modeling by evaluation of the experimental data. The model proves it is applicable to simulate the process of RFFO in controlling filamentous foaming problem. The technology introduced here is a contribution to a further development of activated sludge processes for filamentous foaming control.

LIST OF PUBLICATIONS

Journal Articles

Huangfu, Y. C. and Kan, C.W. (May 2012), "Modeling of Feast-Famine Operation Technology for Filamentous Foaming Control in Activated sludge", (Under submission to Journal)

Liu Y.H., Yang Y., Zhong, D., **Huangfu Y.C.**, Tsang Y.F., Sin, N. Shirley, Lo, W.H. Thomas, Chan, Y.S. Gilbert, Chua H.(2012) "Study of Improvement of Activated Sludge Process by Feast-Fast Operation in Treating High Organic Concentration Wastewater", Bioresource Technology, (submitted)

Conference Papers

Huangfu, Y. C. and Chua, H. (Nov 2011), "Feast-Famine Operation Technology for Filamentous Foaming Control in Wastewater Treatment Process", 47th Annual Water Resources Conference Albuquerque, New Mexico, USA

Huangfu, Y. C. and Chua, H. (Jun 2011), "Role of Wastewater Treatment in the Sustainable Development in Hong Kong", Third International Postgraduate Conference on Infrastructure and Environment, Hong Kong

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CHAPTER 1 INTRODUCTION

1.1 Research Background

As a densely populated international world-trading center, Hong Kong has suffered a water shortage for most of its 160-year history (Lu and Leung 2003). Nowadays, finding adequate water supplies is still a significant task for the local population especially in the current situation of sustainable development in Hong Kong. Treating and recycling the wastewater becomes a critical technology in optimizing the use of water resource. So wastewater treatment plays a significant role in the environmental sustainable development around the world.

Generally speaking, two kinds of method, activated sludge treatment method and membrane process method are commonly used in wastewater treatment plant. Because of lower construction cost and easier operational management, activated sludge treatment method has been widely used in municipal wastewater treatment plants almost a hundred years.

1.1.1 History of activated sludge process

The Activated Sludge process has been widely applied in sewage treatment almost one hundred years. It was discovered in 1913 in the UK by Edward Arden and W.T.Lockett, when conducting research for the Manchester Corporation Rivers

Department at Davyhulme Sewage Works. It was named as activated sludge, because the sludge had been activated during the process that occurs in treating the domestic and industrial wastewater. This treatment method can remove soluble and insoluble organics from the wastewater by growing up a flocculent microbial suspension and settling down in a conventional gravity clarifier.

In the year of 1914, Arden and Lockett distributed the paper about the Activated Sludge Method to treat with wastewater in the Chemical Industrial Annual Conference in United Kingdom, as shown in Figure 1. Hence, this year was the starting year in the history of Activated Sludge Treatment method. At the beginning, fill-and-draw systems were brought into operation. However, it was quickly converted to continuous-flow system. Despite there are many frequent problems occurred, it still became popular and spread world-wide. Donaldson suspected that back-mixing in plug-flow aeration basins, that changes the hydraulic behavior and the substrate regime to a completely mixed mode, was an important factor promoting to the development of bulking sludge.

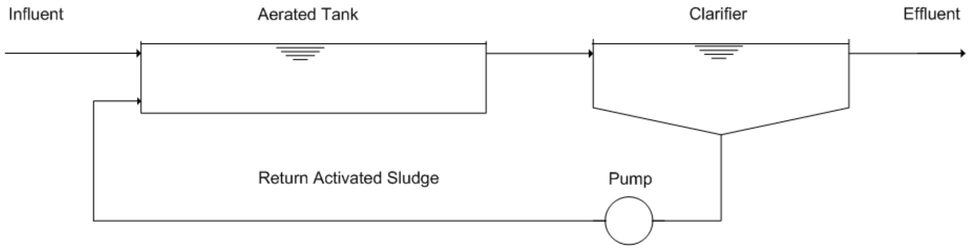


Figure 1The scheme of activated sludge process

On the study of the use of fill-and-draw technology, Pasveer developed the oxidation system. So this kind of system attracted more attention in Europe for several years. But soon, it was converted to continuous-flow oxidation ditches by the addition of a secondary settler and solids recycle. In the 1970s Chudoba et al developed the selector reactor, which was the most widely applied technology to control bulking sludge. The use of selectors has been successful in reducing bulking problems in many activated sludge systems, although there were regular reports of their failure.

However, nowadays, there are still lots of questions and convicted views about this wastewater treatment method, for example, the foaming and bulking problem during the process of Activated Sludge Treatment, though it has already developed for about 90 years. Sludge bulking and bacterial foaming are common problems in most of the activated sludge plants in Hong Kong and overseas countries. Excessive bacterial foam was discovered to be associated with the problem of sludge bulking. It is also reported that 60% of the plants with bacterial foaming had bulking problems (Blackall, 1990).

1.1.2 Activated sludge foaming

Activated sludge treatment method included two crucial biological processes in two tanks. One is called aeration tank, for biochemical processes by removing organic pollution. And another tank is called sedimentation tank, for gravity sedimentation of the formed biomass by microbial growth ((Wanner 1994). Both of them decide the quality of final effluent during wastewater treatment. Two roles played in the sedimentation tanks, which comprises twofold, to separate activated sludge from wastewater and to thicken the separated activated sludge. Water content of residual activated sludge can be minimized before returning to the reaction tank. The categories of solid separation problems occurred in the activated sludge treatment plant are shown as following,

- Dispersed growth;
- Pinpoint flocs;
- Viscous bulking;
- Rising sludge;
- Filamentous bulking;
- Foaming and scum formation

However, there still exist too many operational problems in the sewage treatment plant. Activated sludge foaming is a common operational problem in activated sludge process by integrating the poor ability of solids separation in the treatment plants and deteriorating the quality of final effluent. Foaming formation is a noticeable solid separation problem around the worldwide activated sludge plants. Jenkins described foaming as "formation of a stable, viscous, chocolate-colored scum layer on the surface of aeration basins and secondary clarifiers" (Jenkins

2004). The presence of foaming, which was stated as the presence of thick masses of microbial filaments, is firstly reported by Anon. The cause of foaming is due to the overgrowth of filamentous microorganism, like *Nocardia* foam organisms or *Microthrix parvicella*.

1.1.3 Problems Associated With Foaming

The filamentous foaming attracted a number of problems so that operational costs in the activated sludge plants were being substantially increased during the past two decades. It is recorded that the foam layer can be more than a meter thick and accumulates as much as already covering the walkway. Blackall et al. (1985) categorized the following problems associated with foaming,

1) The operators in the sewage treatment plants need to do extra housekeeping;
2) Foaming blocks scum removal systems;
3) Oxygen transfer is diminished between surface and bottom of the aerated basin;
4) Pathogens in the foam will be dispersed by wind blowing;
5) It can produce odour problems;
6) Quality of final effluent will be seriously deteriorated through an increase in effluent suspended solids and chemical oxygen demand (COD).

1.2 Research Motivation

Although engineering technology dealing with wastewater engineering has a tremendous development in the recent decades, there are still many problems in activated sludge treatment plants. Activated sludge foaming is one of the serious problems occurred in many sewage treatment plants. In this research, it aims to fill up the gap in solving the filamentous foaming problem in the activated sludge plants.

1.3 Research Objectives

This MPhil study aims to conduct research in accompany with the follow four specific goals,

- To identify of the predominant filamentous microorganism;
- To study the factors causing the sludge bulking problems;
- To evaluate a new selector in controlling the foaming problem;
- To develop a mathematical model envisaging the foaming problem control.

1.4 Thesis Outline

The chapters of the dissertation are organized as follows:

Chapter 1 (Introduction), the current chapter, introduces the background and motivation for the proposed research and expounds the objectives to be pursued in this MPhil project.

Chapter 2 (Literature Review) contains a review of the literature regarding activated sludge foaming problem on four topics: Activated sludge separation problem, Filamentous microorganism in activated sludge foaming, control of filamentous foaming, and study of mathematical modeling in activated sludge.

Chapter 3 (Methodology), presents the method to identify the predominant filamentous organism. Then it will introduce the Revised Feast-Famine-Operation (RFFO) System for Filamentous Foaming Control. The study of mathematical modeling in activated sludge foaming control will be included.

Chapter 4 (Results and discussion) indicates the growth kinetic study of the two important microorganisms, including the specific growth rate of *Microthrix parvicella* and *P.auruginosa* under different F/M ratio. Then it focuses on the evaluation of the performance of RFFO in controlling the filamentous foaming problem. Later, the mathematical modeling of the RFFO is presented in this chapter.

Chapter 5 will have a Conclusions and Recommendation for future study.

1.5 Terminology

In this dissertation, a variety of terms have been used for elaborating the specific work conducted in this project, like experimental design, system set-up and modeling work. The terminology used commonly for key concepts and terms in this dissertation is summarized in Table1. In some cases, confusion arises with the use of the terms bacteria, microorganisms, microbes and germs, which are often used interchangeably. In fact, they have the same meaning but different words.

Term	**Definition**
Activated sludge	A group of bio-solids used for treating the wastewater by reaction with air
Filamentous bacteria	These kinds of bacteria are surrounded by a sheath that contains many individual cells
Foaming	A floatation process involving interaction among sludge, gas bubbles, surfactants and hydrophobic particles
Foaming Control	Specific methods in order to inhibit the foaming problem occurred in the activated sludge
F/M ratio	Food to Microorganism ratio, a measure of food provided to bacteria in activated sludge
Feast phase	High F/M ratio, it means the amount of food provided

	largely exceeding the amount of bacteria(Bacteria “feel full” while consuming)
Famine phase	Low F/M ratio, it means the amount of food provided is less than the amount of bacteria(Bacteria “feel hungry” while consuming)
Feast-Famine Operation	During the FFO, the reaction tank switches from Feast(Famine) phase to Famine(Feast) phase after each cycle
HRT	Hydraulic Retention Time
SRT	Sludge Retention Time

Table 1 Terminology commonly used in this project

CHAPTER 2 LITERATURE REVIEW

This chapter reviews literature in five components, including the activated sludge process, the major separation problems in the sewage treatment plants, microorganisms occurred in the filamentous foaming problem, the common control methods of activated sludge foaming and use of mathematical modeling in the wastewater treatment.

2.1 Activated sludge process

2.1.1 Definition of Activated sludge

The reason why it was defined as Activated Sludge is that the sludge had been activated during the process that occurs in treating the sewage and industrial wastewater. This process can remove soluble and insoluble organics from the wastewater and to convert this material into a flocculent microbial suspension. After biochemical reaction, they can settle well in a conventional gravity clarifier and then discharge into the water body. So the activated sludge is the key element in the wastewater treatment process. Richard J. Runion (2005) stated that activated sludge is the process of the wastewater treatment organisms in the aeration tank which grow and multiply to form an active suspension of biological solids. It is a truly aerobic treatment process since the suspension of biological cells is in a liquid medium containing dissolved oxygen.

Generally speaking, the activated sludge process is a wastewater treatment method in which the carbonaceous organic matter of wastewater provides an energy source for the production of new cells for a mixed population of microorganisms in an aquatic aerobic environment. The overall biochemical reaction leading to organic and nutrients removal in an aeration tank can be described by the following equation,

Organic matter + Nutrients + O2 → CO2 + H2O + Biomass + Energy

Furthermore, in order to show the removal procedure of soluble carbon in activated sludge process more clearly, it is introduced the following model, as shown in Figure 2. The Ss stands for soluble carbon. So stands for dissolved oxygen. XB means insoluble biomass

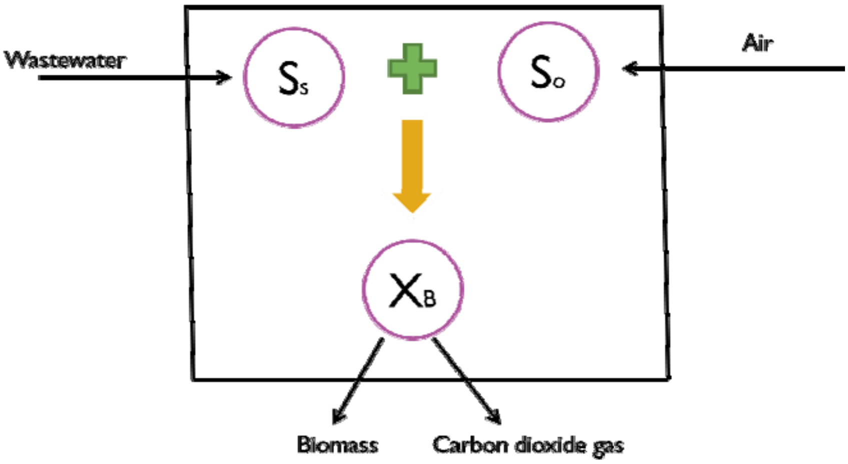


Figure 2 A simple model describing the removal procedure of soluble carbon in activated sludge process

Figure 3 shows the conventional activated sludge process. From the figure, it is noted that the wastewater flow into the aeration tank and out from the clarifier after aeration and sedimentation.

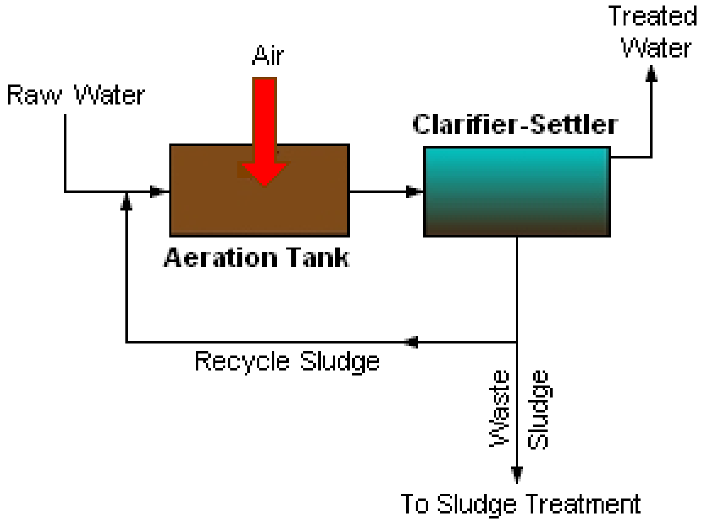


Figure 3 The activated sludge process (Conventional)

2.1.2 Current situation of the Activated sludge method

There are two kinds of methods, activated sludge treatment method and membrane process method, commonly used in the current wastewater treatment plant. Because of lower construction cost and easier operational management, activated sludge treatment method has been widely used in municipal wastewater treatment plants almost a hundred years. However, there are various separation problems occurred in the activated sludge plants. The activated sludge foaming is a common operational problem in activated sludge process by incorporating the poor ability of solids separation in the treatment plants and deteriorating the quality of final effluent.

2.2 Activated sludge separation problem

Many problems can occur in activated sludge treatment plants that adversely affect the quality of final effluent. Activated sludge separation problem is one of the major concerns by inducing to the dysfunction of the operation in treating wastewater. These activated sludge problems include dispersed growth (non-settleable) growth, pin floc problems, nitrification and de-nitrification problem and filamentous bulking and foaming(Richard 2003).

In order to solve the activated sludge separation problems to keep the good quality of final effluent, it is essential to identify such kinds of problems firstly. This section will present the common settling problems occurred in the activated sludge plants and the formation of activated sludge foaming.

2.2.1 Settling problems in activated sludge plants

2.2.1.1 Dispersed growth (non-settleable) and pin floc problems

In the sedimentation tanks of treatment plants, the floc-forming bacteria makes a great role by forming a floc before the sludge settling. Outside of the layer of floc-forming species, there is a kind of material, called glycocalyx, which consists of polysaccharide, protein and cellulose fibrils that can group together the bacteria to form a floc. The formation of floc is only occurred at lower growth rates and lower nutrient levels, essentially the low food to microorganism ratio (F/M) conditions.

Little gravity of floc-forms induces to settling problems in activated sludge sedimentation. It is because of the low sedimentation rate that there is no obvious zone settling occurs in secondary settling tanks. After microscopy visual observation, it was found that the individual cells or small clumps with diameter only ranged from 10-20μm. The principal cause of dispersed growth is due to the low production of extracellular polymers substances existed in the microorganisms. This is again caused by high concentration of readily degradable substrates or the presence of some toxic and inhibitory compounds in sewage (Toni, 2005).

The small flocs, also termed pin floc, ensued from small, weak flocs in activated sludge which subject to hydraulic surge flotation in the final clarifier leading to a turbid effluent(Richard 2003). These kinds of problems are generally described as macrostructure floc-forming failure. Figure 4 presents the common floc components in activated sludge sedimentation.

Figure 4 Common floc components

2.2.1.2 Nitrification and de-nitrification problem

The nitrification and de-nitrification problem will cause the rising sludge in the surface of secondary clarifier. The rising sludge is shown in Figure 5.Common activated sludge separation problems is shown in Table 2.

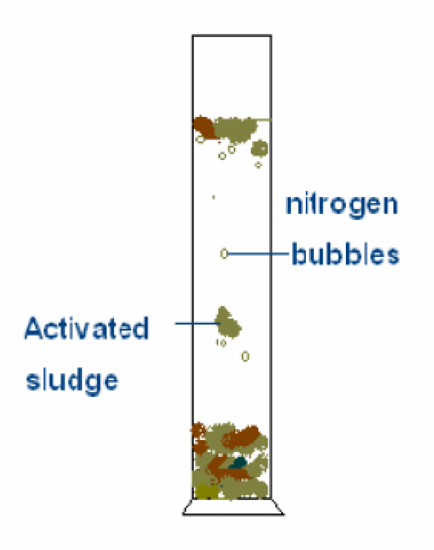


Figure 5 The rising sludge

Table 2 Summary of common activated sludge separation problems (Toni,2005)

Name of Problem	Dispersed growth	Slime (jelly) Viscous bulking	Pin floc (or pinpoint floc)	Bulking	Rising sludge	Foaming/scum formation
Cause of Problem	Microorganisms do not form flocs but are dispersed, forming only small clumps or single cells	Microorganisms are present in large amounts of extracellular slime	Small, compact, weak, roughly spherical flocs are formed, the larger of which settle rapidly. Smaller aggregates settle slowly.	Filamentous organisms extend from flocs into the bulk solution and interfere with compaction and settling of activated sludge.	De-nitrification in secondary clarifier releases poorly soluble N2 gas, which attaches to activated sludge flocs and floats them to the secondary clarifier surface.	Caused by (1) non-degradable surfactants and (2) the presence of *Nocardia* and sometimes (3) the presence of *Microthrix parvicella*
Effect of Problem	Turbid effluent. No zone settling of sludge	Reduced settling and compaction rates. Virtually no solids separation, in severe cases in overflow of sludge blanket from secondary clarifier.	Low sludge volume index (SVI) and a cloudy, turbid effluent.	High SVI; Quality of final effluent is deteriorated seriously.	A scum of activated sludge forms on the surface of the secondary clarifier.	Foams float large amounts activated sludge solids to the surface of treatment units. Foam accumulates and putrefies. Solids can overflow into secondary effluent or overflow onto walkways.

2.2.1.3 Foaming problem in activated sludge plant

Foaming formation in activated sludge plants is a stubborn solid separation problem around the world. Jenkins described foaming as “formation of a stable, viscous, chocolate-colored scum layer on the surface of aeration basins and secondary clarifiers” (Jenkins 2004). The presence of foaming, which was stated as the presence of thick masses of microbial filaments (Anon,1969), is firstly reported by Anon. The cause of foaming is due to the overgrowth of filamentous microorganism, like *Nocardia* foam organisms or *Microthrix parvicella*.

There are also other kinds of foaming problems, such as the white foam arising from poorly biodegradable surfactants (Jenkins 2004). But in this study, it is only focused on the foaming problem caused by certain bacteria. The foams caused by these bacteria occurred with highly stable brown foam or thick scum. In the past 40 years, the foaming problems in the activated sludge plants were reported more frequent than previously (Wells and Garrett, 1971). In the first published paper, the foaming problem was described as the presence of thick masses of microbial filaments. Afterwards, it was revealed that these bacteria were right angled branching *Actinomycetes* under the microscope observation. Later, these bacteria were identified as the genus *Nocardia* (Lechevalier, 1974).

Many problems associated with foaming problem in the activated sludge plants. Firstly, as the thick foam layer, it will be more than a meter thick so that it can cover the walkway, handrails, and surrounding areas in the plants, which can increase the degree of dangerous for the technician. It can also block the access to the equipment, and requires extra housekeeping on the part of operator. The operational cost in the plant will increase if blockage of foam removal systems occurred. Secondly, the foam scums will reduce the oxygen transfer between the surface and the bottom in the reaction tank with aerated condition. Thirdly, the foams will result to odor problems. Finally, the most serious consequence caused by the foaming problems is the deteriorative effluent quality through an increase in effluent suspended solids and BOD, where the foam reaches to the sedimentation tank. In addition, the flied foams carried by wind will enhance the dispersal of harmful pathogen which existed in the foams.

2.2.1.3.1 Types of Activated Sludge Foam

In the normal operations of activated sludge plants, there is more or less a little bit foaming in the aeration tank. However, it will become a large problem when huge amount of foams existing in the aeration tanks or other treatment parts. If so that, it can affect the efficiency of treating industrial and domestic wastewater, and this will be presented the details later.

Generally speaking, there are totally three types of foam, which is shown below,

Firstly, there are some white and frothy foams being observed during the start-up of activated sludge plants. But they will disappear when the process is established;

Secondly, during the process of nitrification in the reaction tank, there will be occurring with the reaction of de-nitrification in the plant, if the air is pumped not enough for the aeration tank or sedimentation tank. Within this procedure, it can produce the gaseous nitrogen. After the gas going up, it can also result to the foaming problems, which are de-nitrification foam.

Thirdly, due to the overgrowth of filamentous bacteria, these kinds of microbes are associated with the foams and flocs, which are stable and hard to damage in a long time. They are the biological foams which were undertaken in this MPhil study.

2.2.1.3.2 Consequence of Foaming Problem in activated sludge

Firstly, the huge amounts of foams existed in the wastewater treatment plants can lead to many disadvantages. It will directly affect the quality of final effluent. Figure 6 can give you an obvious idea on these kinds of problems.

For the upper one plants work, after the treated influent goes into the aeration tank, the biological process starts up normally. Then it flows into the clarifier tank, because of good settling properties of activated sludge, it can separate completely from the wastewater.

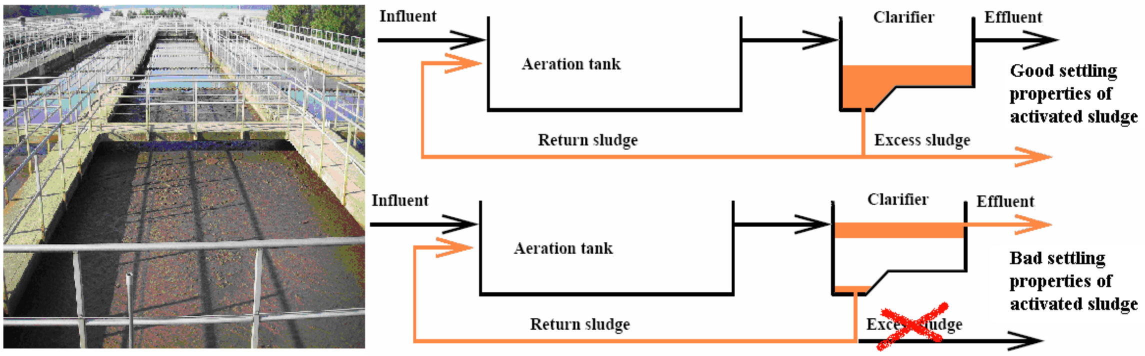


Figure 6 Consequence of the foaming problem occurred in the clarifier

For the lower one plants work, because of the overgrowing filamentous bacteria in aeration tank and sedimentation tank, a large number of foams are present in the surface of treated wastewater after accumulating for some time. The foams not only block all the surface of water, but also can increase the level of BOD with the effluent due to the bad sedimentation.

Secondly, for the obvious effect of bulking and foaming problems in the activated sludge llant is, it can deteriorate sludge settleability, resulting in decreased sludge settling rate and incompact sludge blanket, usually indicated by an increased SVI (Sludge Volume Index). Moreover, foams can interfere level sensors and hinders sequencing batch reactor (SBR) operations.

Thirdly, spillage of foam from aeration tanks to walkways can cause safety problems. Dried foam results in airborne pathogens that cause public health problems. Thick foam blocks scum removal systems and reduces oxygen supply.

Above all, due to the sludge or the foam escaping from clarifiers, foaming problems can increase BOD and suspended solids (SS) level in final effluent.

2.3 Study of Filamentous foaming

In the recent decades, many researchers in this field developed the technique for identifying the causative organisms in activated sludge mixed liquor. The principal methods are the microscopic methods based on early work by Eikelboom(Water Research,1977), which have been already published in the manuals. Most of the scientists are convinced that the foam formation was attributed to an actinomycete called " *Norcardia*", although there were evidence shown that the microorganisms belong to a large range of morphological types. It illustrates that both filamentous and non-filamentous microbes are included in the causative microorganisms in the foaming problem of activated sludge. In activated sludge, there are several kinds of microorganisms causing foaming, such as *Microthrix parvicella*, *Gordonia amarae*-like Organisms (GALO), *Skermania piniformis*, *Nostocoida limicola*, and other filamentous microorganisms. As compared with filamentous bacteria, there is less number of non-filamentous bacteria in causing the activated sludge separation problem.

So, in this MPhil study, it is only emphasis on the filamentous microorganisms, although the non-filamentous foaming microorganisms also causing such kind of problems.

2.3.1 Microbes cause foaming

In the following paragraphs, it will be presented in details for two famous filamentous microorganisms existed in activated sludge foaming, which are *Nocardia amarae* and *Microthrix parvicella*.

2.3.1.1 Nocardia amarae

Nocardia amarae is frequently found in activated sludge foaming. The morphology description of this bacteria is short trichomes, truly brached, Gram positive (Wanner 1994). Chua (1995) investigated that branched-filametnous *Nocardia amarae* was identified as the main causative bacteria in activated sludge foaming. He also proved that fatty acids that are commonly found in municipal sewage, which could be utilized by *Nocardia amara* as the sole carbon source, and their presence in the wastewater could stimulate the growth of this bacteria. It was investigated that the condition of high fatty-acid or grease content sewage could cause an overgrowth of *Nocardia amarae* with (Chua, 1995). Therefore, such scenario lead to the sludge foaming. After microscopic observation of stained samples of foaming sludge, Chua mentioned that the foaming sludge revealed an overgrowth of branched filamentous bacteria. He also discovered that *Nocardia amarae* were Gram positive with filaments of 0.5 – 1.0 by 80 – 160 microns.

2.3.1.2 Microthrix parvicella

Microthrix parvicella is discovered in many countries, such as Europe, Australia, and South Africa, and it is reported that it is a long coiled non-branched gram-positive filamentous actinomycete. In contrast, it has been less noted in the United States. Because of its larger number in cooler seasons in Europe and cooler regions of Australia, it appeared related to the temperature, which means it is more prominent in the cooler environmental condition.

During the aeration conditions, *Microthrix parvicella* is more prominent in growth when aeration is intermittent. It can be suppressed if it is under continuous oxygen supply (18H.Slijkhuis, Water Research, 1988). The reason is that there are more reduced sulfur and nitrogen compounds in the intermittent aeration tanks than the fully aerated reaction tanks. *Microthrix parvicella* requires these kinds of compound in their metabolic processes. This is also the reason for that it is also commonly found in the stages both having anaerobic and anoxic conditions, like biological nutrient plants (BNR).

Dr. Slijikhuis also showed that *Microthrix parvicella* will only grow on long-chain fatty acids but not on the short-chain fatty acids. This study also proves that the rapid uptake of lipids in the metabolism of *Microthrix parvicella*, which can be nearly 35% dry weight (H. Slijkhuis,Appl. Environment Microorganism, 1983). Because of its property in high resistance to chlorination as compared to other filamentous microorganisms, the method by the use of chlorine would be no significant effect in the activated sludge foaming control. Table 3 shows the dominant filamentous microorganisms in foaming activated sludge from different countries. After observation from this table, it is easy to note that *Microthrix parvicella* ranks No.1 in most of the countries.

Table 3 Dominant filamentous microorganisms in foaming activated sludge from different countries

Country	Ranking			Reference
	1	2	3	
Australia	*M.parvicella*	GALOs	Type0092	Seviour *et al.*, 1990
Czech Republic	*M.parvicella*	GALOs	*N.limicola*	Wanner *et al.*, 1998
France	*M.parvicella*	Type0675	GALOs	Pujol et al., 1991
South Africa	Type0092	M.parvicella	GALOs	Blackbeard *et al.*, 1986
The Netherlands	*M.parvicella*	GALOs	*N.limicola*	Eikelboom, 1991
UK	*M.parvicella*	*N.limicola*	GALOs	Foot, 1992
Italy	*M.parvicella*	GALOs	Type0675	Paolo *et al.*,2000

Table 3 Dominant filamentous microorganisms in foaming activated sludge from different countries

2.4 Control methods of filamentous foaming

Activated sludge bulking and bacterial foaming will lead to poor effluent quality. They are caused by the overgrowth of filamentous microorganisms which can be controlled by operational means. These kinds of problems are commonly happened in most of the activated sludge treatment plants as revealed by many surveys done in USA, Australia, Hong Kong, and many parts of the world.

Activated sludge foaming caused by the filamentous microorganisms is commonly occurred in many wastewater treatment plants around the world. There is still no too many efficient methods in controlling the filamentous foaming problem. Therefore, the lack of information on the filamentous microorganisms hinders the development of theoretically-based control strategies (Wanner 1994). Pitt and Jenkins summarized the most available controlling methods by sending questionnaire to each plant in the United States. They mentioned that the foaming control methods currently used includes water sprays, contact zones, chlorination of return activated sludge, and skimming of aeration tanks, aerated channels and final clarifier (Wanner 1994). A similar survey also done in Australia, the most-often used controlling methods were shown as follows in Table 4,

Control methods	Reduction in sludge age	Increase or decrease of aeration	Water sprays	Chlorine addition
Percentage	57%	33%	28%	20%

Table 4 Summary of the control methods for filamentous foaming

However, France Pujol stated that the most effective control methods were initial contact zones (73%); oxidant addition (66%); addition of antifoaming agents (57%), and coagulant addition (46%). In Jurong Sewage Treatment Works, Singapore, Two strategic approaches are taken. One uses a method modified from the floc loading theory adopted at Halifax treatment plants, UK, and another employs a periodic air application strategy.

2.4.1 Manipulation of Loading Rate

The Halifax modification approach is able to cope with sludge bulking problems while the periodic air application approach has consistently produced low SVI and is able to remove the bacterial foam over a period of time. Both methods have incurred very low costs in coping with the problems.

2.4.2 Chemical Additives

Chang also developed a new method in prohibiting the foaming problems in activated sludge treatment plants by addition of toxic chemicals such as chlorine or hydrogen peroxide to the aeration tank or the return sludge line (Chang et al.,2004; Ramothokang et al.,2003).

Moreover, some water researchers also discovered that the metal ions like calcium, magnesium, iron (Philips et al., 2003; Thompson and Forster, 2003; Agridiotis et al., 2007), synthetic polymer (Juang, 2005), are effective in solving the bulking and foaming sludge problems in activated sludge treatment plants. And also, the multi-component additives (Seka, 2001) are observed to control sludge of bulking effectively.

2.4.3 Use of Selector

However, these kinds of chemical treatment methods as mentioned previously, are very costly. Another key point is that they can only offer short-term solution as bulking and foaming will resume when chemical additions are stopped. Finally, if putting too much chemicals, it will affect the quality of effluent water.

Chudoba (1973) discovered a new theory on Kinetic selection which was an alternative way to control filamentous overgrowth effectively under low F/M condition. It also stated that substrate concentration gradient favors the growth of floc-formers, instead of filamentous bacteria, among the activated sludge microbes. In this MPhil Project, this theory is also used as a basis for the Revised Feast-Famine-Operation technology, which will be presented in details later.

2.5 Mathematical Modeling

Mathematical modeling is a very useful tool to study the complex ecosystems, like activated sludge cultures, in which many factors are acting together (Martins, Pagilla et al. 2004). There has been much work to be done in the field of activated sludge modeling. The newest publication by the International Water Association (IWA) task Group presented the Activated Sludge Model 3 (ASM3), which incorporated the modeling of storage polymer metabolism and the conversions occurring in selector-like system(Henze 2000). Basically, two groups of models are considered that includes the bacterial physiology and kinetics model.

In this MPhil study, the mathematical model as a tool to control the filamentous foaming problem. Figure 7 represents the process in the development of a verified model, which indicates the key components in this procedure.

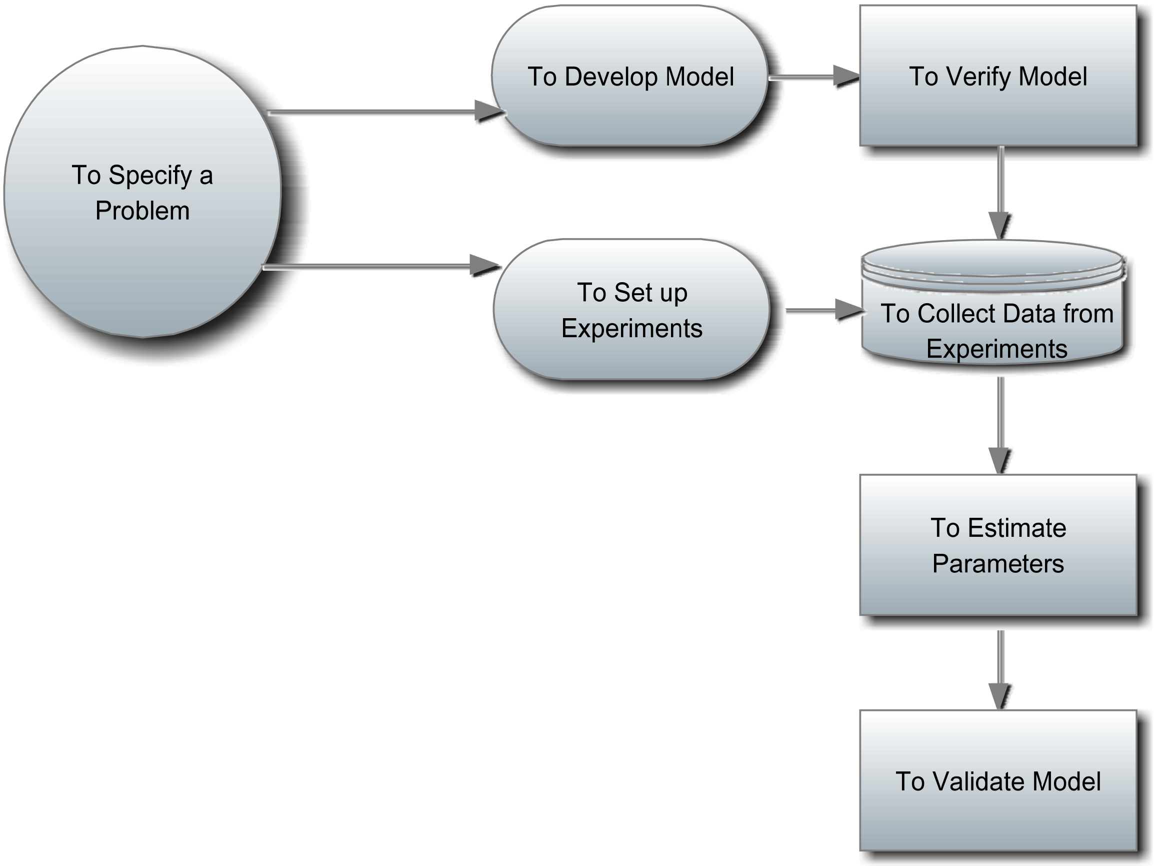


Figure 7 Process to evaluate a model

2.6 Summary of literature review

After completing the literature review part, it was something required to draw two initial conclusions during the MPhil project, which were statement of research problem and research emphasis in this study. Details of these two points are presented in the next two pages.

2.6.1 Statement of Research Problem

The statement of research problems in this MPhil study was presented in Table 5.

Item	**Research Problem**
Filamentous bacteria identification and physiology	What physiology and morphology do the filamentous bacteria have?
Growth kinetics of filamentous bacteria	What growth kinetics characteristics do the filamentous microorganisms have?
Development of control system	Which kind of system is the most effective in controlling the filamentous bulking and foaming problem in activated sludge plants?
Mathematical modeling	Which kind of mathematical model can be best described for filamentous bulking sludge control?
Storage polymers	What storage polymers are stored in the filamentous and non-filamentous microorganisms?

Table 5 Statement of research problem

2.6.2 Research Emphasis in this study

2.6.2.1 Characterization of filamentous foaming problem

Obviously, it is a tough work to identify the filamentous bacteria, because there are huge amount of bacteria existed in the activated sludge system. Based on the morphological characteristics, Eikelboom developed the first identification method to recognize the filamentous bacteria in the activated sludge plants. In this study, in order for the later kinetics growth study, the morphology of the specific filamentous microorganism was approached.

2.6.2.2 Control methods of filamentous foaming problems

Another research hypothesis in this research study is to develop a novel system (Revised Feast Famine Operation System) for controlling the filamentous foaming problem in activated sludge. So it is necessary to evaluate the effectiveness of this system under long time operation.

2.6.2.3 Mathematical Modeling study in controlling filamentous foaming problems

Mathematical modeling is a must in the study of population dynamics of activated sludge systems. In activated sludge system, there are many complicated factors acting together, in which the mathematical modeling can help in the understanding of biological processes.

CHAPTER 3 METHODOLOGY

3.1 Introduction

In this MPhil study, it is the first task to identify the predominant microorganism that was responsible for the activated sludge foaming. In this section, sludge samples were collected from the Tai Po sewage treatment plant, which one was extracted from normal activated sludge, and another one was from the activated sludge with foaming problem. After studying the specified microorganism, it was introduced a novel technology in controlling the activated sludge foaming problem, which was called “Revised Feast-Famine Operation” (RFFO) System. Finally, in order to monitor the process in controlling the foaming problem in activated sludge treatment plants, mathematical modeling was incorporated into this research project.

3.2 Identification of the Predominant Microorganisms in Activated Sludge with Foaming

3.2.1 Microscopic Observation

Two samples of activated sludge were obtained at the Tai Po Sewage Treatment Plant, one was collected when foaming has occurred, while another was collected during operation without foaming. The sludge samples were examined by using light microscopy at magnification up to 400 X with a Meiji ML 5000 microscope.

3.2.2 Isolation of Predominant Microorganism from the activated sludge with foaming

The predominant microorganism in the sample of activated sludge with foaming was isolated by plate culture with Czapek's agar supplemented with 0.4% yeast extract. Afterwards, it was incubated at 28℃ for three weeks. Then, the isolated microorganism was cultured in 500 mL flasks with 100 mL in sterilized LB medium, in an orbital shaker at 28℃ and 200 rpm for 120 hours.

3.2.3 Morphological and Physiological Tests

In this section, the isolated microorganism was tested both with morphological and physiological techniques. By using the microscopy, the specific microorganism was examined in the characteristics of shape of the microbes, cell size and presence of branching. Furthermore, the Gram stain and The Neisser stain were undertaken in the staining techniques.

3.2.3.1 Gram Stain

A drop of the sample was placed in the glass slide by using a disposable pasteur pipette. Before the slide was allowed to dry, the drop was spread to form a thin film on the slide. It was then flooded with crystal violet. The specimen was flooded with gram's iodine after 30 seconds. Then the solution was drained off with decolorizer and alcohol. Then the specimen was washed with tap water for five seconds, and flooded with safranin. Lastly, the slide was washed with water, air dry and examined under microscope by using bright field oil immersion.

3.2.3.2 Neisser Stain

A drop of the sample was placed in the glass slide by using a disposable pasteur pipette. Before the slide was allowed to dry, the drop was spread to form a thin film on the slide. The specimen was stained with working solution (0.066% methylene blue, 0.11% crystal violet, 6.66% alcohol, 3.33% glacial acetic acid) for 15 seconds. The sample was then stained with Bismark Brown counter stain(0.33%) for 1 minute. Finally, it was examined under the microscope with oil immersion and direct illumination.

3.2.4 Growth Kinetics Study

In this section, it presents the method in studying the growth kinetics of the identified predominant filamentous foaming bacteria and another non-filamentous floc-forming species. The specific growth rates of these two kinds of microorganisms under different F/M ratios were investigated.

3.2.4.1 Growth Rate

The growth rate μ was defined as the following equation,

$$\mu = 1/x \cdot dx/dt \qquad \text{Equation 3.2.4.1}$$

Where, x was biomass concentration (g/L), t was time (h) and μ was biomass specific growth rate (h^{-1}).

3.2.4.2 Food to Microorganism (F/M) Ratio

F/M ratio is Food to Microorganism ratio, a measure of food provided to bacteria in aeration tank, and it is defined by the equation as shown below,

$$\frac{F}{M}\left(\frac{gBOD}{[g \cdot MLSS \cdot D]}\right) = \frac{Q \cdot So}{V \cdot X} \qquad \text{Equation 3.2.4.2}$$

Where, Q is wastewater flow rate into the aeration tank; the unit is meter cubic per day. So is concentration of soluble BOD_5 in influent, the unit is mg per liter. V is volume of aeration tank, the unit is meter cubic. X means microorganism concentration (MLSS), the unit is mg per liter. This equation can also be used as manipulation of Food to Microorganism ratio (F/M). Details will be presented in Chapter 4.

This F/M ratio is significant in assessing the metabolism of the organic matter in wastewater treatment systems, and it can also expresses the potential food availability to the microbial population. It is necessary to maintain a proper balance between the BOD of influent sewage (food) and the mass of microorganisms existed in the aerobic tank. In order to have an optimum operation in the activated sludge system, it is crucial to maintain a proper F/M ratio. F/M ratio is high means microorganisms are in feast phase, which is characterized by excess food and maximum rate of metabolism. In contrast F/M ratio is low means microorganism are in famine phase, which is characterized by large mass of microorganisms competes for the relatively smaller amount of food in the influent.

3.3 Introduction of Revised Feast-Famine Operation (RFFO) System

3.3.1 Preliminary Design for RFFO System

Before setting up the reactor, it was necessary to do a preliminary design for the future experimental work, which mainly included the volume of reaction tanks, influent rate, hydraulic retention time and sludge wastage rate. The parameters of preliminary design are shown in Table 6,

Parameters	Unit	Operation status		
		Conventional operation	Feast State	Famine State
Effecive Volume	L	6	3	3
Hydraulic Retention Time (HRT)	h	10	8.3	12.5
Sludge Retention Time(SRT)	day	15	15	15
pH		6~8	6~8	6~8
Dissolved Oxygen	(mg/L)	2~4	2~4	2~4
Influent Flow Rate	(L/h)	0.6	0.36	0.24
Returned sludge rate	(L/h)	0.25	0.06	0.21
F/M Ratio	gBOD/gMLSS-d	0.4	0.65	0.23
Sludge Wastage Rate	(L/d)	0.4	0.2	0.2

Table 6 Operation parameters of Revised Feast-Famine Operation System

3.3.2 Experimental Setup

In this study, it is introduced a new selector, called “Revised Feast-Famine-Operation (FFO)” system. As shown in figure 8, this system is a revised two parallel sequencing batch reactor. The first significant revision of this system, which is different from the previous design of “Feast-Fast-Operation (FFO)” (designed by Prof. Chua), is the addition of an activated sludge mixer, which is used to well mix the activated sludge before returning to the reaction tanks in participating to the reaction of next cycle. The second revision is that both of the Feast Unit Tank and Famine Unit Tank is a single Sequencing Batch Reactor, which was different from the previous Two Stage reactor design. The sludge mixer is also used to control the amount of sludge in returning to the aeration tanks, so that it can manipulate the Food to Microorganisms ratio (F/M ratio) in the activated sludge process.

Figure 10 depicts the scheme of this laboratory scale reactor. It included two parallel aeration tanks, Feast Unit Tank and Famine Unit Tank, in which both of them were equipped with a stirrer and air pump at the bottom. In fact, this reactor is a “Double Revised” Sequencing Batch Reactor (SBR). A mechanical mixer was used to provide well mixed conditions for the activated sludge before returning to the reaction tank. The working volume of Feast Unit Tank, Famine Unit Tank and Activated Sludge Mixer is 3.5L, 3.5L and 1L, respectively. The flow rates of influent, internal transfer and return sludge for each tank were controlled by six peristaltic pumps, as they are shown in the APPENDIXII at the end of this dissertation.

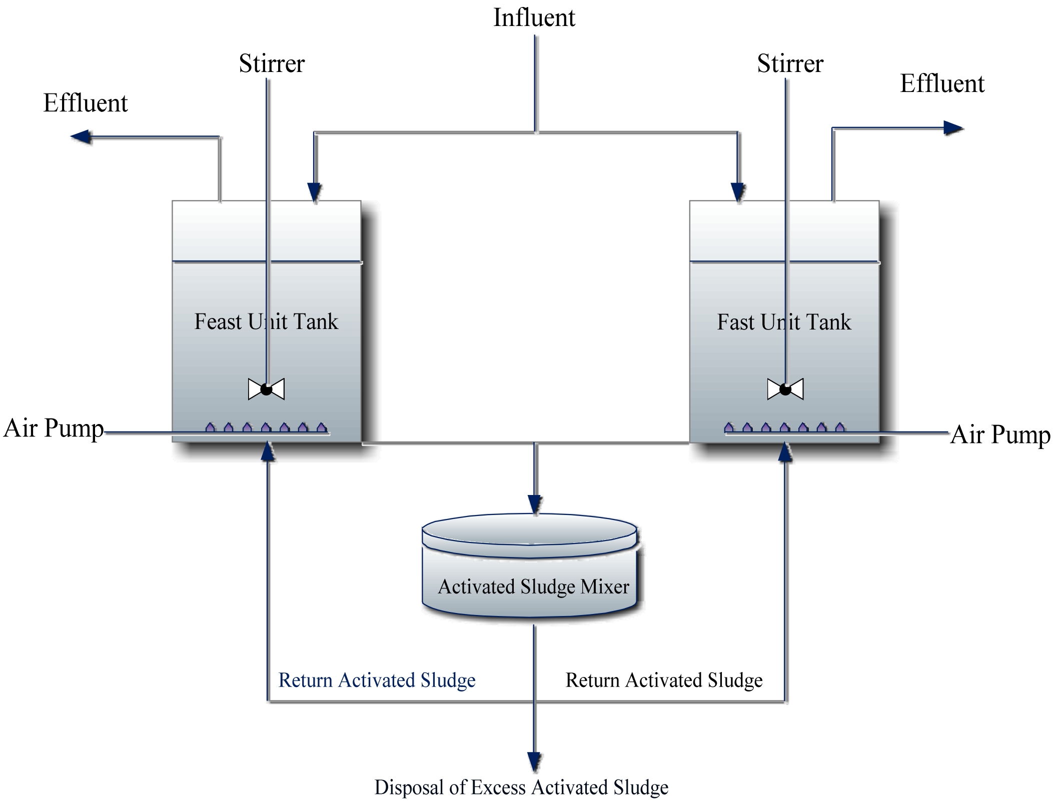


Figure 8 Revised Feast-Famine-Operation system

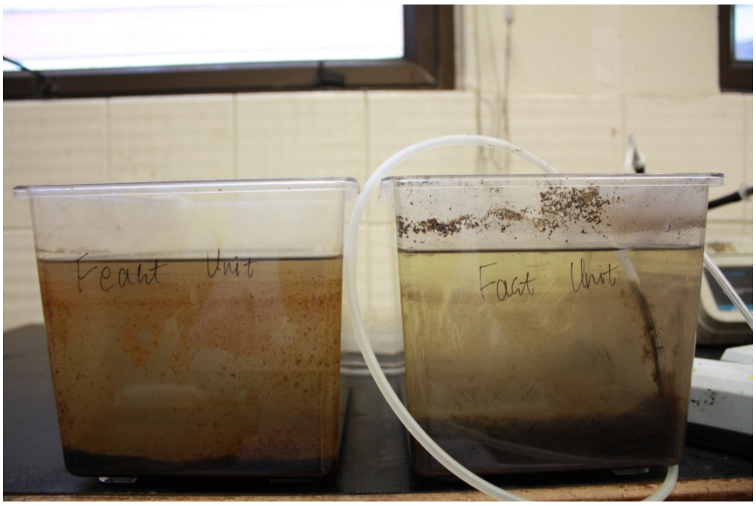


Figure 9 Feast Unit Tank and Famine Unit Tank

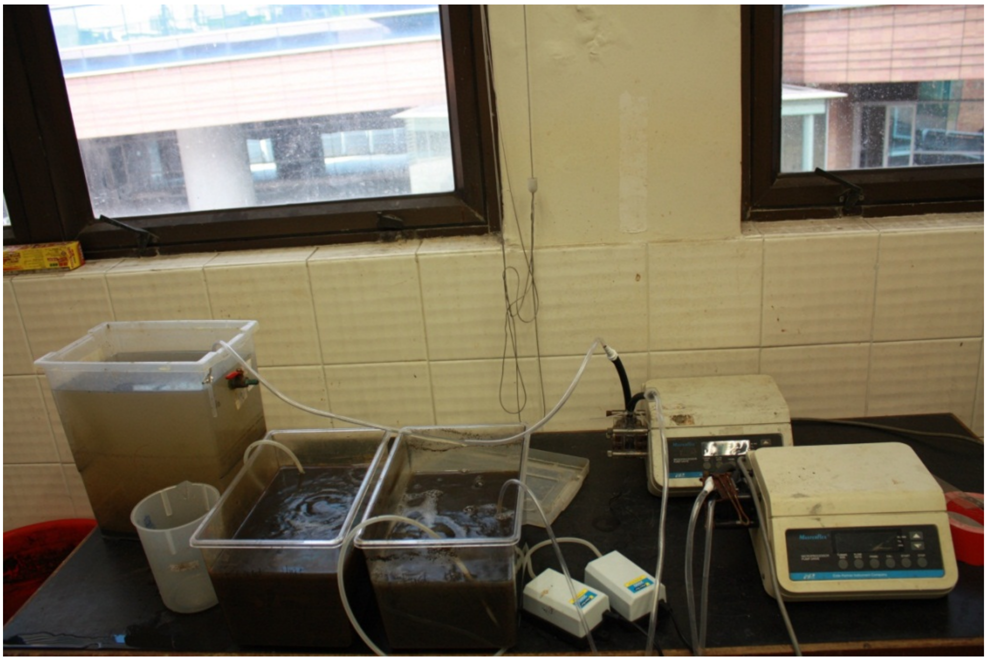


Figure 10 Scheme of RFFO system

3.3.3 Composition of Synthesized Wastewater

In order to ensure a stable and consistent feed to the reactor, the synthetic wastewater was applied throughout these experiments. Composition of synthetic influent is described in Table 7. The prepared synthetic sewage proposed by (Chua, Lo et al. 2000) can result in a biological oxygen demand (BOD_5) with 470 mg/L, chemical oxygen demand (COD) with 800 mg/L, and BOD_5: COD ratio of about 0.6.

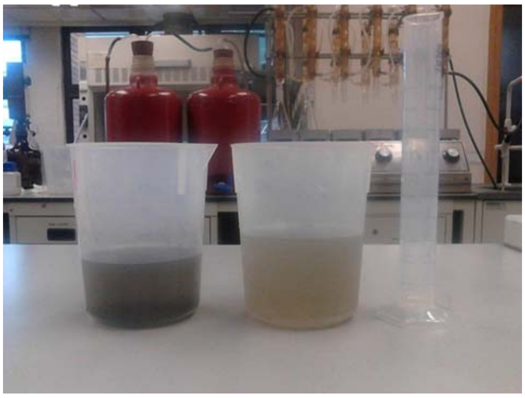


Figure 11 Synthesized Wastewater

Item	Concentration (mg/L)
$C_6H_{10}O_6$	800
NH_4Cl	63
KH_2PO_4	2796
Na_2HPO_4	2834
Nitrilotriacetic acid	200
$MgSO_4$	289
$CaCl_2 \cdot 2H_2O$	67
$(NH_4)_2Mo_7O_{24} \cdot 4H_2O$	0.185
$FeSO_4 \cdot 7H_2O$	2.480
EDTA	0.250
$ZnSO_4 \cdot 7H_2O$	1.095
$MnSO_4 \cdot 4H_2O$	0.203
$CuSO_4$	0.020
$CoSO_4 \cdot 7H_2O$	0.024
$Na_2B_4O_7 \cdot 10H_2O$	0.018

Table 7 Composition of Synthesized Wastewater

3.3.4 Process of the Revised Sequencing Batch Reactor

In this study, the reactor of Revised Feast-Famine-Operation system was actually two parallel Sequencing Batch Reactors, so it was also called the Revised Sequencing Batch Reactor. For the process of the Revised Sequencing Batch Reactor (RSBR), it operates in a number of distinct time phases. The procedure of fill, react, settle and decant phases of the typical activated sludge sequencing batch reactor (SBR) are shown in Figure 12.

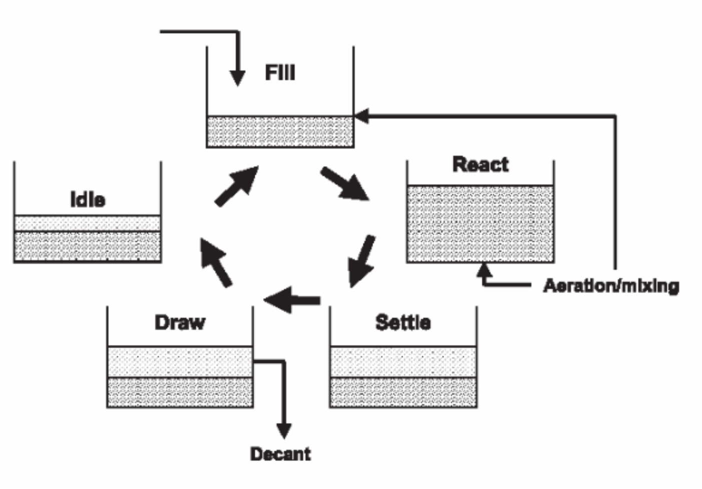


Figure 12 Process of the Sequencing Batch Reactor (SBR)

3.3.5 Analytical methods in each batch

Daily detection like COD, SVI, MLSS and DO were conducted in analyzing all mixed liquor and effluent quality parameters according to the standard methods for the examination of water and wastewater (American Public Health, Eaton et al. 2005).

3.3.5.1 Chemical Oxygen Demand (COD)

The Chemical Oxygen Demand (COD) is used as a measure of oxygen equivalent of the organic matter content of a sample that is susceptible to oxidation by a strong chemical oxidant. For samples from a specific source, COD can be related empirically to BOD, organic carbon, or organic matter. The test is useful for monitoring and control after correlation has been established. In this study, the COD is used only for monitoring the quality of final effluent.

Figure 13 Equipment in testing COD

3.3.5.2 Sludge Volume Index (SVI)

Sludge Volume Index (SVI) is the indicator of sludge settling ability for most of the wastewater treatment plant. To maintain good quality of sludge in activated sludge process, SVI is a very important index. A low SVI means that the sludge is settling well in the sedimentation tank and giving rise to a clear effluent, so the low SVI is desirable. In most of the considerations, the sludge with SVI of less than 100 was taken as a concern of good settling behavior, for the SVI larger than 200 indicates the sludge in an ill-conditioned sludge. Well settled activated sludge leaves a clear supernatant after sedimentation.

3.3.5.3 Dissolved Oxygen (DO)

Dissolved Oxygen (DO) play a critical role in the activated sludge. In this study, normally it was controlled in the level between 3 mg/l to 5 mg/l. The DO was measured by DO meter (YSI Model 5000).

3.3.5.4 Mixed liquor suspended solids (MLSS)

Mixed Liquor Suspended Solid (MLSS), is used to quantify the mixed liquor sample and suspended solids. It is also treated as a level in monitoring the suspended growth in treatment plants process. The general theory to measure is that we use the increase of weight of the filter to represent the total suspended solids, which there is a well-mixed sample filtering through a weighed standard glass-fiber filter and the retained residual in the filter is dried to a stable weight by oven, as shown in Figure 14. So the weight of total suspended solids can be obtained and the solids dissolved and total solids can be determined.

Figure 14 Heating machine and filter paper for testing MLSS

3.3.5.5 Degree of foaming

To assess the efficiency of the RFFO system in controlling the filamentous foaming problem, a foam measurement method, test of degree of foaming was employed. The results of these tests could then be used to forecast the actual depth of the foam or scum layer in the treatment plant. The test of degree of foaming was developed by Chua (Chua, 1996). It has been successfully used both in the industrial sewage treatment plant and the laboratory. The sludge samples, which were used in each test, were returned to the reactor after measurement. Details of the test can be found in the APPENDIXII.

3.4 Mathematical modeling of Revised Feast-Famine Operation System

The mathematical modeling of Revised Feast-Famine Operation (RFFO) System in controlling the activated sludge foaming problem was presented in this section. Symbols in the modeling is attached in the APPENDIX I at the end.

3.4.1 Explanation about this mathematical model

3.4.1.1 The Mass Balance Principle

Mass balance analysis is the basic concept involved in this mathematical model, that mass is neither created nor destroyed, but the form of the mass can be altered (Metcal & Eddy, 2003). The General statement is given by

Rate of accumulation of reactant within the system = Rate of reactant into the system – Rate of reactant out of the system + Rate of generation of reactant within the system

The simplified statement is given by

Accumulation = in – out + generation

In this research project, biological treatment of wastewater, it involved three components; soluble carbon, oxygen and heterotrophic biomass. The system was under steady- state conditions, so the rate of accumulation for each component is zero. Details of the mass balance equation regarding to different concentrations will be presented in 3.4.3.1.

3.4.1.2 Kinetic Models

The kinetic models are used to define the reaction rate or growth rate for each component as mentioned above. Activated sludge stoichiometry and kinetics, which are developed by the IWA (International Water Association) in the issue of Activated Sludge No.1 Model, were incorporated with the mathematical models in this research project. Details about the reaction rate and growth rates were included in 3.4.3.2.

3.4.2 Assumptions before the study of modeling

The model in this study was developed with the following assumptions:

- The two reaction tanks were perfectly mixed during the aeration phase.
- There was no dynamics in the sedimentation phase.
- There was no oxygen in the sludge wastage and sludge recycling.
- There were same substrate in the effluent, sludge wastage and sludge recycling.
- There was exponential relationship between air flow rate and oxygen mass transfer parameter.

3.4.3 The Mathematical modeling in the RFFO system

3.4.3.1 Mass Balance Equations

There is an expression can be derived from the Revised Feast Famine Operation (RFFO) system while it applies to all the variables in the process of biological reaction.

In — Out + Generation = Accumulation

The balance equation of organism in the reactor system is then:

$$(q_{in} + q_r)X_m = (q_r + q_w)X_{unm}$$

$$\Rightarrow \qquad X_{unm} = (\frac{q_{in}+q_r}{q_r+q_w})X_m \qquad (3.4.2.1)$$

The microorganisms mass balance equation in the aeration tank can be written as,

$$\frac{d}{dt}(VX_m) = q_{in}X_{inm} + q_rX_{unm} - (q_{in} + q_r)X_m + r_HV \qquad (3.4.2.2)$$

The carbon mass balance equation in the aeration tank will be,

$$\frac{d}{dt}(VS_s) = q_{in}S_{ins} - q_{out}S_s + r_sV \qquad (3.4.2.3)$$

The oxygen mass balance equation in the aeration tank will be,

$$\frac{d}{dt}(VS_o) = q_{in}S_{ino} - q_{out}S_o + r_oV + K_{La}\left(S_{o,sat} - S_o\right)V \qquad (3.4.2.4)$$

3.4.3.2 Kinetics Model

From the activated sludge model 2 (ASM 2) (Henze & Mogens, 2000}, I can determine the stoichiometry and kinetics for the reaction rate for biomass growth r_m , reaction rate for nutrient r_s and oxygen consumption rate r_o.

For biomass growth r_m ,

$$r_m = \mu_m\left(\frac{S_s}{K_s+S_s}\right)\left(\frac{S_o}{K_{OH}+S_o}\right)X_m - b_mX_m \qquad (3.4.2.5)$$

For reaction rate for nutrient r_s

$$r_s = -\frac{1}{Y_m}\mu_m\left(\frac{S_s}{K_s+S_s}\right)\left(\frac{S_o}{K_{OH}+S_o}\right)X_m + (1-f_P)b_mX_m \qquad (3.4.2.6)$$

For oxygen consumption rate r_o,

$$r_o = \frac{Y_m-1}{Y_m}\mu_m\left(\frac{S_s}{K_s+S_s}\right)\left(\frac{S_o}{K_{OH}+S_o}\right)X_m \qquad (3.4.2.7)$$

Based on the equations from 1 to 7, the mass balances for the substrate, dissolved oxygen and microorganisms will be written as,

The mass balances for the substrate,

$$\frac{dS_s}{dt} = \frac{q_{in}}{V}(S_{ins}-S_s) - \frac{1}{Y_m}\mu_{mm}\left(\frac{S_s}{K_s+S_s}\right)\left(\frac{S_o}{K_{OH}+S_o}\right)X_m + (1-f_P)b_mX_m \qquad (3.4.2.8)$$

The mass balances for dissolved oxygen,

$$\frac{dS_o}{dt} = \frac{q_{in}}{V}S_{ino} - \left(\frac{q_{in}+q_r}{V}\right)S_o + \frac{Y_m-1}{Y_m}\mu_{mm}\left(\frac{S_s}{K_s+S_s}\right)\left(\frac{S_o}{K_{OH}+S_o}\right)X_m + a(1-e^{-\frac{qA}{b}})(S_{o,sat}-S_o) \qquad (3.4.2.9)$$

The mass balances for microorganisms

$$\frac{dX_m}{dt} = \frac{q_{in}}{V}X_{inm} - \frac{1}{Y_m}\mu_{mm}\left(\frac{S_s}{K_s+S_s}\right)\left(\frac{S_o}{K_{OH}+S_o}\right)X_m - \frac{q_w}{V}\left(\frac{q_{in}+q_r}{q_w+q_r}\right)X_m + (1-f_P)b_mX_m \qquad (3.4.2.10)$$

The maximum specific growth rate and half-velocity constants(Ks) of Monod kinetics model were obtained from the batch culture growth data, by processing with non-linear regression method in the MATLAB. In addition, after setting the model, it is necessary to fit the experimental data to this model. In this project, real experimental data in several days were picked out to conduct the fitting. All the data including modeling data and experimental data were processed in the MATLAB.

Finally, the assessment of the model will be conducted in order for assessing the model in fitting the real experimental data. Details of the work will be discussed in the Chapter 4.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Introduction

In this Chapter, the results and discussion of this research project are presented. There are three components, which are identification of the predominant microorganisms in activated sludge with foaming, performance of revised feast-famine operation system in controlling the foaming problem and mathematical modeling of revised feast-famine operation system (RFFO), respectively.

4.2 Study of the Predominant Microorganisms in Activated Sludge with Foaming

4.2.1 Identification of the Predominant Microorganism

The predominant microorganism in the foaming activated sludge was isolated and examined with different morphological tests. The microscopic examination of isolated microorganism is shown in Figure 15. The filamentous cells showed bent or twisted filaments without branching and the filament length less than 200 μm. It has the cell diameter of ca. 0.5 μm without sheath. Moreover, the isolated microorganism was found Gram positive and Neisser positive. These morphological properties confirmed that the bacteria as *Microthrix parvicella(Foot, Kocianova et al. 1992; Jenkins 2004)*. It is a renowned filamentous microorganism in causing the foaming and bulking problem. *Microthrix parvicella* was reported to peak in the population at the end of the winter and to minimize in summer(Hwang and Tanaka 1998). The conditions of low F/M ratio condition and higher fatty acids are favourable to the growth of *Microthrix parvicella*. In order to control the growth of this low F/M induced filamentous microorganism, further investigation of its growth kinetics was conducted.

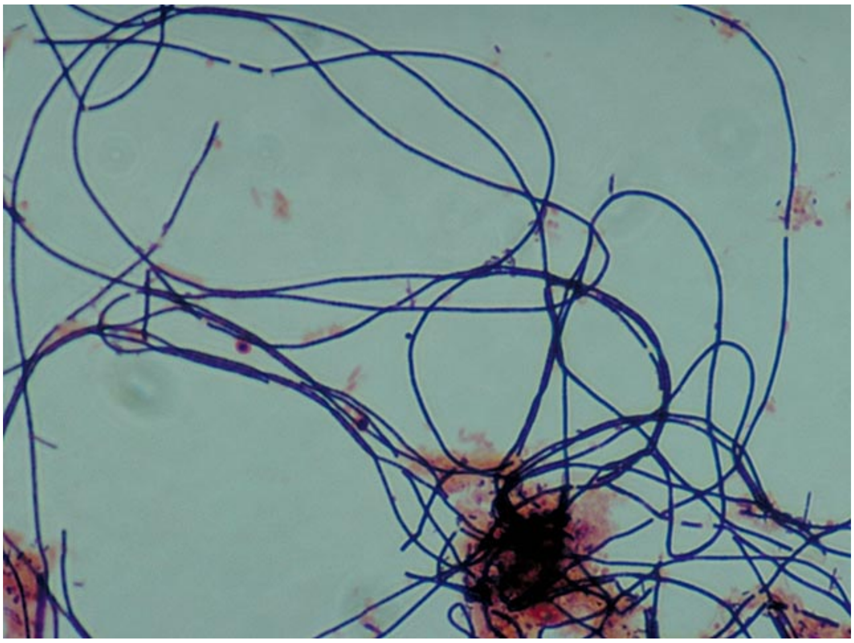


Figure 15 The Characteristic without Branching of *M. Parvicella*

M. Parvicella is identified as the dominant microorganism in causing the filamentous foaming problem in activated sludge. In the previous chapter, it is presented that the dominant filamentous microorganisms of activated sludge foaming in different countries. *Microthrix parvicella* is the most common filamentous microorganism in Eikelboom's system, This is also in agreement with the outcome from this research project. *Pseudomona auruginosa* is selected as the non-filamentous microorganism in this study.

4.2.2 Growth Kinetics Study

It is necessary to find the relationship between the growth of microorganism and the operational condition of activated sludge process. The specific growth rate of *Microthrix parvicella* and *P.auruginosa* are plotted with different F/M ratio. The

Figure 16 shows the growth rate under the different F/M ratio for of bacteria *Microthrix parvicella* and *P.auruginosa*.

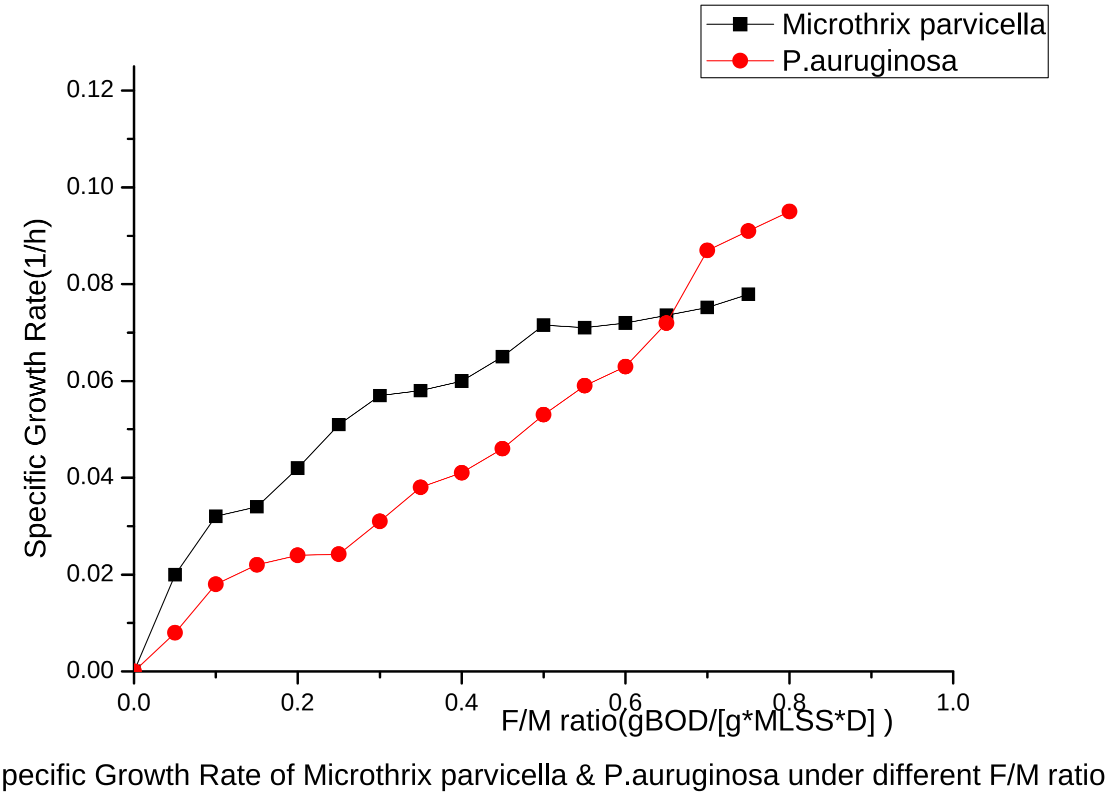


Figure 16 Specific Growth Rate of *Microthrix parvicella & Pseudomonas aeruginosa* under different F/M ratio

From the figure shown above, the cut-off value of F/M ratio ,about 0.67 g BOD/[g MLSS · d], for the growing condition of these two kinds of bacterias *Microthrix parvicella* and *Pseudomonas aeruginosa* can be discovered. From this cut-off value, the filamentous bacteria *Microthrix parvicella* will be dominant in the activated sludge if they are exposed to the growing condition with F/M ratio below 0.67. The non-filamentous bacteria *Pseudomonas aeruginosa* will be dominant if they are exposed to the growing condition with F/M ratio above 0.67. During the experimental work, it is based on this cut-off value to manipulate the F/M ratio in the reactor.

From kinetic selection study, it is obvious to know that the growth of filamentous microorganism like *Microthrix parvicella* can be controlled by adjusting the F/M ratio in activated sludge treatment plant. Based on this, the experimental work was conducted in establishing a laboratory scale reactor to simulate the activated sludge process, and then control the foaming problems by manipulation of F/M ratio or lower F/M ratio to avoid the long time exposure of higher F/M ratio for the whole ecosystem of the internal activated sludge.

4.2 Performance of Revised Feast-Famine Operation System

In this section, it is presented the performance of the Revised Feast-Famine Operation (RFFO) System in a period of 200 days. The variation of each items like MLSS, SVI, and COD removal Efficiency will be shown in the following parts.

4.2.1 Variation of MLSS and F/M ratio

4.2.1.1 Mixed Liquor Suspended Solids (MLSS)

In practical designs, there is a wide range of MLSS concentration, between 2000 and 5000mg/l for the activated sludge system, typically. In order to allow the development of a flocculent biomass, it is necessary to set a minimum MLSS concentration. Otherwise, biomass flocculation will be poor if the process is operated at MLSS concentration below this value. In addition, entrapment of particulate organic matter will be inadequate and a good settling activated sludge will not develop. So it will lead to the result of a turbid, poor quality final effluent.

Therefore, it is crucial to monitor the MLSS concentration. Through adjusting the sludge return rate and influent flow rate, the MLSS concentration is manipulated in the reactor system.

Figure 17 shows the variation of MLSS among conventional operation (1st Phase) and feast-famine operation (2nd Phase) in the Feast Unit tank and Famine Unit Tank, respectively. In the starting period, because the microbial system need some time to get accustom to the new life in the reactor, the reactor did not provide too much work load for them (means the lower organic loading rate) and the influent flow rate was set at 2.3 L/d for the two tanks. The hydraulic retention time (HRT) was set at 1.3d. Initially, MLSS operated with 5000mg/L in the feast and famine unit tanks. After the adaptive period, as the activated sludge microbial system getting more and more mature, the influent rate was set at a higher value afterwards and the return activated sludge rate was also adjusted in the daily operation. In the first phase, the microbial ecosystem acclimatized to the process conditions, the MLSS decreased to a stable level. Afterwards, MLSS in feast unit tank decreased to 3836mg/L on the last day of 1st phase (100th day). MLSS in the famine unit tank gradually descended to 3818mg/L at the end of 1st Phase (100th day).

After switching to the Feast-Famine Operation condition, the reactor system was entering into 2nd Phase from 101st day. In the famine unit tank, it is eager for the microbial system to uptake the substrate because of the famine operation condition. In other words, the MLSS concentration was very high in the environment with limited amount of substrate. The bacteria felt hungry, so it was called Famine Phase. In contrast, the MLSS concentration was very low in the environment with sufficient amount of substrate, so it was called Feast Phase by feeling replete. The influent flow rate in Feast Unit tank and Famine Unit tank were set at 8.64L/d and 5.76 L/d respectively. By adjusting the Return Activated Sludge (RAS) rate, MLSS for the Feast Unit tank continued declining to 2017mg/L finally. In contrast, the MLSS rose to a stable level of 4156mg/L for the Famine Unit tank.

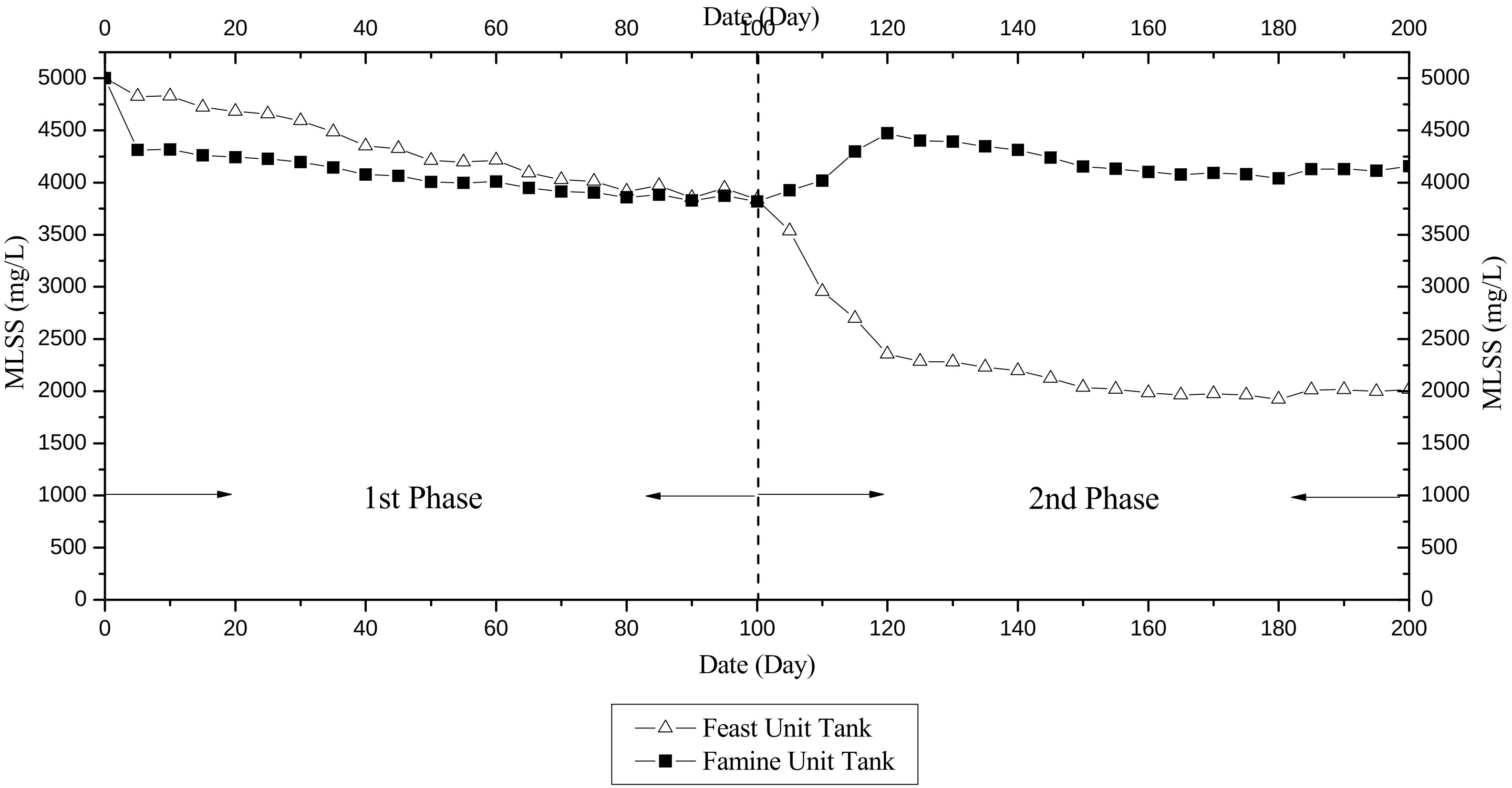


Figure 17 Variation of Mixed Liquor Suspended Solids (MLSS)

4.2.1.2 Food to Microorganism (F/M) ratio

As mentioned in the previous chapter, it is crucial to maintain a proper F/M ratio in the reaction tank for creating an optimum operation to the activated sludge microbial system.

The kinetics selection study revealed that activated sludge process operating at F/M ratio of above 0.67 g BOD/[g MLSS · d] rendered non-filamentous bacteria to be dominant in the microbial population. In the contrary, filamentous bacteria is more competitive than non-filamentous bacteria when the F/M ratio below 0.67 g BOD/[g MLSS · d] in the microbial system. The range of conventional operational F/M is from 0.1 to 0.5. In this project, because both of the feast and famine unit tanks are operated in the same condition during the 1st phase, the trend line of F/M ratio was similarly to each other. In the starting period, the F/M ratio was set at 0.07, which was a low sludge loading ratio in the adaptive period. After the bacteria getting accustom to the life of reactor, the F/M ratio was increased gradually by adjusting the amount of return sludge and influent flow rate. On the 100th day, the last day of 1st phase, the F/M ratio reached to the level of 0.59 for both of the feast and famine unit tanks. From the 60th day, foams were observed from the surface of two aeration tanks, and it became severely afterwards. This observation indicated that the quantity of filamentous bacteria within the activated sludge ecosystem were in dominant relatively with the F/M ratio reaching to a typical value below 0.67.

After switching to the Feast-Famine Operation condition, the reactor system was entering into 2nd Phase from 101st day. In the Feast Unit tank, in order to create a feasting environment for the bacteria in activated sludge, the influent rate and amount of return sludge were manipulated. In the end of 2nd phase, F/M reached the peak at a stable level 0.7 g BOD/[g MLSS · d]. In contrast, in order to create a famine environment for the bacteria in activated sludge, the influent rate and amount of return sludge were also adjusted. Hence, F/M was declined to a level at 0.22 g BOD/[g MLSS · d] in the Famine Unit tank.

After sedimentation and decanting the effluent, the residual sludge would be transferred to the sludge mixer before returning to the aeration tank. In the sludge mixer, the residual sludge produced from the two reaction tanks were well-mixed in order to keep the amount of bacteria in balance before distributing them to the famine and feast unit tanks. Through the sludge mixer, the activated sludge avoided prolonged exposure to the environment of a high F/M ratio (feasting phase) or a low F/M ratio (famine phase). So the overall F/M ratio for the activated sludge ecosystem was still in the cut-off value 0.67 g BOD/[g MLSS · d]. It was also observed that foams appeared to be less in the 2nd phase. Details of the foams will be shown later.

Therefore, the FFO mode successfully suppressed the overgrowth of filamentous bacteria by manipulation of the F/M ratio.

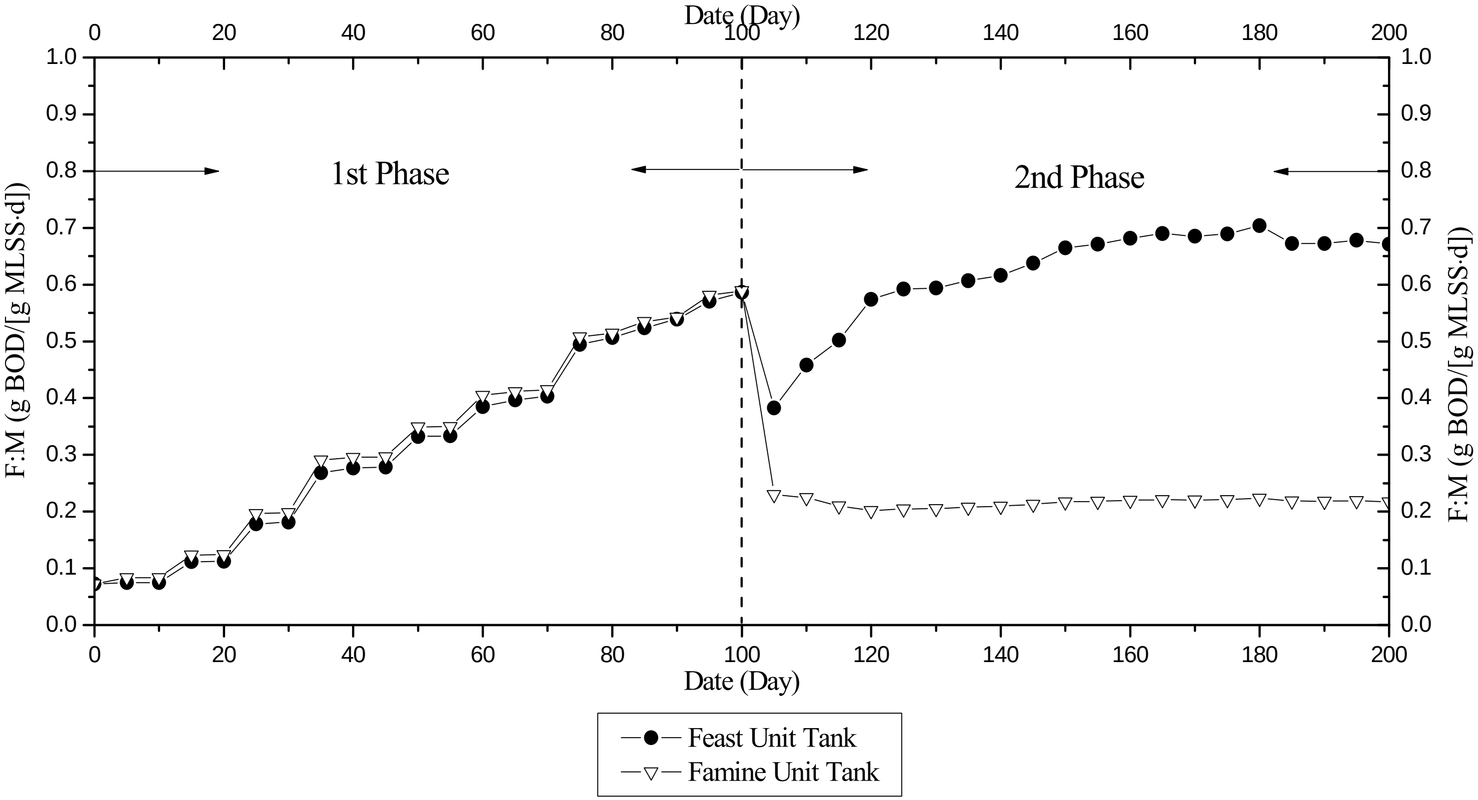


Figure 18 Manipulation of Food to Microorganism (F/M) ratio

4.2.2 Overall performance of COD removal and SVI

The ultimate function of the wastewater treatment system is to remove the organic matter in order to meet the corresponding discharge standard set by the government (EPD, 2005). Hence, the performance of COD removal in the aeration tanks is presented in this section. In addition, Sludge Volume Index (SVI) is a general criterion to describe the settleability of activated sludge, so the profile of SVI is also covered here.

4.2.2.1 COD removal and SVI in Famine Unit Tank

It is manifest from Figure 19 that COD removal and profile of SVI in Famine Unit tank. In the starting period, the reactor system operated under conventional condition for microbial acclimatization. The system was fed with synthesized wastewater and seeded with sludge obtained from Tai Po Sewage Treatment Plant. In the famine unit tank, the SVI and average COD removal efficiency were 50mL/g and 75 percentages, respectively. After the adaptive period, the reactor system performed better in removing the organic matter and forming the flocculation. The COD removal efficiency increased to a stable level at 95 percentages. The SVI also reached to a healthy level, but then it still rose to a higher value, which indicated the activated sludge was getting worse. From the 50th days, the SVI exceeded 200ml/g, which indicated that the settleability of the activated sludge was bad. Similarly, the efficiency of COD removal in the Famine Unit tank also decreased lower and lower, which was from the peak level of 95 decreasing to 50 in the end of 1st phase. SVI reached to a peak level nearly 300 ml/g on the 100th day. After microscopic observation, it indicated that there were huge amount of filamentous bacteria existed in the activated sludge, which played a negative role in the solid liquid separation process. This investigation is in agreement with the statement of kinetic selection study in the previous section.

After switching to the FFO mode, the SVI started to drop from the 101st day. It shown that the settleability of the activated sludge getting better after manipulating the F/M ratio in the aeration tank and mixing the residual sludge. In the perspective of microorganism, the excess filamentous bacteria were washed out day to day. And there was a balance among the amount of filamentous bacteria and non-filamentous bacteria after about 40 days. The SVI value finally kept in a healthy level, below 100, which the average is 75 ml/g in the 2nd phase. This investigation indicated that the overgrowth of filamentous foaming bacteria was inhibited successfully. For the COD removal efficiency, it then returned to a high level as well as the performance of SVI. Finally, it grew to the level above 90 percentages in the end of 2nd phase. This illustrated that after switching to the FFO mode, the function of removing the organic matter in the reactor system was regular.

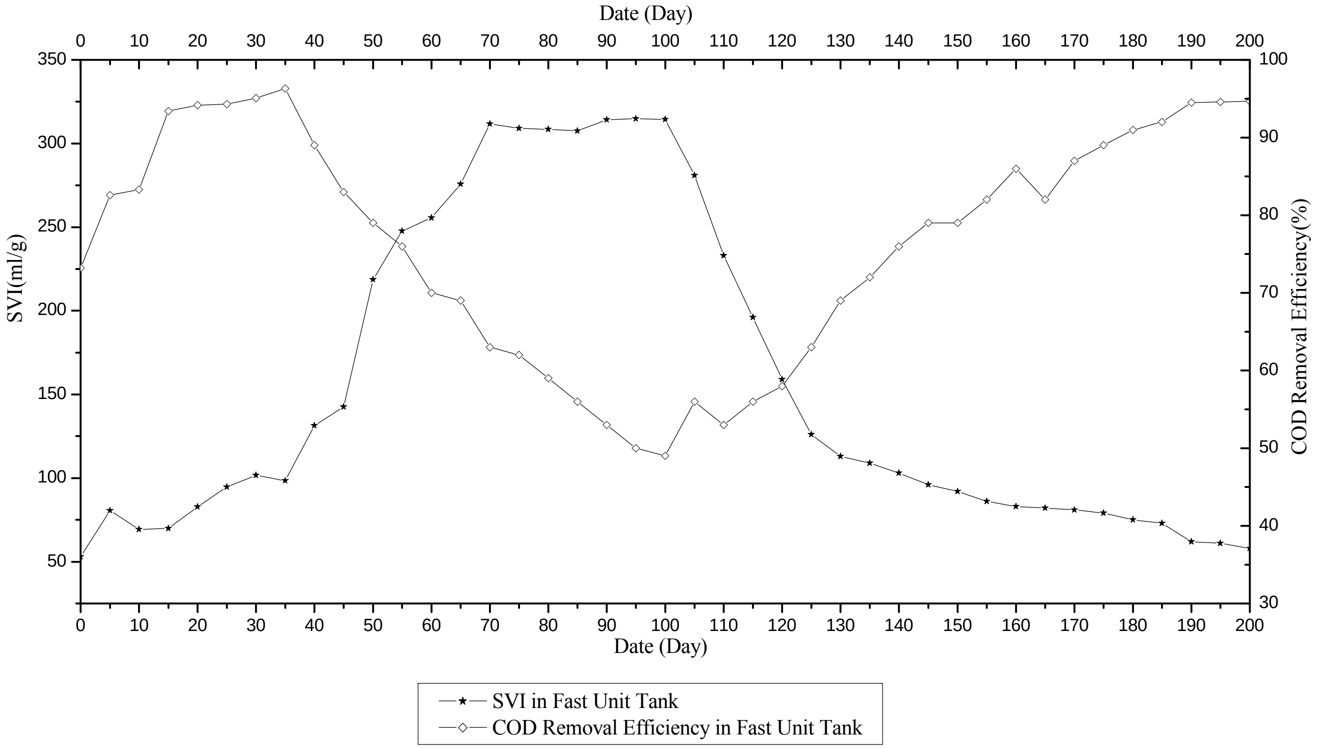


Figure 19 Variation of Removal Efficiency of Chemical Oxygen Dissolved (COD) in Famine Unit Tank

4.2.2.2 COD removal and SVI in Feast Unit Tank

The performance of COD removal and SVI in Feast Unit Tank, as illustrated in Figure 20, due to the manipulation of mixing return activated sludge. Initially, the reactor system was operated under conventional condition for microbial acclimatization. The system was fed with synthesized wastewater and seeded with sludge obtained from Tai Po Sewage Treatment Plant. In the feast unit tank, during the adaptive period, the SVI and average COD removal efficiency were 50mL/g and 73 percentages, respectively. After the adaptive period, the reactor system performed better in removing the organic matter and forming the flocculation. The COD removal efficiency increased to a stable level at 95 percentages lasting about 3 weeks. The SVI also reached to a healthy level, but then it still rose to a higher value, which indicated the activated sludge was getting worse. From the 55th days, the SVI exceeded 200ml/g, which indicated that the settleability of the activated sludge was bad. Similarly, the efficiency of COD removal in the Feast Unit tank also decreased lower and lower, which was from the peak level of 96 decreasing to 48 in the end of 1st phase. SVI reached to a peak level nearly 307 ml/g on the 100th day. After microscopic observation, it indicated that there were huge amount of filamentous bacteria also existed in the feast unit tank as well as the famine unit tank, which played a negative role in the solid liquid separation process. This investigation is in agreement with the statement of kinetic selection study in the previous section.

After switching to the FFO mode, the SVI started to drop from the 101st day. It was discovered that the settleability of the activated sludge getting better by manipulating the F/M ratio in the aeration tank and mixing the residual sludge. In the perspective of microorganism, the excess filamentous bacteria were washed out every day. There was a balance among the amount of filamentous bacteria and non-filamentous bacteria after about 50 days. The SVI value finally kept in a healthy level, below 100, which the average is 77 ml/g in the 2nd phase. This investigation indicated that the overgrowth of filamentous foaming bacteria was also inhibited successfully in the feast unit tank. For the COD removal efficiency, it then returned to a high level as well as the performance of SVI. Finally, it grew to the level above 90 percentages in the end of 2nd phase. The experimental results illustrated that after switching to the FFO mode, the function of removing the organic matter in the reactor system was advanced.

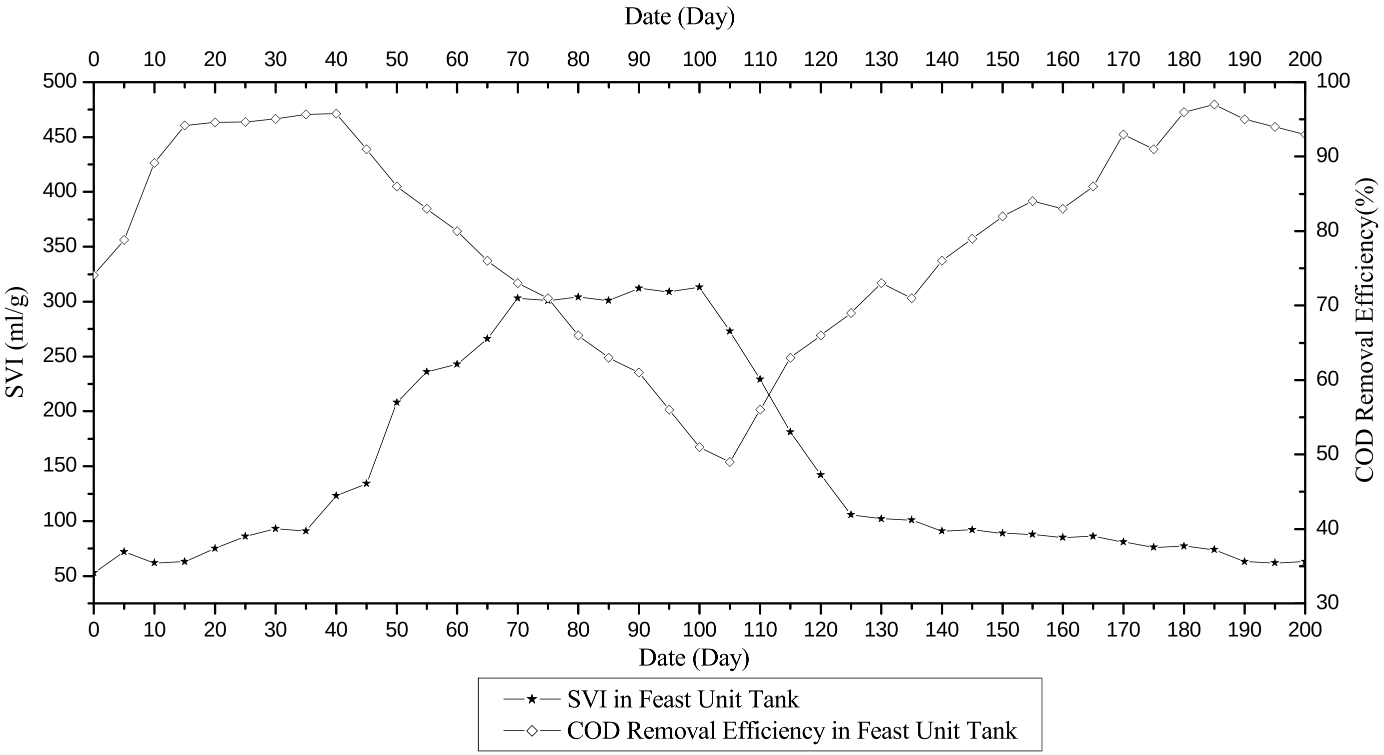


Figure 20 Variation of Removal Efficiency of Chemical Oxygen Dissolved (COD) in Feast Unit Tank

4.2.3 Overall performance of degree of foaming

The test of degree of foaming was performed throughout the entire operation of the reactor system. The degree of foaming was also used as indicator for the dominance of filaments in the microbial ecosystem. Chua (2000) discovered that 60-80 mL of foam and 0-20 mL of foam were typical values for severely foaming and healthy sludge, respectively.

In the starting period, the average degree of foaming was about 20 mL for both of the feast and famine unit tanks. After the adaptive period, the degree of foaming in the famine unit tank increased significantly to the level of 70mL after 80days. In the feast unit tank, the degree of foaming also increased from 20 to 79 mL at the end of 1st phase. These results indicated that there was severely foaming existing in the two tanks. It also demonstrated that the filamentous bacteria were overgrowth and overwhelming in the reactor ecosystem. After switching to the RFFO strategy, the reactor system was entering into the 2nd Phase.

The degree of foaming in the two tanks started to drop down after 10 days. In the famine reaction tank, the degree of foaming dropped further from the 120th day, although there was a peak level on the day 110. In the feast reaction tank, the degree of foaming was also going down gradually. There were about 40 days with degree of foaming keeping in the range of 60mL to 20mL for the two tanks. At the end of 2nd phase, the degree of foaming in the famine unit tank and feast unit tank reached to 20 mL and 19mL, respectively. This illustrated that the foaming problem was controlled well after turning to the RFFO mode.

Hence, it is observed from the figure 21 of overall performance of degree of foaming that the RFFO strategy effectively and rapidly restrained the overgrowth of filamentous bacteria in the reactor system.

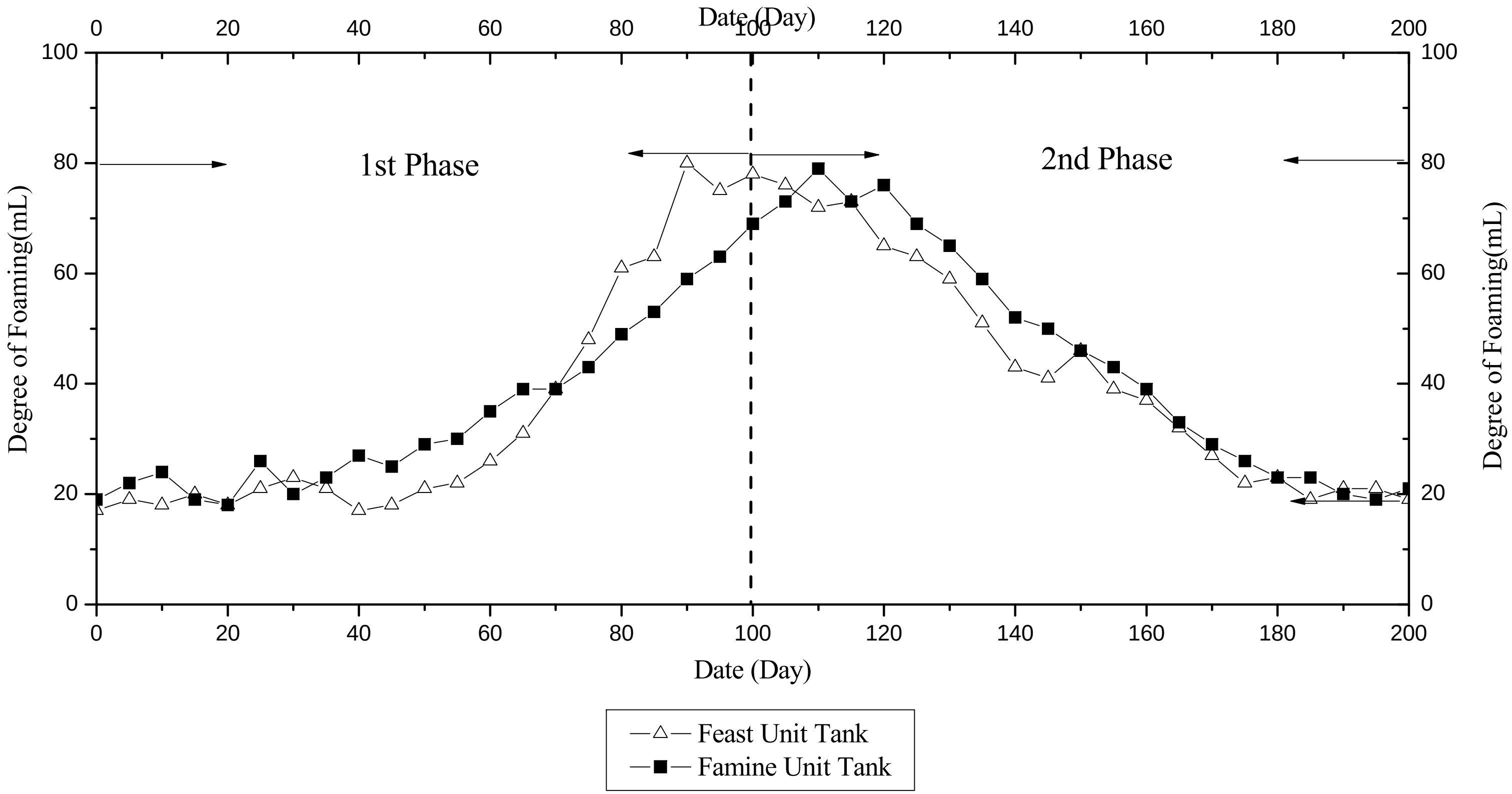


Figure 21 Overall performance of degree of foaming

4.2.4 Comparison of the performance between Conventional and RFFO

The following figures, from Figure 22 to Figure 25 will demonstrate the comparison of the performance under Conventional condition and RFFO strategy in respect to the SVI and COD removal efficiency. The height of column represents the days of the relevant performance, and the horizontal line represents the SVI range or the range of COD removal efficiency.

In Figure 22, it is obviously discovered that there is higher column for the RFFO strategy in the range of SVI in 50-100 mL. It indicates that there were more days with good settleability sludge for the RFFO strategy than the conventional operation in Feast Unit Tank.

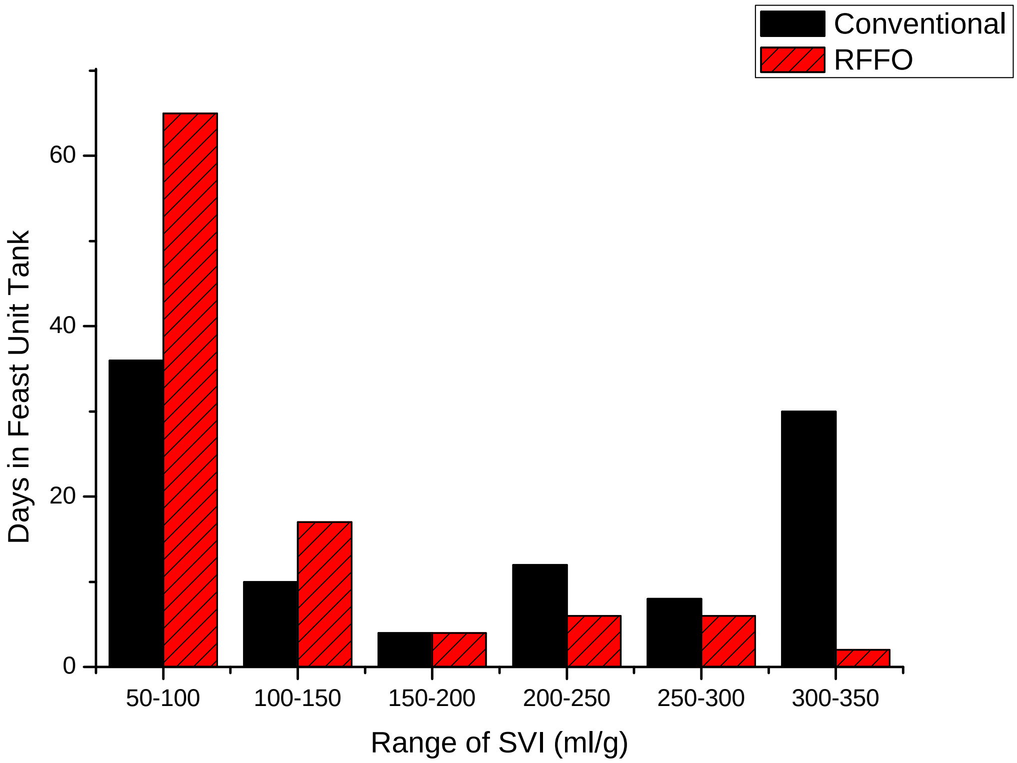


Figure 22 Comparison of the Performance (SVI) in Feast Unit Tank

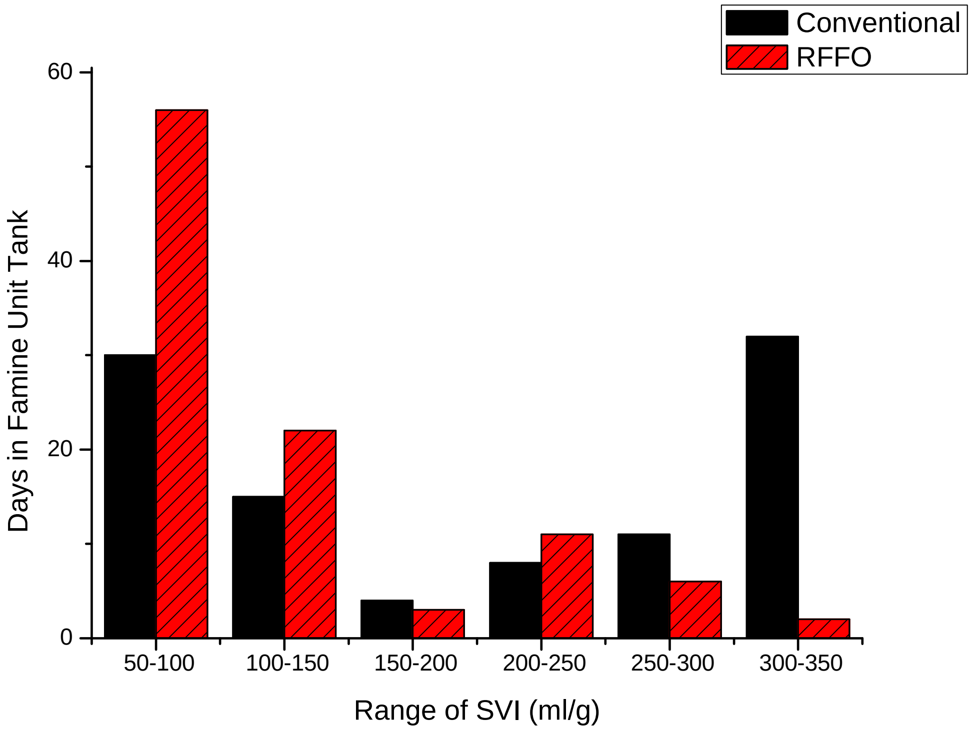


Figure 23 Comparison of the Performance (SVI) in Famine Unit Tank

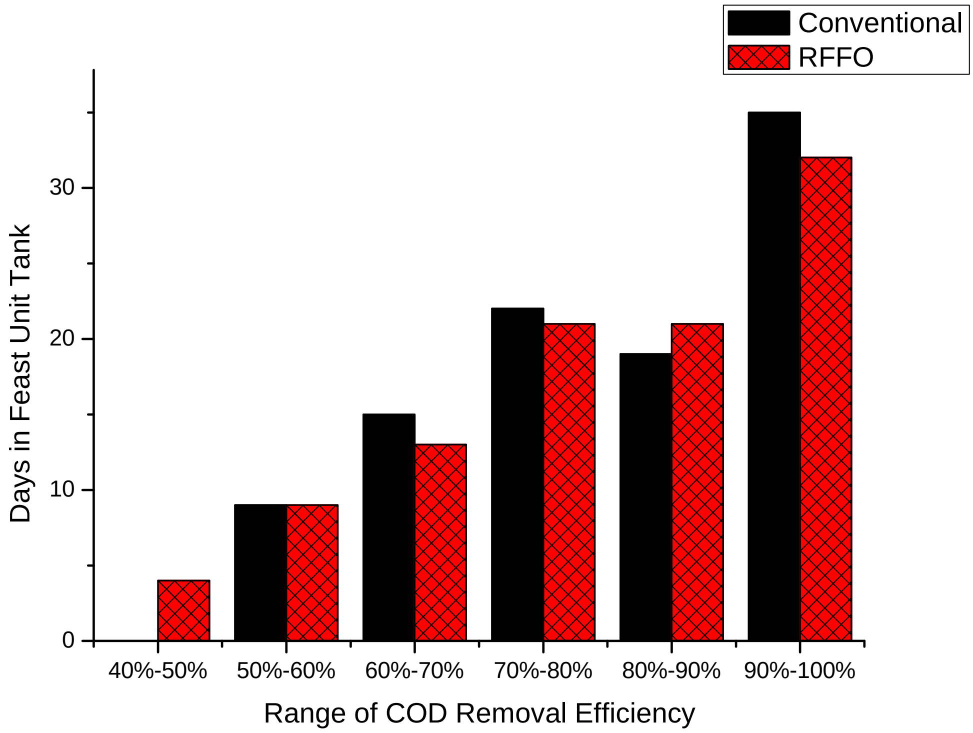


Figure 24 Comparison of the Performance (COD Removal) in Feast Unit Tank

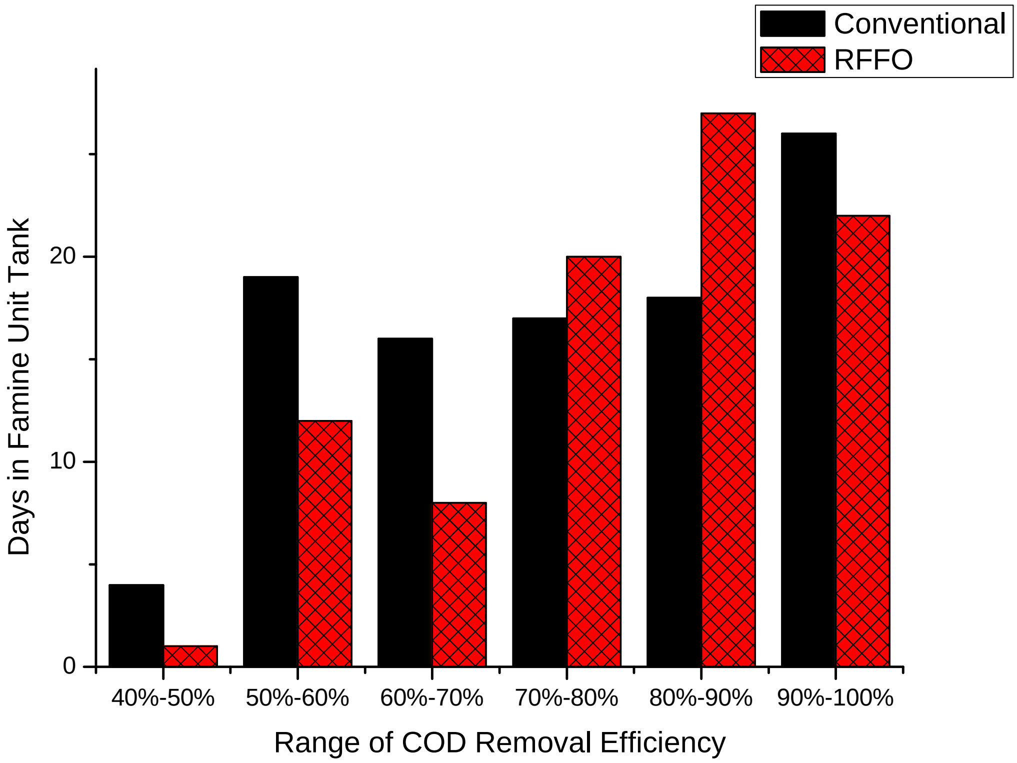


Figure 25 Comparison of the Performance (COD Removal) in Famine Unit Tank

From Figure 23, Figure 24 and Figure 25, as compared with the height of two columns in regarding to the high range of SVI value and high range of COD removal efficiency, it is obviously noted that the performance of RFFO strategy more advantageous than the Conventional operation condition.

This illustrates that the statistical analysis of the results arising from the experimental work reveals the facts that the RFFO strategy can successfully control the foaming problem in activated sludge.

4.3 Mathematical modeling of Revised Feast-Famine Operation System

4.3.1 Introduction

As mentioned in Chapter 1 and Chapter 3, the mathematical modeling of Revised Feast-Famine Operation System was a crucial part in this MPhil project. The mathematical modeling is a useful tool in studying the complicated biochemical reaction like the use of RFFO in controlling the activated sludge foaming problem. The kinetic models in the study of phases of Feast and Famine showed their excellent fitting to the performance of experimental works. The kinetic parameters were estimated by integration of the experimental results, by the method of minimized least square, and partial data were assumed before conducting the modeling work.

A large number of experiments performed under different conditions have been evaluated with the procedure described above. In the following section, the modeling results and the experimental work of 15th day in Feast Unit Tank and 45th day in Famine Unit Tank were shown here as examples. Whereas, Ss ,DO, and Xh mean the influent substrate concentration(COD concentration), Dissolved Oxygen, and Heterotrophic concentration (Xh), respectively. The data in each batch were taken during every half an hour. Variables and typical values are shown in details in Appendix I.

4.3.2 15th day in Feast Unit Tank

On 15th day, the experimental data was selected as to compare with the modeling data. The parameters related to this for both Feast and Famine Unit tank are shown as following figures,

Influent rate = 3.36 L/d, HRT = 0.89 d, and F/M = 0.11(gBOD/gMLSS·d).

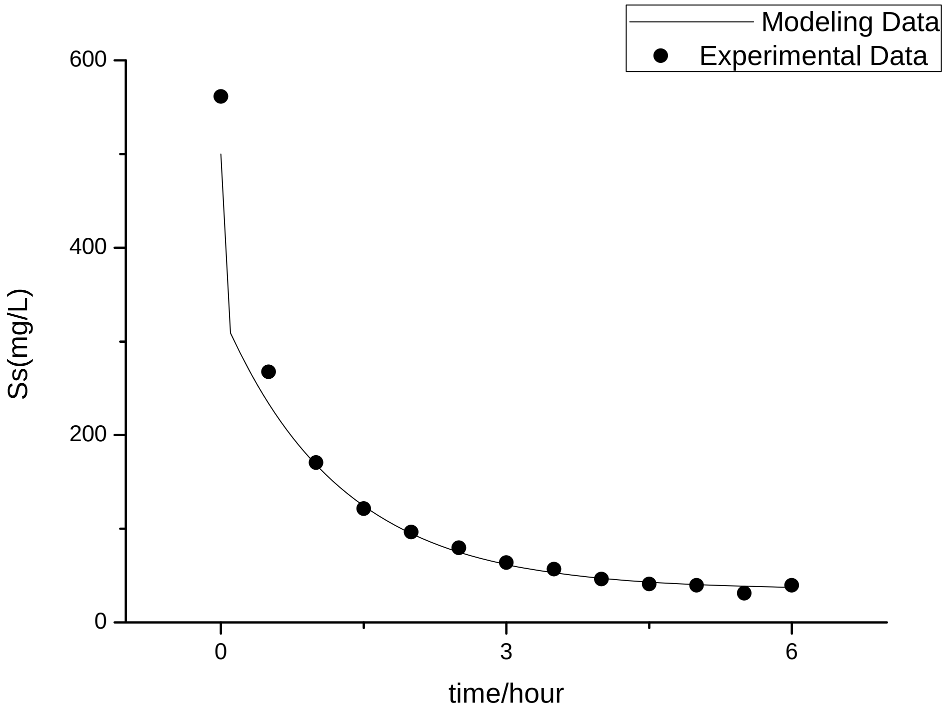


Figure 26 Responses to Substrate concentration (Ss) in Feast Unit Tank

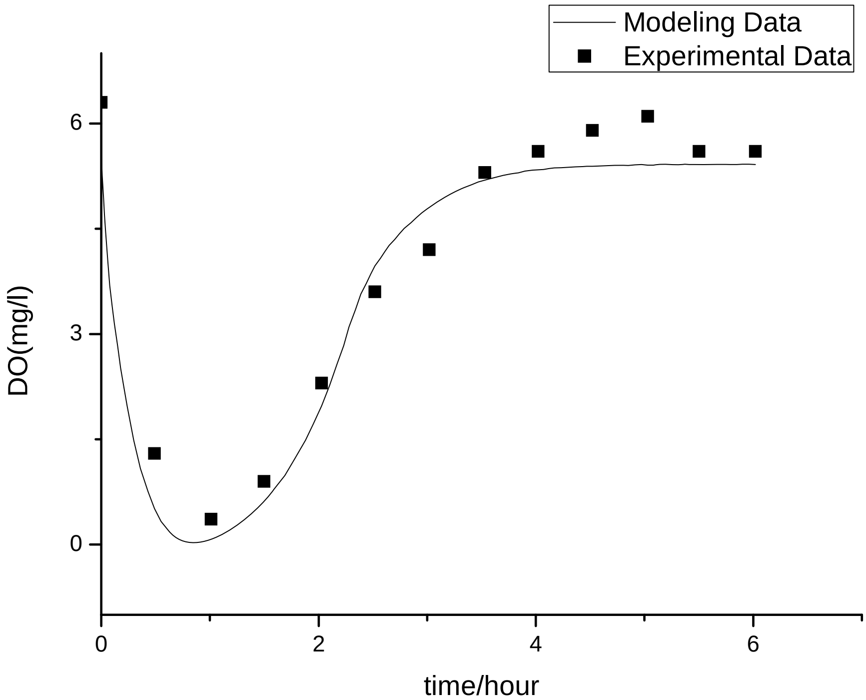


Figure 27 Responses to Dissolved Oxygen (DO) in Feast Unit Tank

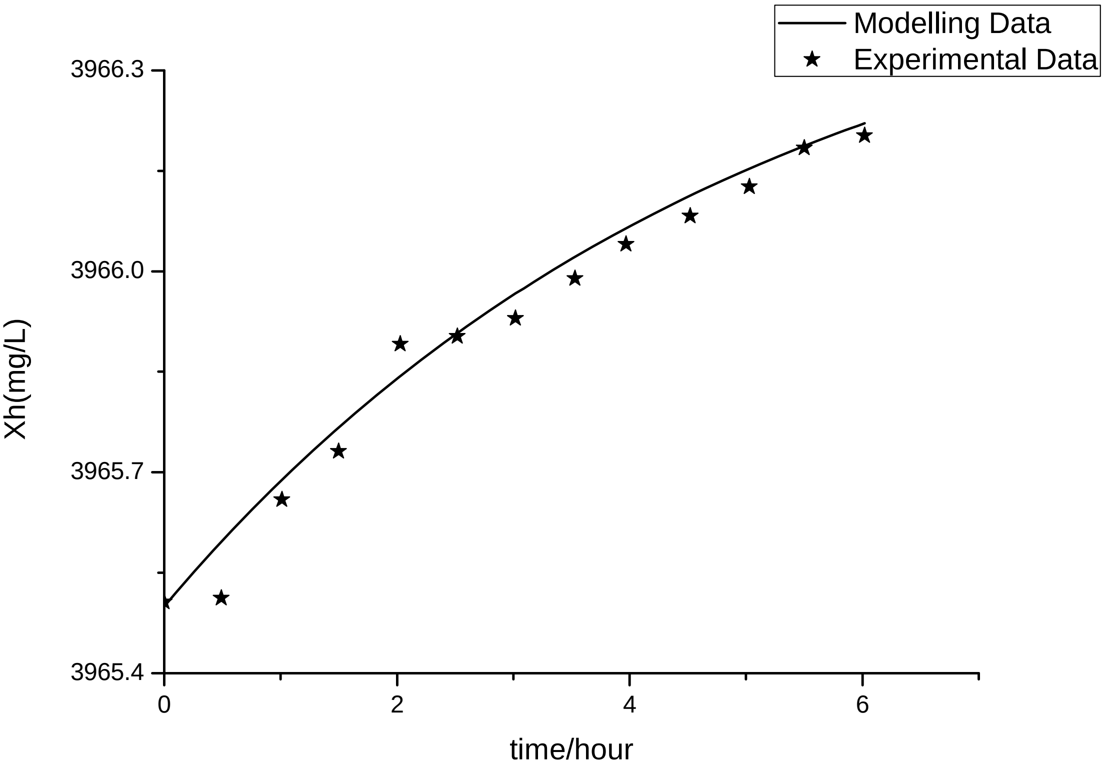


Figure 28 Responses to heterotrophic concentration (Xh) in Feast Unit Tank

4.3.3 45th day in Famine Unit Tank

On 45th day, the experimental data was selected as to compare with the modeling data. The parameters related to this for both Feast and Famine Unit tank are shown as follow,

Influent rate = 7.69 L/d, HRT = 0.39 d, and F/M = 0.28(gBOD/gMLSS·d).

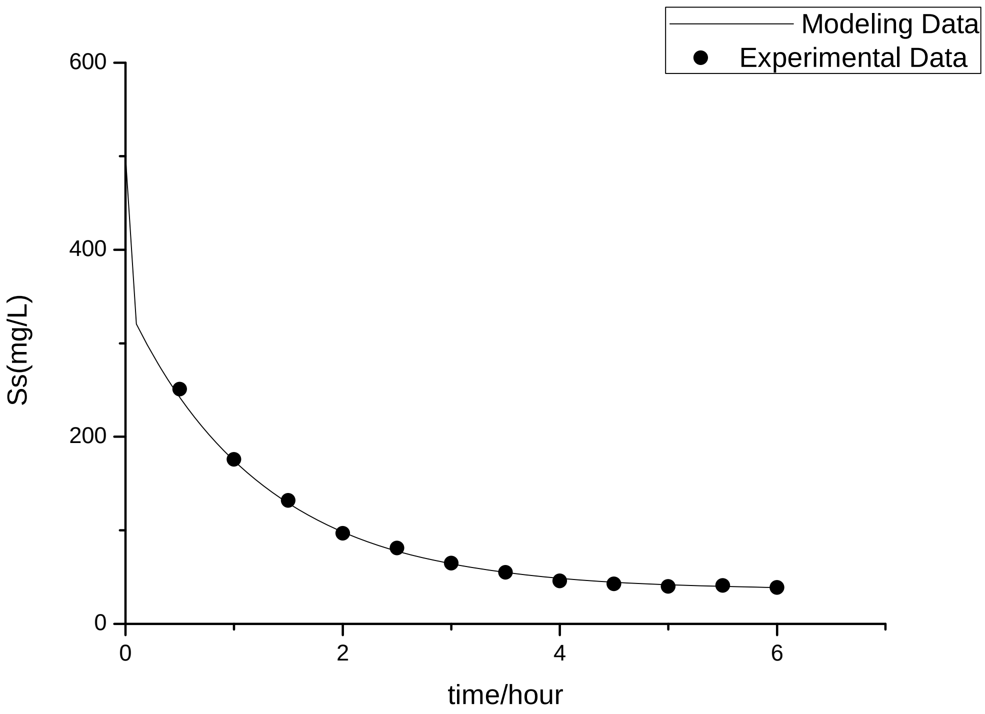


Figure 29 Responses to Substrate concentration (Ss) in Famine Unit Tank

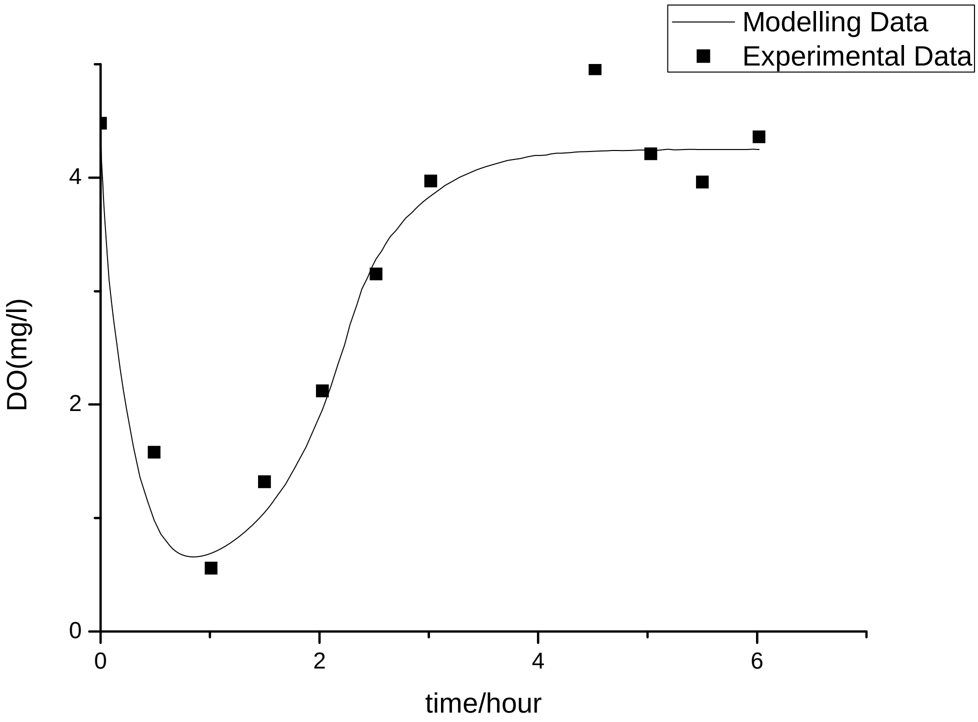


Figure 30 Responses to Dissolved Oxygen (DO) in Famine Unit Tank

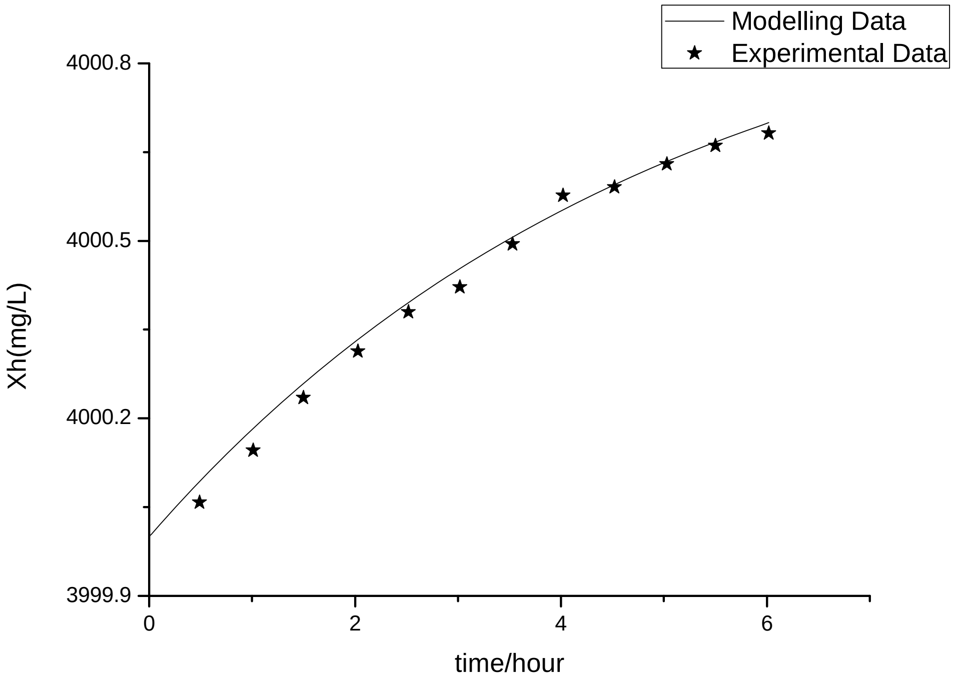


Figure 31 Responses to heterotrophic concentration (Xh) in Feast Unit Tank

4.3.4 Assessment of Model

In the previous experimental work and modeling work, a set of values are obtained, either for estimated parameters or for other data. The assessment of the model fit is more important than the model itself. The Residuals tests were undertaken to the assessment procedure. The Residuals tests can indicate whether the model is a good one or not, and it is meaningful for the researchers to determine if there is the case either the model is deficient or the real experimental data is deficient.

4.3.4.1 Residuals Tests

A perfect model means we have no plant-model mismatch. In the residual Tests, y and y_p represent the modeling data and experimental data, respectively. Residuals, $y - y_p$, represents simply the experimental error. The residuals should be randomly distributed near zero for a perfect fitting model. A percentage of the total variation about the mean is expressed in the following equation:

$$V = 100X \frac{\sum_i (y_i - \overline{y})^2 - \sum_i (y_i - y_{p,i})^2}{\sum_i (y_i - \overline{y})^2}$$

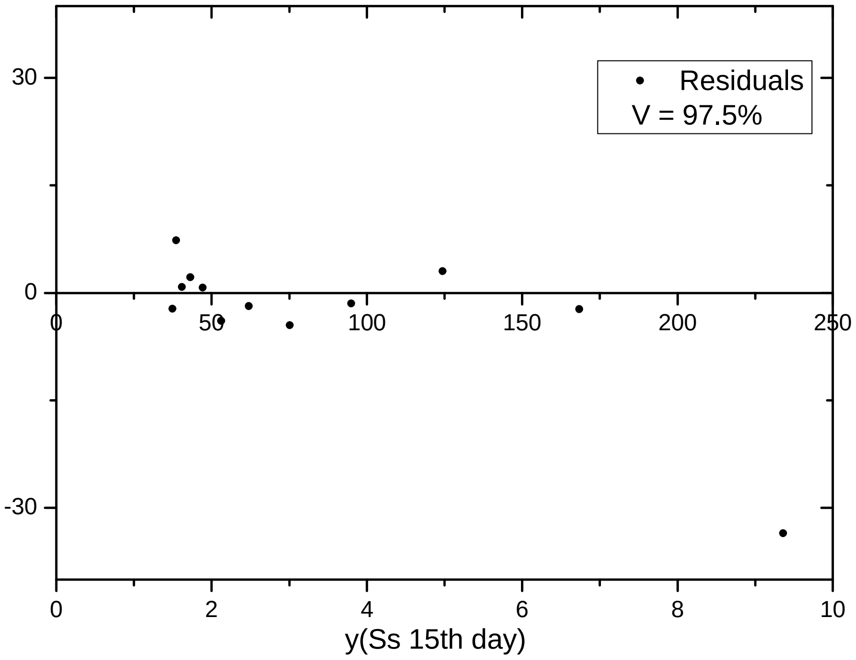


Figure 32 Residual Test for Substrate Concentration in 15^{th} day

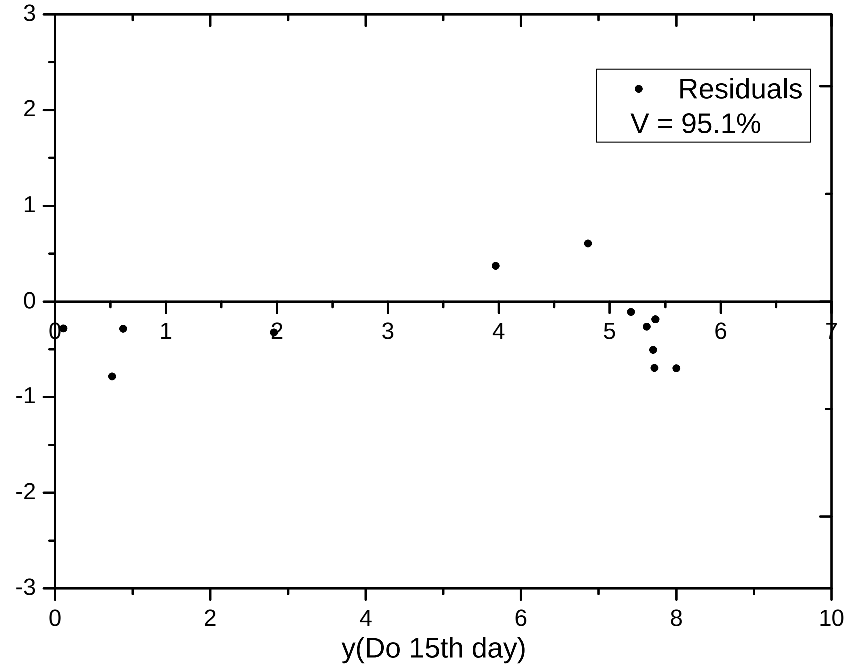


Figure 33 Residual Test for Dissolved Oxygen Concentration in 15th day

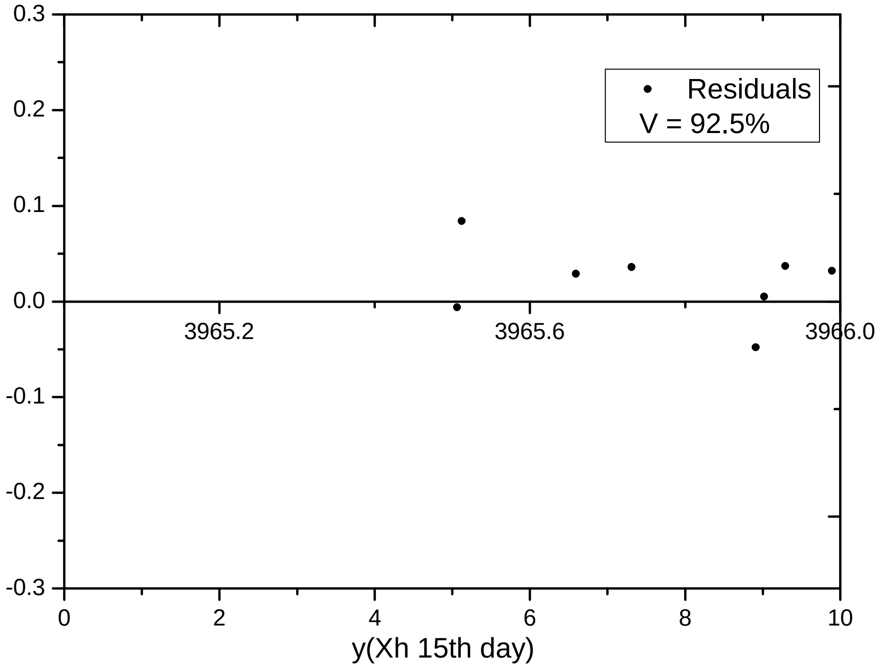


Figure 34 Residual Test for Heterotrophic Concentration in 15th day

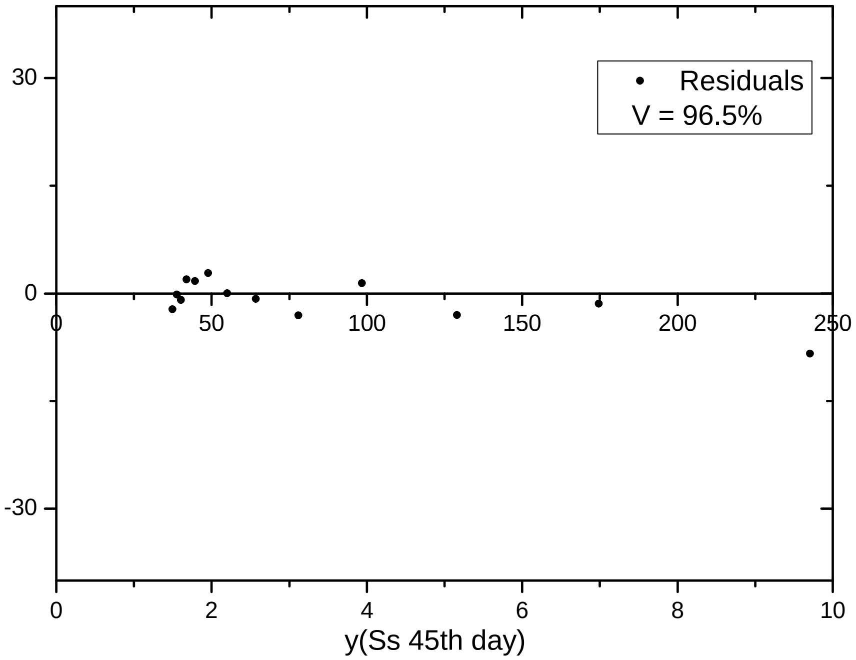


Figure 35 Residual Test for Substrate Concentration in 45th day

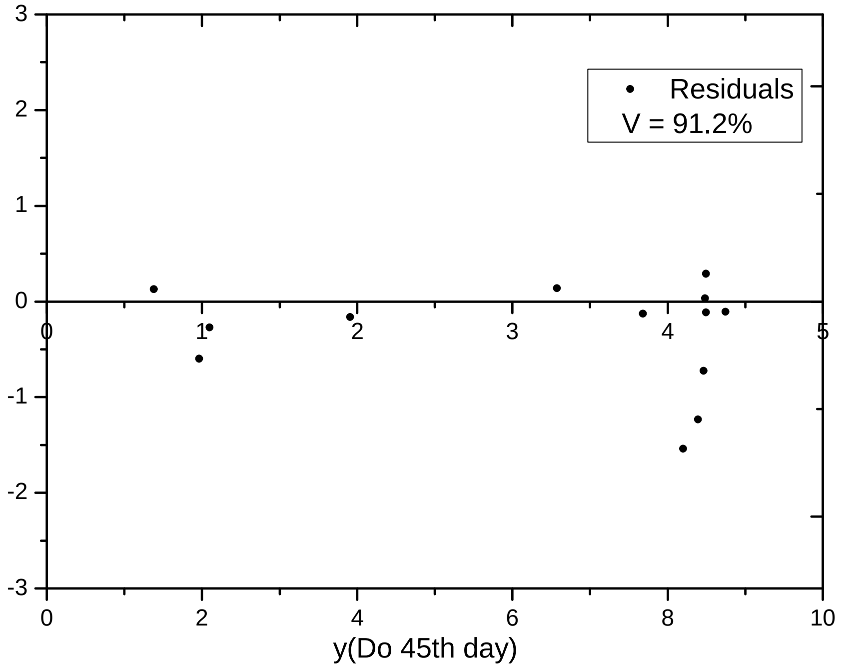


Figure 36 Residual Test for Dissolved Oxygen Concentration in 45th day

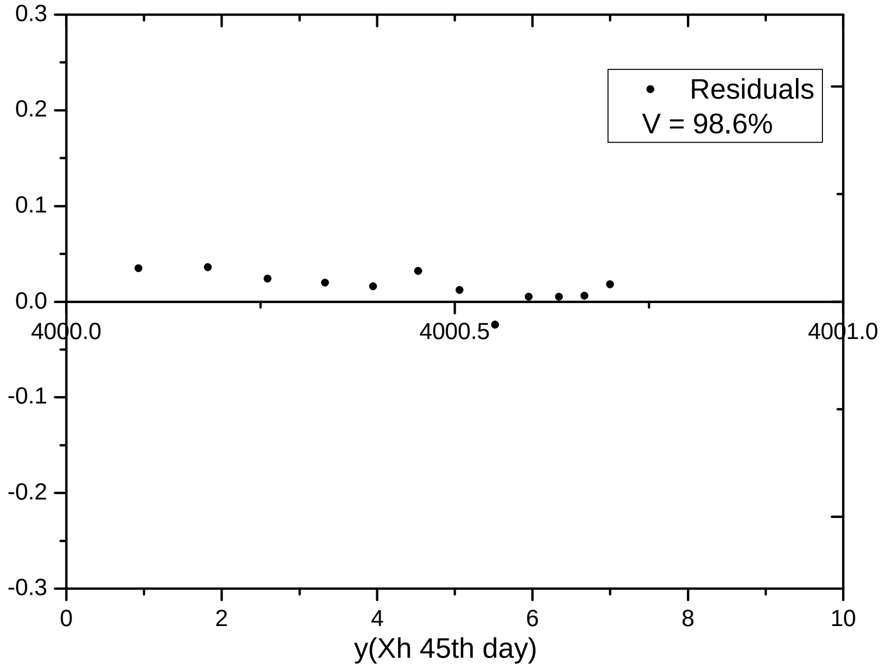


Figure 37 Residual Test for Heterotrophic Concentration in 45th day

Therefore, the plots in the above figures show responses to the variation of other operating parameters. The variables of output, Ss, DO and Xh, show the model fitting to describing the process of RFFO in controlling filamentous foaming problem. After the assessment of the model, by the residuals tests, most of the values in the residuals tests for Substrate concentration, DO concentration, and heterotrophic concentration are distributed nearly zero which indicated that a good fitting model in describing the performance of reactor system.

A percentage of the total variations about the mean are above 90 percentages for all of these three parameters. This illustrated that this model is perfect in simulating the RFFO system.

CHPATER 5 CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

After the laboratory scale work, mathematical modeling work and data analysis, the following items are concluded to in controlling the filamentous foaming problems in activated sludge.

Firstly, before the experimental work, it was identified that the *Microthrix parvicella* is the predominant filamentous microorganism in causing the activated sludge foaming problem.

During the conventional operational phase, the two unit tanks were set with the same conditions, like MLSS, DO, and F/M ratio. The reason for doing this is to create the same environment for both of the two reaction tanks. This also help the activated sludge in the two tanks gradually getting accustom to the living condition in the beginning of the laboratory work.

Secondly, as the sludge foaming became more and more serious, the reactor was switched to the FFO phase, which the F/M ratio was manipulated by adjusting the amount of return sludge in each tank. It induced to high F/M ratio (around 0.65) in the Feast unit tank, and low F/M ratio (around 0.23) in Famine Unit Tank. In addition, because of the use of sludge mixer, it can well mix the activated sludge before the sludge returning to the aeration tanks. This strategy avoids the activated sludge prolonged exposure to a consistent low F/M ratio. Instead, all the bacteria in activated sludge stays intermittently within the two tanks.

Thirdly, from the overall performance of degree of foaming that the RFFO strategy effectively and rapidly restrained the overgrowth of filamentous bacteria in the reactor system.

Fourthly, the Sludge Volume Index (SVI) in the two tanks was decreased sharply after they are switched to FFO mode. The low SVI value after switching to FFO phase in each tank indicated that the settleability of the activated sludge was good. The removal efficiency of COD did not significantly differ throughout the whole experimental work. It was above the 90 percentage for both of the two tanks.

Finally, it is necessary to conclude the advantages of using the mathematical modeling for experimental data evaluation that: (i) the principle of mass balance is applicable, (ii) better estimates for biomass concentrations can be obtained, which is crucial for predicting the amount of microorganisms, (iii) better estimates for dissolved concentration and substrate concentration, leading to clearer trends when predicting at any time point of an experiment, rather than just judging from the experimental measured data, (iv) the model helps understanding the sequencing batch reactor in treating wastewater. This is crucial for controlling the activated sludge foaming problem in activated sludge.

5.2 Innovation arising from this research

It is too ambitious to say that the work had been done in this research project can fill up the gap in this area. The contribution is to provide a new solution to the foaming problem in the separation problems of activated sludge. This research work also provides some suggestions in controlling the foaming problem in activated sludge. Hopefully the outcome of this research project is beneficial to the operation of wastewater treatment plant in the industry.

In general, as regarding to the innovation arising from this research, there are three parts in originality of the work,

Firstly, it is identified that the predominant bacteria causing the foaming problem in activated sludge;

Secondly, it is developed the RFFO (Revised Feast-Famine-Operation) system to control the foaming problem in activated sludge;

Thirdly, it is developed the mathematical model to simulate the operation of RFFO system.

5.3 Recommendation for further study

Firstly, it is necessary to use mathematical modeling as a tool in solving the simulating the dynamic growth of microorganisms in activated sludge.

Secondly, molecular approaches are particularly possible for the study of foam communities, such as applying FISH probes and hybridization after RNA extraction.

Thirdly, evaluation of biomass density is also a new method to study the poor settling caused by the dominance of filamentous foaming in activated sludge.

Finally, pilot scale of the Revised Feast Famine operation is a good suggestion in conducting the further research about the filamentous foaming control.

APPENDIX I LIST OF SYMBOLS IN THE MODELLING

Symbol	Definition	Typical Value	Units
q_{in}	Influent flow rate	Daily Varied	L/d
S_{ins}	Influent substrate concentration	Daily Varied	mg/l
S_{ino}	Influent oxygen concentration	Daily Varied	mg/l
X_{inm}	Influent microorganisms concentration	Daily Varied	mg/l
X_{inf}	Influent filamentous bacteria concentration	-	mg/l
X_{inff}	Influent floc-forming bacteria concentration	-	mg/l
X_{unm}	Under flow microorganisms concentration	Daily Varied	mg/l
X_{unf}	Under flow filamentous bacteria concentration	-	mg/l
X_{unff}	Under flow floc-forming bacteria concentration	-	mg/l
q_a	Air flow rate	10	m^3/min
q_r	Recycled activated sludge rate	Daily Varied	l/d
q_w	Wasted activated sludge rate	Daily Varied	l/d
V	Reaction tank volume	3	L
S_s	Substrate concentration in reaction tank	Out put	mg/l
S_o	Oxygen concentration in reaction tank	Out put	mg/l
X_m	Microorganisms concentration in reaction tank	Out put	mg/l
X_f	Filamentous bacteria concentration in reaction tank	-	mg/l
X_{ff}	Floc-forming bacteria concentration in reaction tank	-	mg/l
μ_{mm}	Maximum growth rate of microorganisms	Daily Varied	d^{-1}

μ_{mf}	Maximum growth rate of filamentous bacteria	-	d^{-1}
μ_{mff}	Maximum growth rate of floc-forming bacteria	-	d^{-1}
K_s	Substrate saturation coefficient	20	mg/l
K_{OH}	Oxygen saturation coefficient	0.2	mg/l
K_{La}	Mass transfer from the aeration	-	-
Y_m	Yield coefficient for Microorganisms	0.6	-
Y_f	Yield coefficient for filamentous bacteria	-	-
Y_{ff}	Yield coefficient for floc-forming bacteria	-	-
b_m	Microorganisms decay rate		d^{-1}
b_f	Filamentous bacteria decay rate	-	d^{-1}
b_{ff}	Floc-forming bacteria decay rate	-	d^{-1}
f_P	Fraction inerts on decay	Estimated	-
a	KLa value at infinite air flow rate	206	d^{-1}
b	KLa exponent coefficient	16	m^3/min
$S_{o,sat}$	Saturated oxygen concentration	10	mg/l
r_m	Reaction rate for biomass growth	Estimated	mg/l/d
r_s	Reaction rate for nutrient	Estimated	mg/l/d
r_o	Oxygen consumption rate	Estimated	mg/l/d

APPENDIX II LIST OF TESTING EQUIPMENTS

Air Pump used in the Revised Feast-Famine-Operation System

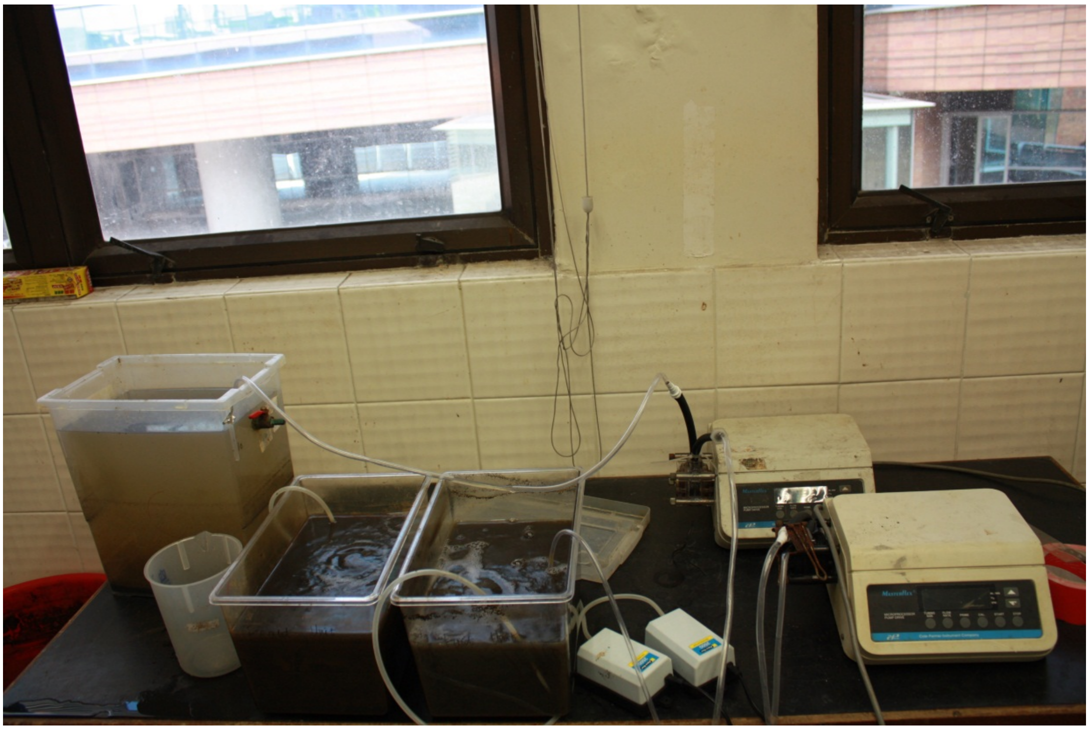
Water Pump used in the Revised Feast-Famine-Operation System

Chemical Oxygen Demand (COD) testing equipment

Dissolved Oxygen (DO) Meter

Mixed Liquor Suspended Solid (MLSS) testing equipment

The entire facilities in the laboratory work



APPENDIX III LIST OF TESTING METHODS

i. Mixed Liquor Suspended Solid (MLSS)

Objective: To determine the Mixed Liquor Suspended Solid (MLSS).

General Description

We use the MLSS, standing for Mixed Liquor Suspended Solid, to analyze the mixed liquor sample and suspended solids. It is also treated as a control level of controlling the suspended growth in treatment plants process. The general theory to measure is that we use the increase of weight of the filter to represent the total suspended solids, which there is a well-mixed sample filtering through a weighed standard glass-fiber filter and the retained residual in the filter is dried to a stable weight by oven. So we can obtain the weight of total suspended solids and calculate the solids dissolved and total solids.

Apparatus

Aluminum weighing dishes;

Membrane filter funnel;

Suction flask, have sufficient capacity for sample size selected;

Muffle furnace for operation at 550°C;

Desiccator, which is used to provide with a desiccant containing a color indicator of moisture concentration;

Drying oven, operating at 103 - 105 °C;

Analytical balance, which is used to weigh to 0.1 mg;

Magnetic stirrer with stirring bar;

Wide-bore pipets;

Graduated cylinder;

Low-form beaker.

Procedure

1. To apply vacuum and wash disk with 3 successive 20-mL portions of reagent-grade water;
2. Then continue suction to remove all traces water;
3. Remove the filter and transfer it to an weighing dish;
4. Dry in an oven 103- 105℃ for 1 h;
5. Choose the sample volume to yield between 2.5 and 200mg dried residue.
6. Wet filter with a small volume of reagent-grade water to seat it. Then to stir sample at a speed , and to obtain a more uniform particle size;
7. Remove the filter and dry for at least 1 hr at 103 to 105℃ in an oven, cool in a desiccators to balance temperature and weigh.
8. Repeat the cycle of drying , cooling , desiccating, and weighing until a constant weight is obtained when the weight change is less than 4% of the previous weight.

Calculation

MLSS mg total suspended solids/L = (A – B) x 1000/ sample volume, mL

Where: A = weight of filter + dried residue, mg, and

B = weight of filter, mg

ii. Biochemical oxygen demand (BOD)

Objective: To determine the BOD amount of water and wastewater.

General description:

Biochemical Oxygen Demand (BOD) is used to determine the oxygen required for oxidizing the biodegradable organics in domestic or industrial wastewater samples after going through the biochemical process. In fact, the BOD is a measurement of the organic strength of the samples mentioned above. And these parameters used are commonly for the pollutions study, wastewater treatment plant design and operation.

Apparatus:

Dissolved Oxygen meter;

Air tight bottles for the Biochemical Oxygen Demand used;

Dilution Water;

Constant temperature incubator around 20℃.

Procedure:

1. Make 2 or 3 different dilution of the original sample with dilution water provided according to the attached Table 1;

2. Prepare dilutions water either in the volumetric flask and then transfer to BOD bottles or prepare directly in BOD bottles;

3. Determine the Dissolved Oxygen of the diluted samples and dilution water blank immediately before incubation using the DO meter and express as $DO_{t=0}$.

4. Then, to incubate the diluted samples and dilution water blank in BOD bottles at 20℃ for 5 days;

5. Finally, to determine the DO of the diluted samples and dilution water blank after incubation using DO meter and express as $DO_{t=5}$.

6. Calculation:

To calculate the value of BOD_5 is using the following equation,

$$BOD_5 = \frac{D_1 - D_2}{P} \, mg/L$$

Where $D_1 = (DO_{t=0} - DO_{t=5})_{sample}$, $D_2 = (DO_{t=0} - DO_{t=5})_{blank}$

P = decimal volumetric fraction of sample used.

Table 2 BOD measurable with various dilutions of samples.

Using Percent Mixtures		By direct pipetting into 300 mL bottles	
% mixture	Range of BOD (mg/L)	Volume (mL)	Range of BOD (mg/L)
0.01	20,000-70,000	0.02	30,000-105,000
0.02	10,000-35,000	0.05	12,000-42,000
0.05	4,000-14,000	0.1	6,000-21,000
0.1	2,000-7,000	0.2	3,000-10,500
0.2	1,000-3,500	0.5	1,200-4,200
0.5	400-1,400	1.0	600-2,100
1.0	200-700	2.0	300-1,050
2.0	100-350	5.0	120-420
5.0	40-140	10.0	60-210
10.0	20-70	20.0	30-105
20.0	10-35	50.0	12-42
50.0	4-14	100.0	6-21
100.0	0-7	300.0	0-7

iii. Sludge Volume Index (SVI)

Objective: To determine the settling characteristics of sludge sample.

General description:

To reduce the sludge volume and hence increase the solid content is an important process after the wastewater treatment. The reason for doing this is very high water content in the sludge, which is more than 90 percent water, so it behaves like liquid but not the form of solid. Because of the economic considerations, to reduce the volume of sludge significantly before disposal becomes very important.

For the Sludge Volume Index (SVI), it has been the indicator of sludge settling property for many years. To maintain good quality of sludge in activated sludge process, SVI is a very important index. A low SVI means that the sludge is settling well in the sedimentation tank and giving rise to a clear effluent, so the low SVI is desirable. In most of the considerations, the sludge with SVI of less than 100 was taken as a concern of good settling behavior, for the SVI larger than 200 indicates the sludge in an ill-conditioned sludge.

Apparatus and Materials

Sludge sample;

Stop watch;

1 L measuring cylinder;

Pre-treated filter paper for suspended solid determination

Filter set

Oven at 103 ℃

Procedure

1. Thoroughly mix the sludge sample;
2. To measure 1 L mixed liquor and pour it into a 1 L graduated measuring cylinder;
3. Then wait for 30 minutes;
4. Record the volume of the settled sludge;
5. And stop the cylinder and remix the settled sludge;
6. To collect 25 mL of the mixed liquor and determine its suspended solids;

Calculation

Calculate the SVI as following equation:

We calculate the SVI using the following equation,

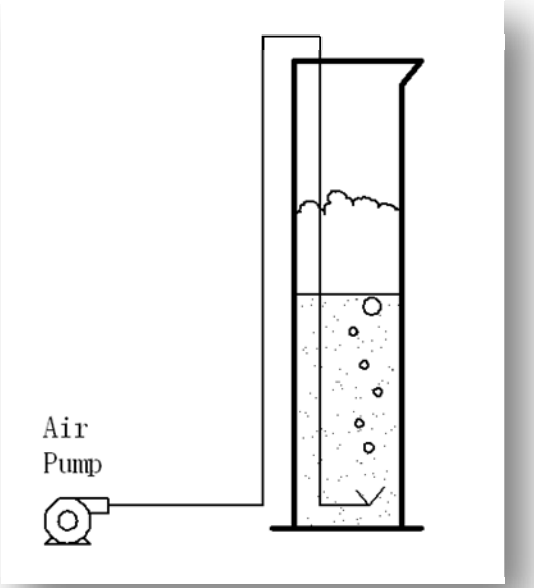
$$SVI = \frac{Settled\ volume\ of\ sludge\ after\ 30\ mins.\ (mL) \times 1000}{MLSS\ (mg/L)}$$

iv. Test of Degree of foaming

Objective: To determine the degree of foaming

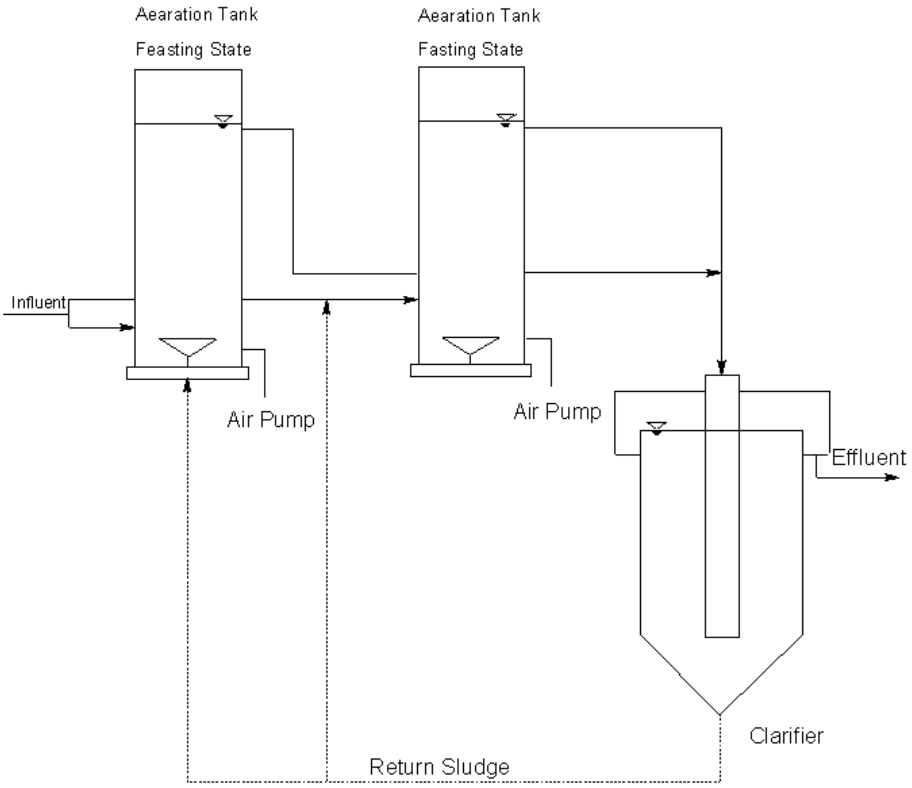
Steps in testing the degree of foaming

1. Place a 500-mL sample of activated sludge mixed liquor in a 1-L graduated cylinder;
2. Aerate the cylinder from the bottom, at an air flow rate of 2 L/min through a sintered-sand diffuser for 60 seconds;
3. The mixture is left under quiescent conditions for another 60 seconds;
4. Record the instantaneous foam height in every 15 seconds throughout the 120-second period;
5. The maximum volume of foam produced during the aeration period is the degree of foaming.



APPENDIX IV PREVIOUS DESIGN OF FFO

Original Feast-Fast Operation System Designed by Professor Chua Hong in the year of 1997.



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