TREATMENT OF SURFACE WATER AND MUNICIPAL WASTEWATER BY HYBRID CERAMIC MICROFILTRATION SYSTEMS

by

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Abstract

Concerns of limitations of conventional technologies for surface water treatment and reuse potentials of municipal wastewater have led to increased interest in membrane technologies. One of the most attractive membrane materials in the water and wastewater works nowadays that has been researched and developed is ceramic membrane. The ceramic membrane has many advantages for overcoming problems generated from conventional water and waste treatment systems. This research was conducted with hybrid ceramic microfiltration (CMF) systems in which pre-treatment processes were used to enhance the micro-filtration, in the ambient conditions of the tropical region. Feed waters for the pilot systems were synthetic water, surface water, and municipal wastewater.

It was found out that the hybrid ceramic microfiltration systems were very attractive on surface water treatment. When combined with pre-treatment coagulation-flocculation, the hybrid ceramic microfiltration removed highly almost all of pollutants including microbial pathogens. Suspended solid, total coliform, and fecal coliform, were removed completely in all direct and hybrid CMF systems. Giardia and Cryptosporidium removal efficiency of 99.77% and 99.92 % was achieved in poly aluminum chloride (PACl) + CMF hybrid system and powder activated carbon (PAC) + PACl + CMF hybrid systems, respectively. The highest TOC and DOC removals were more than 80 % with the PACl + PAC + CMF hybrid system. Permeate of the hybrid systems was very good for portable water.

Furthermore, the research also investigated that ceramic membrane could be applied attractively in municipal wastewater treatment. The highest pollutants removal rates were achieved in the PACl + CMF hybrid system. BOD and COD were removed at 67 % and 63 %, respectively. Total coliform and fecal coliform were removed completely. Almost all of measured parameters of permeate in the hybrid systems met standards for reuse activities such as irrigation and other agricultural purposes.

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List of Abbreviations

AIT	Asian Institute of Technology
APHA	American Public Health Association
BOD	Biochemical Oxygen Demand
BW	Backwashing
CMF	Ceramic Microfiltration
Crypto	Cryptosporidium
COD	Chemical Oxygen Demand
DBPs	Disinfection By-Products
DFe	Dissolved Iron
DMn	Dissolved Manganese
DOC	Dissolved Organic Carbon
DW	De-ionized Water
HAs	Humic Acids
EBW	Enhanced backwashing
EPA	Environmental Protection Agency (United State)
EPS	Extracellular Polymetric Substance
Giardia	Giardia Zamblia
MF	Microfiltration
MWW	Municipal Wastwater
MWWT	Municipal Wastwater Treatment
ND	None Detected
NF	Nanofiltration
NOM	Natural Organic Matter
UF	Ultrafiltration
NTU	Nephelometric Turbidity Unit
RO	Revere Osmosis
SDWA	Safe Drinking Water Act
SW	Surface Water
SWT	Surface Water treatment
THMs	Trihalomethanes
TOC	Total organic carbon
TFe	Total Iron
TMn	Total Manganese
TS	Total Solid
TSS	Total Suspended Solid
PAC	Powdered Activated Carbon
PACl	Poly Aluminum Chloride
PG	Pressure Gauge
PLC	Programmable Logic Controller
PN	Protein
POC	Particulate Organic Carbon
PVC	Polyvinyl Chloride
WHO	World Health Organization
WW	Wastewater

Chapter 1

Introduction

1.1 Background

The shortage of ground water sources having good quality necessitates a need for the better surface water treatment for drinking water. Conventionally, water treatment technologies for surface water treatment were based on conventional physico-chemical processes including coagulation, flocculation, sand filtration, disinfection, and etc. Although these technologies have been used for along time but they have been showing some problems such as the low organic removal, wasteful chemicals, large area requirement, especially low pathogens removal efficiency.

The reality mentioned as above needs alternatives in term of economic, engineering and transferring technology aspects for a higher quality of treated water from surface water. Membrane technologies have advantages for overcoming the problems generated from conventional water treatment systems. One kind of membrane filters widely applied for surface water treatment by hybrid system is ceramic membrane filter. Although it has been developed in recent years, ceramic microfiltration is being known as a good solution for surface water treatment due to its advantages on turbidity, total organic carbon, and especially micro particles removal. When combined with pre-treatment processes such as chlorination, adsorption by powdered activated carbon (PAC) and coagulation, the membrane filtration has a high rate on removing pollutants in surface water as 98.8 – 99.9% for turbidity and 96-99.8% for micro particles of 1-50 μm (Yuasa, et al., 2006).

There is a great potential for application of the ceramic membrane technology in developing countries. However, the operation of the new technology is usually depended on the specific characteristics of surface water sources taken and other local factors such as temperature, pH, turbidities, etc. Therefore, the study was conducted with a hybrid ceramic microfiltration (CMF) system, which is the combination of chlorination, PAC adsorption, coagulation process and microfiltration using ceramic membrane, in the ambient conditions. The study was implemented with different operational scenarios and different feed water qualities.

Furthermore, the ceramic membrane also can be applied in municipal wastewater (MWW) treatment for reuse activities. However, literatures and information on the development of ceramic microfiltration for reusing municipal wastewater are very limited. The functions of ozonation, PAC adsorption and coagulation-flocculation can be effectively contributed to CMF system for reusing municipal wastewater. Therefore, it is possible to investigate the important effect of a hybrid CMF system for municipal wastewater treatment for reuse.

Comparisons among scenarios were pointed out clearly, and problems related to dead-end ceramic microfiltration were investigated. Beside, comparisons between the quality of treated water or wastewater and standards or guidelines were also conducted. The study created good recommendations in transferring advanced technology for the treatment of surface water and domestic wastewater as well. In addition, starting results allowed having good directions for continually ongoing researches in the ceramic membrane filtration.

1.2 Objectives of the study

The objectives of the study are the followings:

1. Evaluate efficiency of the hybrid ceramic microfiltration system on surface water treatment for potable water with aspects of removal of physical, chemical and biological pollutants, in which efficiencies of removing natural organic mater and pathogens (bacteria and protozoa) are the most important interests.

2. Investigate potential and evaluate efficiency of the ceramic membrane technology on municipal wastewater treatment for reuse activities.

3. Investigate operational problems related to dead-end filtration for surface water treatment and municipal wastewater reclamation by the hybrid ceramic microfiltration technology in the tropical condition.

1.3 Scope of the study

The study served as both experimental and practical types in which the practical aspect was the dominant expectation. The study was carried in pilot scale including two stages:

1. Stage 1: Research with synthetic water.

   The aim of this stage is to:

   - Find out any problem generated while operating and solution for solving it
   - Optimize the system for next stage from experiences in this stage
   - Evaluate, analyze, and recommend gained results

2. Stage 2: Research with surface water (AIT pond water) and municipal wastewater (AIT wastewater)

   The aim of this stage is to get the real result on treatment of surface water and municipal wastewater by the hybrid ceramic microfiltration system. The stage pointed out much useful information for evaluations of removing pollutants and comparisons with standards for differently use activities of treated water and wastewater. In addition, requirements were also investigated to enhance the system when transferring the technology to the reality.

Chapter 2

Literature Review

2.1 Surface water and reclamation of municipal wastewater

2.1.1 Importance of surface water

Nowadays, the rapid growths of population and industrialization in the world lead to a big increase in water consumption. In Thailand, industrial growth of 8 to 10% per year requires a lot of water supply, estimated that industries consume water of 800 km^3/year. In addition, agriculture needs about 2,800 km^3 /year. Thailand has ground water consumption of 8.99 km^3 /year, while surface water available of 199 km^3 /year, this points out the need of using surface water as the main water supply source to satisfy economic development of the country (Aim, 2007).

In a larger view, figure 2.1 shows in detail all available water sources and limited amount of surface water in the world. The consideration that sea water occupies 96% of 1.386 million km^3 of total water in the world. In addition, 68.7 % of total fresh water is existed in ice; 30% is ground water; surface water sources such as rivers and lakes have total volume of 93.100 km^3 or 1% of total water of the world. Although surface water has a small amount compared with other water sources, it is the main source for daily human activities.

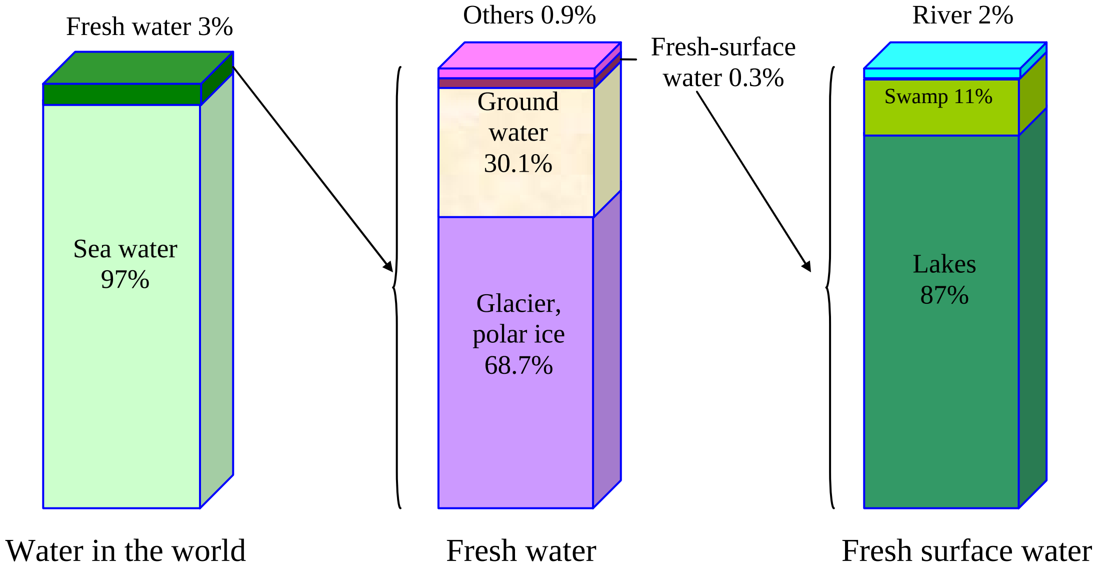


Figure 2.1 Water distributions in the world (Gleick, 1996)

Between 1900 and 1995, the world water use increased by a factor of six – more than double the rate of population growth during the same period. The world population is projected to increase from the current six billion or so to 8.3 billion in 2025. The result is already evident in the competition for water for agricultural, domestic and industrial purposes. Growing tensions over water resources are becoming a potentially explosive source of conflict. Many predict that wars of the next century will be over water, not oil or politics (Schonfeldt, 1999).

2.1.2 Contaminations of surface water

Microbial contamination (pathogens):

Microorganisms present in water supplies can cause immediate and serious health problems. Infections by bacteria, viruses, and protozoa usually cause gastrointestinal distress; however, some, such as the bacteria Vibrio cholerae, can result in death. There is a vast number of pathogenic organisms exist, and water suppliers cannot feasibly monitor for all of them. Therefore, they monitor for indicator organisms instead. The total coliform group of bacteria is the most common indicator. Unfortunately, some pathogens (e.g., viruses and protozoa) are more resistant to conventional water treatment processes than are total coliforms.

Protozoa cysts are the largest pathogens in drinking water, and are responsible for many of the waterborne diseases. Protozoa cysts range is size from 2 to 15 μm, but can squeeze through smaller openings. In order to insure cyst filtration, filters with an absolute pore size of l μm or less should be used. The two most common protozoa pathogens are *Giardia Zamblia* (Giardia) and *Cryptosporidium* (Crypto). Both organisms have caused numerous deaths in recent years in the U.S. and Canada, the deaths occurring in the young and elderly, and the sick and immune compromised. Many deaths were a result of more than one of these conditions. Neither disease is likely to be fatal to a healthy adult, even if untreated. Outside of the US.and other developed countries, protozoa are responsible for many cases of amoebic dysentery, but so far this has not been a problem in the U.S., due to the application of more advanced wastewater treatment technologies. This could change during a survival situation. Tests have found Giardia and/or Crypto in up to 5 % of vertical wells and 26% of springs in the U.S (American Water Works Association, 1999).

Bacteria are smaller than protozoa and are responsible for many diseases, such as typhoid fever, cholera, diarrhea, and dysentery. Pathogenic bacteria range in size from 0.2 to 0.6 μm, and a 0.2 μm filter is necessary to prevent transmission. Contamination of water supplies by bacteria is blamed for the cholera epidemics, which devastate undeveloped countries from time to time. Even in the U.S., E. coli is frequently found to contaminated water supplies. Fomately, E. coli is relatively harmless as pathogens go, and the problem isn't so much with E. coli found, but the fear that other bacteria may have contaminated the water as well. Never the less, dehydration from diarrhea caused by E. coli has resulted in fatalities. One of hundreds of strains of the bacterium Escherichia coli, E. coli 0157:H7 is an emerging cause of food borne and waterborne illness. Although most strains of E. coli are harmless and live in the intestines of healthy humans and animals, this strain produces a powerful toxin and can cause severe illness. E. coli 0157:H7 was first recognized as a cause of illness during an outbreak in 1982 traced to contaminated hamburgers. Since then, most infections are believed to have come from eating undercooked ground beef. However, some have been waterborne. The presence of E. coli in water is a strong indication of recent sewage or animal waste contamination. Sewage may contain many types of disease-causing organisms. Since E. coli comes from human and animal wastes, it most often enters drinking water sources via rainfalls, snow melts, or other types of precipitation, E. coli may be washed into creeks, rivers, streams, lakes, or groundwater. When these waters are used as sources of drinking water and the water is not treated or inadequately treated, E. coli may end up in drinking water. E. coli 0157:H7 is one of hundreds of strains of the bacterium E. coli. Although most strains are harmless and live in the intestines of healthy humans and animals, this strain produces a powerful toxin and can cause severe illness. Infection often causes severe bloody diarrhea and abdominal cramps; sometimes the infection causes non-bloody diarrhea (American Water Works Association, 1999).

Frequently, no fever is present. It should be noted that these symptoms are common to a variety of diseases, and may be caused by sources other than contaminated drinking water. In some people, particularly children under 5 years of age and the elderly, the infection can also cause a complication, called hemolytic uremic syndrome, in which the red blood cells are destroyed and the kidneys fail. About 2%-7% of infections lead to this complication. In the U.S. hemolytic uremic syndrome is the principal cause of acute kidney failure in children, and most cases of hemolytic uremic syndrome are caused by E. coli 0157:H7. Hemolytic uremic syndrome is a life-threatening condition usually treated in an intensive care unit. Blood transfusions and kidney dialysis are often required. With intensive care, the death rate for hemolytic uremic syndrome is 3 %-5%. Symptoms usually appear within 2 to 4 days, but can take up to 8 days. Most people recover without antibiotics or other specific treatment in 5-10 days. There is no evidence that antibiotics improve the course of disease, and it is thought that treatment with some antibiotics may precipitate kidney complications. Antidiarrheal agents, such as loperamide (Imodium), should also be avoided. The most common methods of treating water contaminated with E. coli is by using chlorine, ultra-violet light, or ozone, all of which act to kill or inactivate E. coli. Systems, using surface water sources, are required to disinfect to ensure that all bacterial contamination is inactivated, such as E. coli. Systems using ground water sources are not required to disinfect, although many of them do. According to EPA regulations, a system that operates at least 60 days per year, and serves 25 people or more or has 15 or more service connections, is regulated as a public water system under the Safe Drinking Water Act (SDWA). If a system is not a public water system as defined by EPA's regulations, it is not regulated under the SDWA, although it may be regulated by state or local authorities. Under the SDWA, EPA requires public water systems to monitor for coliform bacteria. Systems analyze first for total coliform, because this test is faster to produce results. Any time that a sample is positive for total coliform, the same sample must be analyzed for either fecal coliform or E. coli. Both are indicators of contamination with animal waste or human sewage. The largest public water systems (serving millions of people) must take at least 480 samples per month. Smaller systems must take at least five samples a month, unless the state has conducted a sanitary survey - a survey in which a state inspector examines system components and ensures they will protect public health - at the system within the last five years (American Water Works Association, 1999).

Viruses are the second most problematic pathogen, behind protozoa. As with protozoa, most waterborne viral diseases don't present a lethal hazard to a healthy adult. Waterborne pathogenic viruses range in size from 0.020-0.030 pm (American Water Works Association, 1999), and are too small to be filtered out by a mechanical filter. All waterborne enteric viruses affecting humans occur solely in humans, thus animal waste doesn't present much of a viral threat. At the present viruses don't present a major hazard to people drinking surface water in the U.S., but thls could change in a survival situation as the level of human sanitation is reduced. Viruses do tend to show up even in remote areas, so a case can be made for eliminating them now.

Chemical contamination:

- *Inorganic contaminants:*

Toxic metals and other inorganic compounds contaminate water supplies from both human-made and natural sources. Nitrates, common in groundwaters, cause methemoglobinemia or "blue-baby syndrome" in infants. Fluoride, added by many water suppliers in small doses to prevent tooth decay, causes a weakening of the bones called skeletal fluorosis at concentrations above 4 mg/L. Radon, a naturally occurring radionuclide, may cause lung cancer from long-term exposures in the air after being released from water.

- *Organic contaminants:*

Water can be contaminated by a number of organic compounds, such as chloroform, gasoline, pesticides, and herbicides from a variety of industrial and agricultural operations or applications. One exception is when the aquifer is located in limestone. Not only will water flow faster through limestone, but the rock is prone to forming vertical channels or sinkholes that will rapidly allow contamination from surface water. Surface water may show great variations in chemical contamination levels due to differences in rainfall, seasonal crop cultivation, or industrial effluent levels. Also, some hydrocarbons (the chlorinated hydrocarbons in particular) form a type of contaminant that is especially troublesome.

Total organic carbon (TOC) is a measure of the dissolved and particulate material related to the formation of disinfection by-products. Certain naturally occurring organic substances (particularly humic and fulvic acids) react with chlorine to form these by-products. Natural organic matter (NOM) consists of naturally occurring organic material derived from decaying organic matter and dead organisms. Other portions of TOC are derived from domestic and industrial activities that include wastewater discharge, agricultural and urban runoff, and leachate discharge.

Humic substances are typically the major component of NOM in water supplies. They are derived from soil and are also produced within natural water and sediments by chemical and biological processes such as the decomposition of vegetation. Humic substances are anionic polyelectrolytes of low to moderate molecular weight, and their charge is primarily caused by carboxyl and phenolic groups. They have both aromatic and aliphatic components and can be surface active; they are refractive and can persist for centuries or longer. Humic substances are defined operationally by the methods used to extract them from water or soil. Typically, they are divided into the more soluble fulvic acids (FAs) and the less soluble humic acids (HAs), with FAs predominating in most waters (Christman, 1983). The concentration of NOM in water is typically expressed using the amount of organic carbon. Organic carbon that passes through a 0.45 μm pore-size membrane filter is defined as dissolved organic carbon (DOC), and the amount that does not is known as particulate organic carbon (POC).Total organic carbon (TOC) is the sum of DOC and POC. The DOC of lakes ranges from 2 mg/L or less (oligotrophic lakes) to 10 mg/L (eutrophic lakes) (Thurman, 1985).The DOC of small, upland streams will typically fall in the range 1 to 3 mg/L; the DOC of major rivers ranges from 2 to 10 mg/L. The highest DOC concentrations (10 to 60 mg/L) are found in wetlands (bogs, marshes, and swamps). The DOC concentration in upland lakes has been shown to be directly related to the percentage of the total watershed area that is near-shore wetlands (Driscoll et al., 1994). The median raw water TOC concentration for U.S. plants treating surface water is approximately 4 mg/L (Krasner, 1996).

Aesthetic aspects of water quality:

- *Color and turbidity:*

Inorganic metals such as iron and organic compounds such as NOM cause color. In addition to being aesthetically undesirable, color in the form of NOM is a precursor to the formation of disinfection by-products (DBPs), which may cause cancer. Turbidity is the cloudiness of water and is determined by measuring the amount of light scattered by suspended particles in water. The unit of turbidity is the nephelometric turbidity unit (NTU). Although not a direct threat to health, turbidity decreases the efficiency of disinfection, and particles that cause turbidity can transport harmful chemicals through a treatment plant.

- *Taste and odor:*

Zinc, copper, iron, and manganese can be detected by taste at concentrations of 1 mg/L. Hydrogen sulfide, a common contaminant in groundwaters, is detectable at concentrations of 100 ng/L. Many tastes and odors in surface waters result from biological activity of filamentous bacteria and blue-green algae. They produce geosmin and methylisoborneol, which cause an earthy or musty smell. Both are detected at concentrations of 10 ng/L (Arnold, 1990).

- *Alkalinity:*

Alkalinity is a measure of the buffering capacity of water. Alkalinity determines the magnitude of pH changes during coagulation and affects the solubility of calcium carbonate in the distribution system. In natural waters the carbonate system dominates alkalinity. In such systems, bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), and hydroxide (OH^-) ions are the major species of alkalinity.

- *Temperature and pH:*

Temperature and pH affect coagulation, disinfection, and corrosion control. Equilibrium constants and reaction rates vary with temperature. The hydrogen ion concentration, measured as pH, is an important chemical species in these processes. Furthermore, the density and viscosity of water vary with temperature; thus, it is an important variable in the design of mixing, flocculation, sedimentation, and filtration process units.

Table 2.1 Major concerns on quality of surface water (American Water Works Association (1999), WHO (2008))

Parameter	Sources	Effects on water supplier
Solids, turbidity	Domestic sewage, urban and agricultural runoff, construction activity	Hinder water treatment process. Reduce treatment effectiveness. Shield microorganism against disinfectants. Reduce reservoir capacity
Nutrients	Septic system leachate, wastewater plant discharge, lawn and road runoff, animal feedlots, agricultural lands, eroded landscapes, landfill leachate, rainfall (especially nitrogen)	Nitrates that may be toxic to infants and unborn fetuses. Accelerates eutrophication: high levels of algae; dissolved oxygen deficiencies. Increase algae activity. High color and turbidity. Disinfection by-product formation. Taste and odor problems
Natural organic matter (NOM)	Naturally occurring; wetlands in the watershed tend to increase concentrations	Influence nutrient availability. Mobilize hydrophobic organics. Disinfection by-product formation
Synthetic organic contaminants	Domestic and industrial activities, spills and leaks, wastewater discharges, agricultural and urban runoff, leachate, wastewater treatment and transmission	Adverse impacts on human health and aquatic life.
Coliform bacteria	Domestic sewage from wastewater discharges, sewers, septic systems, urban runoff, animal farms and grazing, waterfowl droppings, land application of animal wastes	Fecal coliform are indicators of warm-blooded animal fecal contamination that pose a threat to human health
Cryptosporidium and Giardia	Eggs are shed through feces, where they can enter lakes, reservoirs and other sources of drinking water	Causes acute short-term infection, chronic diarrhea, intestinal illness Fecal-Oral, Water, & possibly respiratory secretions. May become severe in children and immune compromised
Metals	Industrial activities and wastewater, runoff	Adverse effect to aquatic life and public health
Aesthetics	Taste and Odor: industrial chemicals, algae metabolites, NOM, urea Color: metals, NOM, algae, AOC, Turbidity: solids and algae, Staining: Metals	Aesthetic problems Reduce public confidence in water supply safety
Toxics	Agriculture, lawn care, industrial sites, roads and parking lots, wastewater	Toxic to humans and aquatic life

2.1.3 Reclamation of municipal wastewater

Wastewater reuse presents a promising solution to the growing pressure on water resources. However, wastewater reuse implementation faces obstacles that include insufficient public acceptance, technical, economic and hygienic risks and further uncertainties caused by a lack of awareness, accepted standards, uniform guidelines and legislation. So far, there are no supra-national regulations on water reuse in Europe and further development is slowed by lack of widely accepted standards, e.g. in terms of required water quality, treatment technology and distribution system design and operation (Wintgens et al., 2004). Treatment technology encompasses a vast number of options and membrane processes are regarded as key elements of advanced wastewater reclamation and reuse schemes and are included in a number of prominent schemes world-wide, e.g. for artificial groundwater recharge, indirect potable reuse as well as for industrial process water production. For dual reticulation purposes in urban areas two types of systems have been built, a centralized type of treatment with dual membrane processes, including e.g. microfiltration (MF) and reverse osmosis (RO), and small-scale systems using membrane bioreactors.

Reclamation and reuse of municipal wastewater is a very common practice worldwide (Bixio et al., 2004). By reclaiming wastewater, the circulation of water through the natural water cycle can be short-circuited, such that a contribution to human water needs is made and the environmental impact thereof limited. Furthermore, a main characteristic of reclaimed wastewater is that its "production" is relatively constant during the year, due to its source being dependent not on rainfall, but on the production of municipal sewage. Thus, reclaimed water can increase the reliability of a water supply, comprising as it does, a further source of water. Similarly, recycled water can be viewed as an independent source of water capable of increasing the reliability of a water supply (Anderson et al., 2002). This opportunity has to date been used in various countries using a range of technologies for different water applications.

Reclamation technologies of the treatment can be classified as secondary, tertiary or quaternary level. The wastewater reclamation refers to the treatment or processing of water to make it fit for reuse, which is defined as any kind of beneficial use of reclaimed water (Lens et al., 2002). A number of definitions require further details; secondary treatment - here also including nutrient removal - is characteristic of restricted agricultural irrigation (i.e. for food crops not consumed uncooked) and for some industrial applications such as industrial cooling (except for the food industry). Additional filtration/disinfection steps (tertiary treatment) are applied for unrestricted agricultural or landscape irrigation as well as for process water in some industrial applications. Quaternary treatment is defined here as a treatment producing a quality comparable to drinking water - often involving a "dual membrane" step to meet unrestricted residential uses and industrial applications requiring ultrapure water. Table 2.2 lists the main categories of municipal wastewater reuse applications (listed in order of decreasing projected volume of use).

Conventionally treated wastewater contains a wide range of contaminants from suspended solids to the smallest of inorganic salts. Many of these are known or suspected to be detrimental to various reuse applications. Microorganisms represent the most common threat to the reuse of waste water, due the large concentration of potentially infectious species that routinely are present in the effluent of waste water from secondary treatment plants.

Table 2.2 Municipal wastewater reuse and applications (Metcalf& Eddy, 1991)

Categories	Reuse applications
Agricultural irrigation	Crop irrigation; Commercial nurseries
Landscape irrigation	Park; Golf course; Residential
Industrial recycling and reuse	Cooling; Boiler feed; Process water
Groundwater recharge	Groundwater replenishment; Salt water intrusion control
Environment	Lakes and ponds; Streamflow augmentation; Fisheries
Non-potable urban uses	Fire protection; Air conditioning; Toilet flushing
Potable reuse	Blending in water supply reservoir; Pipe to pipe water supply

2.2 Conventional technologies for surface water treatment

2.2.1 A typically conventional technology for surface water treatment

Figure 2.4 shows conventional treatment processes in surface water treatment plant. After being withdrawn from a source (lake or river), raw water is a suspension of small, stable colloidal particles whose motions are governed by molecular diffusion. In coagulation these particles are destabilized by the addition of a coagulant during rapid mixing. Flocculation promotes the collisions of these unstable particles to produce larger particles called flocs. In sedimentation, these flocs settle under the force of gravity. The particles that do not settle are removed during filtration. A disinfectant such as chlorine is then added, and, after a certain amount of contact time, the treated water is distributed to consumers. Direct filtration plants omit the sedimentation and occasionally the flocculation processes. These plants are suitable for raw waters with low to moderate turbidities and low color. The following sections describe the underlying theory and design of each of the major processes: coagulation, sedimentation, filtration, and disinfection.

Coagulation:

Coagulation is the process of adding chemicals to water to make dissolved and suspended particles bind together and form larger particles that will settle out of the water as floc. It is a safe and effective form of water treatment used by many cities to treat drinking water. Coagulation improves the quality of water by reducing the amount of organic compounds, iron and manganese, colour, and suspended particles

In coagulation, small particles combine into larger particles. Coagulation consists of three separate and sequential processes: coagulant formation, particle destabilization, and interparticle collisions. The first two steps occur during rapid mixing, whereas the third occurs during flocculation. In natural waters, particles (from 10 nm to 100 μm in size) are stable, because they have a negative surface charge (Amirtharajah, 1999).

- *Mechanisms of destabilization:*

The possible mechanisms of particle destabilization are double layer compression, polymer bridging, charge neutralization, and sweep coagulation. In water treatment the last two mechanisms predominate; however, when organic polymers are used as coagulants, polymer bridging can occur. In charge neutralization the positively charged coagulant, either the hydrolysis species of a metal salt (alum or ferric chloride) or polyelectrolytes, adsorbs onto the surface of the negatively charged particles. As a result, the particles have no net surface charge and are effectively destabilized. In sweep coagulation a metal salt is added in concentrations sufficiently high to cause the precipitation of a metal hydroxide (e.g., aluminum hydroxide). The particles are enmeshed in the precipitate, and it "sweeps" the particles out of the water as it forms and settles.

With metal salt coagulants, the mechanism of coagulation is determined by the coagulant dose and the pH of the equilibrated solution. The most common coagulant is alum $[Al_2(SO_4)_3.14.3\ H_2O]$. The alum coagulation diagram, shown in figure 2.3, indicates the regions where each mechanism dominates. A similar diagram exists for ferric chloride (Amirtharajah and O' Melia, 1990).

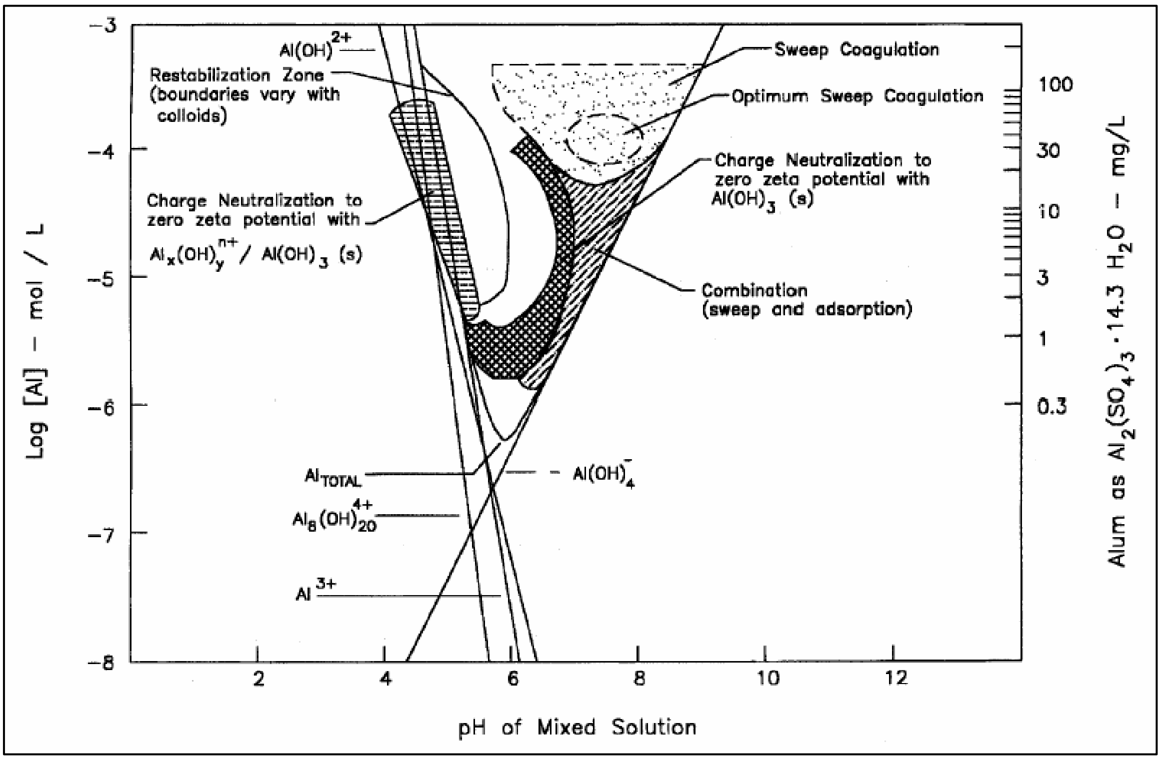


Figure 2.2 The alum coagulation diagram that defines the mechanism of coagulation based on pH and alum dose (Amirtharajah et al., 1982.).

At a fundamental level the rapid-mixing unit provides encounters between molecules and particles in the source water and the coagulant species. These encounters are controlled by the hydrodynamic parameters and geometry of the mixer, molecular properties of the source water, and the kinetics of the coagulation reactions. Research indicates that coagulation by sweep coagulation is insensitive to mixing intensity. Although its applicability is questionable on theoretical grounds, the *G*-value is widely used to represent mixing intensity in both rapid mix and flocculation units. The *G*-value is computed as the following equation.

$$G = \sqrt{\frac{P}{\mu V}} = \sqrt{\frac{\varepsilon}{v}}$$

where G is the velocity gradient (s^{-1}), P is the net power input to the water (W), μ is the dynamic viscosity of water (Ns/m^2), V is the mixing volume (m^3), ε is the rate of energy dissipation per mass of fluid (W/kg), and ν is the kinematic viscosity (m^2/s) Mixing time, t, is an important design parameter, and it can vary from less than one second in some in-line mixers to over a minute in back-mix reactors. In general, short times (< 1 s) are desired for the charge neutralization mechanism and longer times (10 to 30 s) for sweep coagulation.

Flocculation:

In flocculation, physical processes transform smaller particles into larger aggregates or flocs. Interparticle collisions cause the formation of flocs, and increased mixing with increased velocity gradients accelerates this process. However, if the mixing intensity is too vigorous, turbulent shear forces will cause flocs to break up. Studies of the kinetics of flocculation (Argaman and Kaufman, 1970) indicate that a minimum time exists below which no flocculation occurs regardless of mixing intensity and that using tanks in series significantly reduces the overall time required for the same degree of flocculation. Figure 2.3 illustrates these two conclusions. In current designs, *G*-values are tapered from one tank to the next with the highest *G*-value in the first tank and decreasing in each successive compartment. *G*-values are between 60 and 10 s^{-1}, and total detention times are close to 20 minutes.

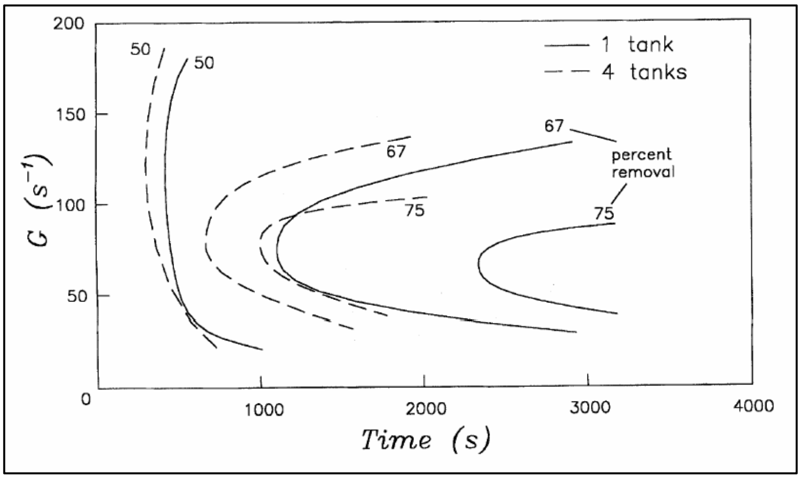


Figure 2.3 A graph illustrating the benefit of tanks in series for flocculation (Argaman et al., 1970)

Sedimentation:

During sedimentation, gravity removes the flocs produced during the preceding flocculation process. These flocs continue to aggregate as they settle, and, as a result, experimental techniques are required to describe their settling behavior. Rectangular sedimentation basins are the most common in water treatment practice. Designs are based on the overflow rate, which is the flow rate divided by the surface area. The overflow rate indicates the settling velocity of the discrete (non-flocculant) particles that are removed with 100% efficiency. Typical overflow rates are 1.25 to 2.5 m/h. Plate and tube settlers are often added to the last two thirds of a basin to increase the overflow rate.

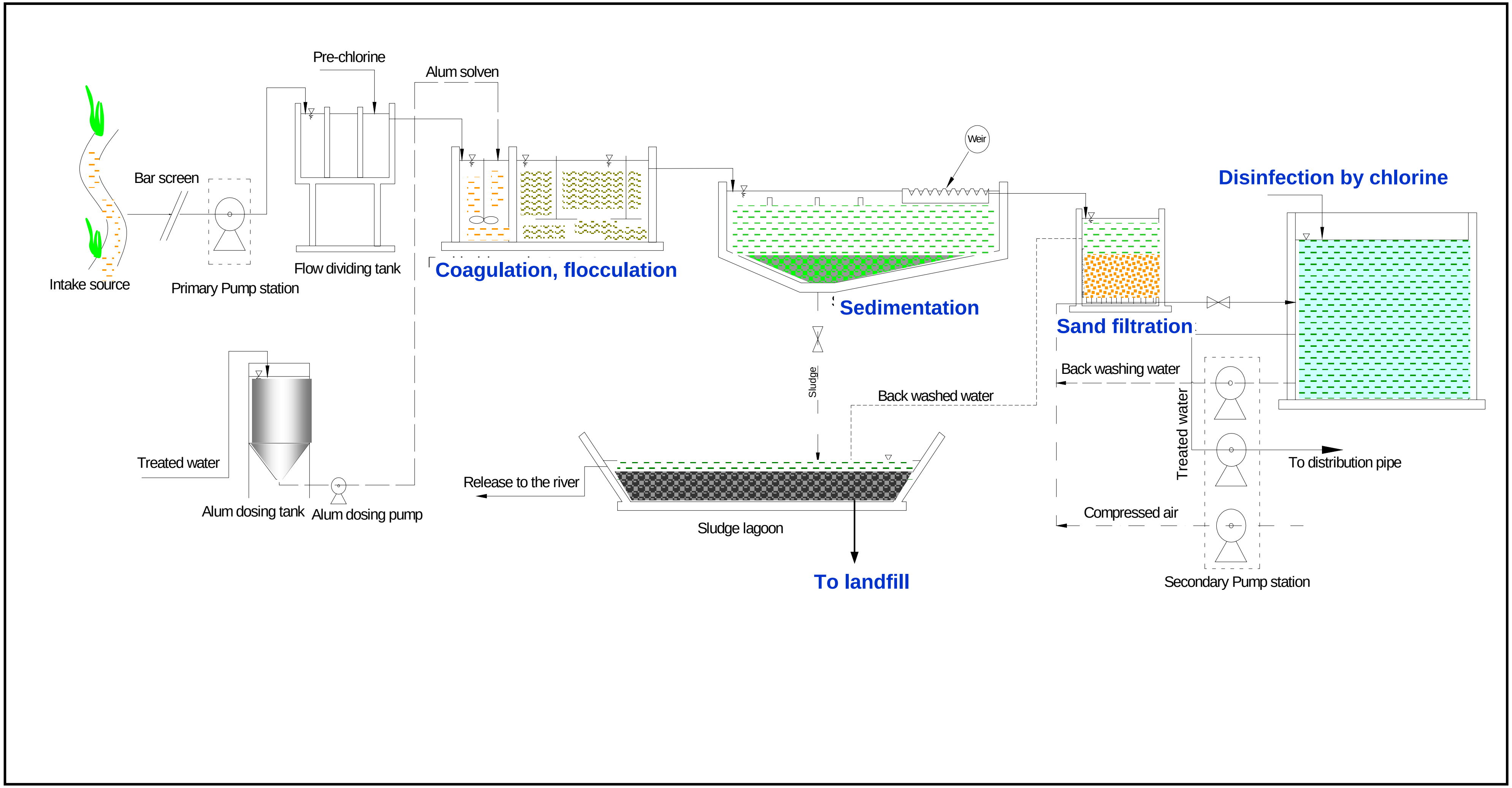


Figure 2.4 Schematic of a conventional water treatment plant

Filtration:

The most common filters are dual-media filters, in which water flows by gravity through a porous bed of two layers of granular media. The top layer is anthracite coal, and the bottom layer is sand. Filters are operated until one of two criteria is exceeded the effluent turbidity standard or the allowable head loss through the filter. The filters are cleaned by backwashing to remove the particles that have been collected on the filter media. The removal of particles in a dual-media filter occurs within the pores of the filter and is mediated by transport mechanisms that carry small particles across fluid streamlines to distances close to the filter grains (also called collectors). When particles are very close to the collectors, short-range surface forces cause the collector to capture the particle.

The dominant transport mechanisms in water filtration are diffusion and sedimentation. Diffusion is transport resulting from random Brownian motion by bombardment of the particle by molecules of water. Diffusion is increasingly important for particles less than 1 μm in size. Sedimentation is due to the force of gravity and the associated settling velocity of the particle, which causes it to cross streamlines and reach the collector. This mechanism becomes increasingly important for particles greater than 1 μm in size (for a size range of 5 to 25 μm). The combination of these two mechanisms results in a minimum net transport efficiency for a size of approximately 1 μm. It is interesting to extrapolate this result to two important microbial contaminants. Cysts of Giardia lamblia, with dimensions of 10 to 15 μm, are probably removed by the sedimentation mechanism, whereas Cryptosporidium, with a dimension close to 3 to 5 μm, is probably close to the minimum net transport efficiency. Unfortunately, a theory of filtration that is sufficiently general and predictive does not yet exist. Therefore, designers must rely on empirical evidence from pilot-scale tests for guidance.

Disinfection:

A variety of disinfectants are available in water treatment, including chlorine, chloramines, chlorine dioxide, and ozone. However, chlorine is the most common disinfectant in almost all of developing countries. Chlorine gas is added to water to form hypochlorous acid (HOCl). At pHs between 6 and 9, HOCl dissociates to form the hypochlorite ion (OCl^-) and hydrogen ion (H^+). HOCl has the greatest disinfection power. The extent of disinfection in a water treatment plant is determined by computing *CT* values, where C is the concentration of disinfectant and *T* is the contact time between disinfectant and water. The *CT* value required varies with chlorine concentration, pH, and temperature. Although increasing the *CT* value may provide a large factor of safety against microbial contamination, disinfection causes the formation of disinfection by-products (DBPs), which are suspected carcinogens. DBPs result from reactions between disinfectants and NOM, which is ubiquitous in natural waters. The most common DBPs from chlorine are the THMs: chloroform, bromodichloromethane, dibromochloromethane, and bromoform.

2.2.2 Advantages and disadvantages of the conventional technologies

Major advantages and disadvantages of the conventional technologies for surface water treatment are given in table 2.3. The most noticeable limitations of the technologies are low pathogens removal efficiency. High level of DOC after the treatment of highly DOC contaminated water sources may cause taste, odor and color. In addition, low DOC removal leading to potentials of creating harmful substances from conventional disinfection. DOC is one precursor contributing to generation of disinfection by-products, THMs, in the chlorine disinfection.

Table 2.3 Advantages and disadvantages of conventional technology for surface water treatment

Advantages	Disadvantages
Simple and easy operation	Waste chemical
Low capital cost due to cheap building materials	Produce disinfection by-products causing cancer
Suitable for pure surface water sources	Low pathogens removal rate Low natural organic mater removal rate
Low maintenance and operation cost, low cost of water supply, suitable for weakly developing countries	Large area requirement Water containing a high level of DOC may cause taste, odor and color problems and sand filtration can not effectively remove DOC Not sufficient for high quality requirement of water supplies in developed countries

2.3 Membrane technologies for treatment of surface water and municipal wastewater

2.3.1 Background on membrane filtration

Type of membrane filtration process:

The classification of membrane process can be based on different aspects such as driving force, membrane type and configuration, and removal capacities. For application on drinking water industry, membrane processes are used for desalting, softening, dissolved organics and color removal, turbidity and pathogens removal. Although the membrane technologies for water treatment become commercially available more than 25 years ago, they are experiencing rapid development and improvements.

Based on the driving force used to promote the water treatment, membrane process can be classified as pressure, electrical voltage, tem pressure, concentration gradient, and combinations types. Actually, commercially available and commonly used membrane processes for water treatment are pressure-driven and electrically driven membrane processes in which pressure-driven process is more commonly used and popular.

Based on pore size, the pressure-driven membranes are classified into four different types: revere osmosis (RO), nanofiltration (NF), ultrafiltration (UF) and microfiltration (MF). The classification of membranes is presented in table 2.4.

Table 2.4 Classification of membranes

Membrane process	Driving force	Mechanism of separation	Pore size (μm)	Membrane material	Membrane module	Operating pressure (bar)
MF	Pressure or vacuum	Sieve	0.1 - 10	Ceramic, Polysulfone, Polyvinylidenedifluoride	Tubular, hollow fiber	< 2
UF	Pressure	Sieve	0.01 - 0.1	Ceramic, Polysulfone, Polyvinylidenedifluoride, Cellulose acetate thin film	Tubular, hollow fiber, spiral wound, plate-and-frame	1 – 10
NF	Pressure	Sieve + Solution/diffusion + exclusion	0.001 - 0.01	Cellulose acetate thin film	Tubular, spiral wound, plate-and-frame	5 - 35
RO	Pressure	Solution/diffusion + exclusion	< 0.001	Cellulose acetate thin film	Tubular, spiral wound, plate-and-frame	15 - 150

Sources: (Stephenson et al., 2000 and Wagner, 2001)

The applications of membranes depend on their specific types. Figure 2.5 presents major applications of the respective types of membranes.

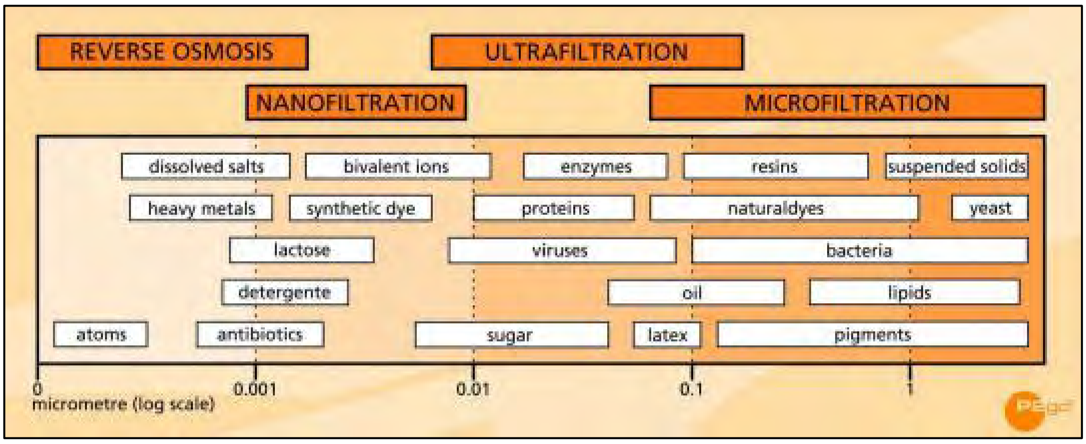


Figure 2.5 Application size range of membrane filtration process (Scott and Huges, 1996)

Based on configurations of operating a filtration process, membrane processes can be classified into two types as the followings:

• *Dead-end filtration:*

The most basic form of filtration is dead-end filtration. The complete feed flow is forced through the membrane and the filtered matter is accumulated on the surface of the membrane. The dead-end filtration is a batch process as accumulated matter on the filter decreases the filtration capacity, due to clogging. A next process step to remove the accumulated matter is required. Dead-end filtration can be a very useful technique for concentrating compounds.

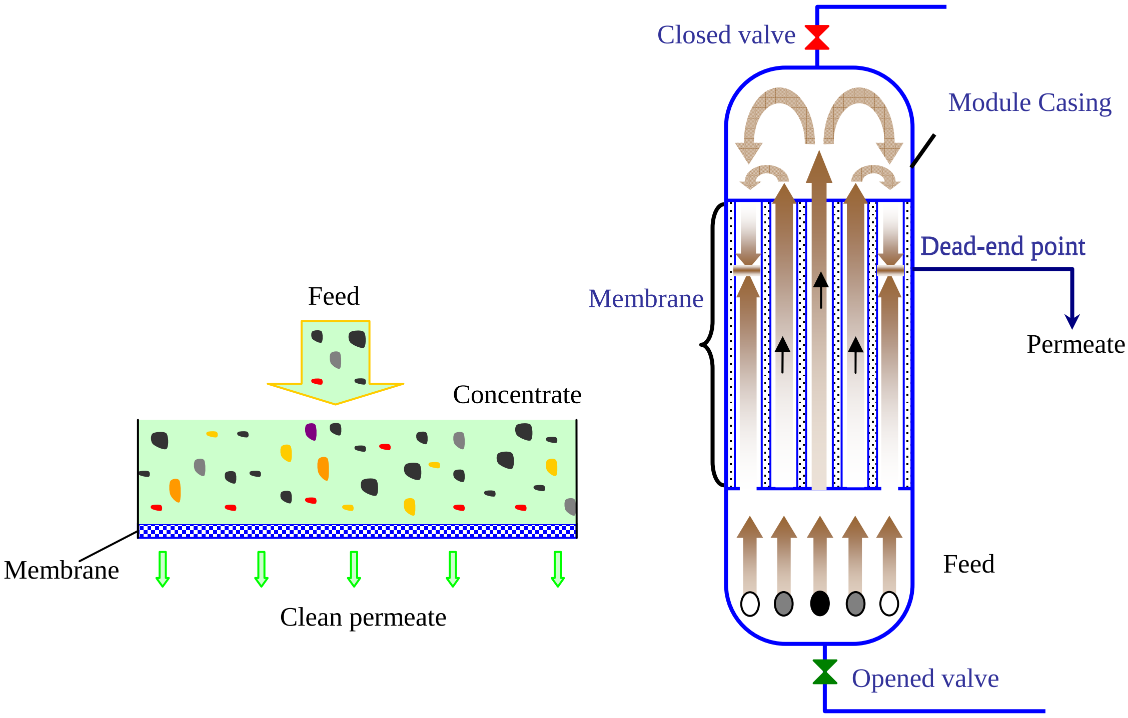


Figure 2.6 Dead-end mode and its configuration for tubular ceramic membrane

- *Cross-flow filtration:*

With cross-flow filtration a constant turbulent flow along the membrane surface prevents the accumulation of matter on the membrane surface. The membranes used in this process are commonly tubes with a membrane layer on the inside wall of the tube. The feed flow through the membrane tube has an elevated pressure as driving force for the filtration process and a high flow speed to create turbulent conditions. The process is referred to as "cross-flow", because the feed flow and filtration flow direction have a 90 degrees angle. Cross-flow filtration is an excellent way to filter liquids with a high concentration of filterable matter.

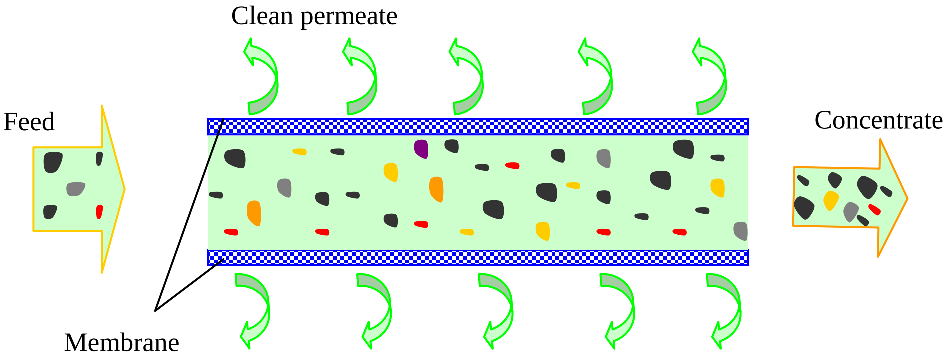


Figure 2.7 Cross-flow membrane filtration

Permeate flux:

The capital and operating costs of membrane systems typically scale directly as a function of the membrane permeate flux. Where it is possible to move more water across a unit area of membrane per time unit, less membrane area will be required to provide for the design flow. This results in a lower cost for membrane modules, peripheral piping and pumps, monitoring equipment, skids, foundations, and buildings. The cost of replacing membranes as reflected in the membrane life is often the single largest component of operating cost. By reducing the amounts of membrane area to be replaced, a higher permeate flux also corresponds to a lower operating cost. Thus, permeate flux and the factors that influence it are central considerations in determining membrane performance and cost.

Transmembrane pressure (TMP):

Transmembrane pressure (TMP) is defined as the difference between the average feed/concentrate pressure and the permeate pressure. It is effectively the driving force associated with any given flux for low-pressure membranes. The TMP of the membrane system is an overall indication of the feed-pressure requirement and it is used with the flux to assess membrane fouling (WEF Press, 2006).

It was investigated that there is a correlation between micro-particle concentration and TMP of ceramic membrane filtration. Recently, researchers have been researched on a hybrid ceramic microfiltration using the effluent from a conventional rapid sand filtration process as the feed water. A clear relationship between micro-particale concentration and TMP was pointed out. It would suggest a significant effect of the flocculation on the filterability in the monolith channel. The micro-particles, larger than 1 μm in the shear field, are subjected to a lift force such as the lateral migration and shear-induced diffusion which are proportional to square and cubic power of the equivalent particle diameter, respectively (Watanabe et al., 2007).

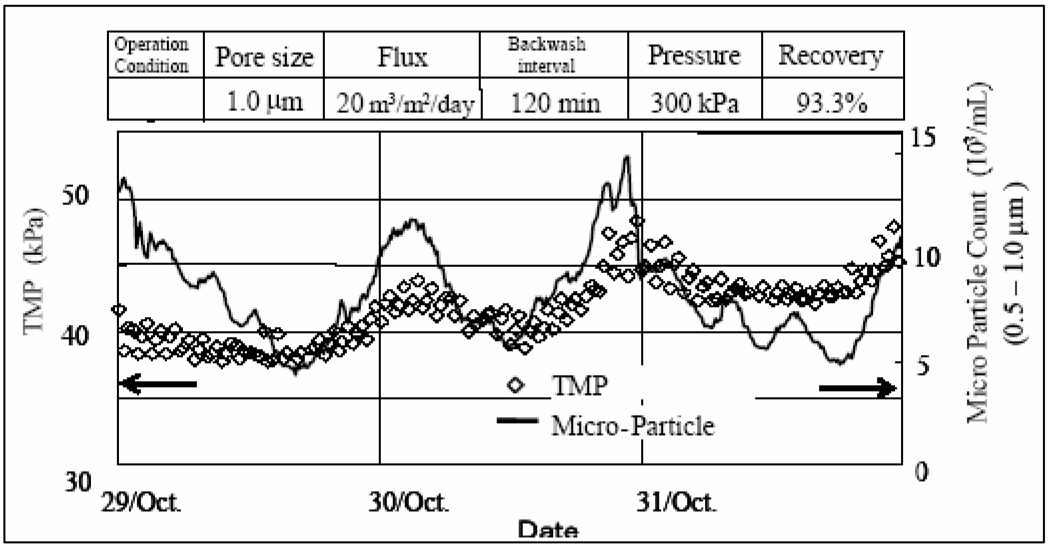


Figure 2.8 Correlation between TMP and micro-particle concentration (Watanabe et al., 2007)

Membrane fouling:

If membrane separations are to be economical, high fluxes are required. Unfortunately, most membrane separations exhibit flux decline as a result of fouling. Fouling may be defined as the deposition of matter on or in the membrane such that the membrane performance is altered. During the flow of a clean liquid through a porous layer, the resistance is constant and the flow rate is constant for a given pressure difference. But when the liquid contains suspended particles, the resistance of the porous layer will progressively increase as the particles accumulate on it, resulting a corresponding drop in the permeate rate at a constant pressure drop. Although fouling is very complicated, it can be classified into two types (Davis, 1992):

(1) Internal membrane fouling: The attachment of material within the internal pore structure of the membrane or directly to the membrane surface due to adsorption, precipitation, pore plugging, particulate adhesion, etc.

(2) External cake fouling: The formation of a atagnant cake layer of the membrane surface due to concentration polarization as the material being filtered is carried to the membrane by permeate flow and is then rejected by the membrane.

Based on fouling materials, membrane fouling can be distinguished by four types:

(1) Inorganic fouling/scaling is caused by the accumulation of inorganic precipitates such as metal hydroxides, and “scales” on membrane surface or within pore structure. Precipitates are formed when the concentration of chemical species exceeding their saturation concentrations.

(2) Particle/colloids fouling in most cases, particles and colloids do not really foul the membrane because the flux decline caused by their accumulation on the membrane surface is largely reversible by hydraulic cleaning measures such as backwash and air scrubbing. A rare case of irreversible fouling by particles and colloids is that they have smaller size relative to membrane pore size. Therefore, those particles and colloids can enter and be trapped within the membrane structure matrix, and not easily be cleaned by hydraulic cleaning.

(3) Microbial fouling: The formation of biofilms on membrane surfaces. Once bacteria attach to the membrane, they start to multiple and produce extracellular polymetric substances (EPS) to form a viscous, slimy, hydrated gel. EPS typically consists of heteropolysaccharides and have high negative charge density. This gel structure protects bacterial cells from hydraulic shearing and from chemical attacks of biocides such as chlorine (Syed et al., 2000).

(4) Organic fouling: Organic fouling is profound in membrane filtration with source water containing relatively high natural organic matters (NOM). Surface water (lake, river) typically contains higher NOM than ground water, with exceptions. For source water high in NOM, organic fouling is believed to be the most significant factor contributed to flux decline (Mallevialle et al., 1996; Lahoussine et al, 1990).

Membrane cleaning:

Fouling including irreversible and reversible fouling is the major disadvantage of membrane filtration. Two main techniques, backwashing and chemical cleaning, are developed for overcoming fouling problems.

• *Membrane backwashing:*

Backwashing of the membrane is a common technique used with low-pressure, hollow-fiber membranes to maintain the design operating flux of the system. Backwashing removes the layer of contaminants retained on the feed side of the membrane that have accumulated during the previous operating cycle. This fouling layer presents additional hydraulic resistance to fluid flow across the membrane. To overcome this additional resistance, elevated TMPs are required, which results in increased operating costs. The frequency of backwashing events should be optimized to maintain low TMPs throughout normal operating cycles. Because filtrate production stops when a unit is backwashed, increasing the frequency or duration of backwashes reduces the net daily production of water. Further, most systems require filtrate for all or a portion of the backwash water so that the use of increased volumes of backwash water reduces the overall recovery of water. When the total daily backwash time and volume exceed the design values, overall system production will drop below design (WEF Press, 2006).

• *Membrane chemical cleaning:*

Regular backwashing is very effective in removing a significant portion of contaminants retained on the feed side of the membrane. However, a fraction of these contaminants remains on the surface of or embedded in the membrane. Periodic chemical cleaning will be required to recover a portion of the productivity not recovered by normal backwashing subsequences. Chemical cleaning procedures vary with membrane manufacturer, membrane configuration, membrane material, type of suspected foulant, and degree of fouling. Procedures for chemical cleaning range from a prolonged backwashing cycle enhanced by chemical addition to extended periods of immersion in a chemical bath. Chemicals typically used in chemical cleanings include acids, bases, and surfactants. Chlorine and chloramines-resistant membrane may also be disinfected through the addition of free or combined chlorine residuals. Before addition of any chemical to the membrane system, compatibility and recommended concentrations must be verified by manufacturer.

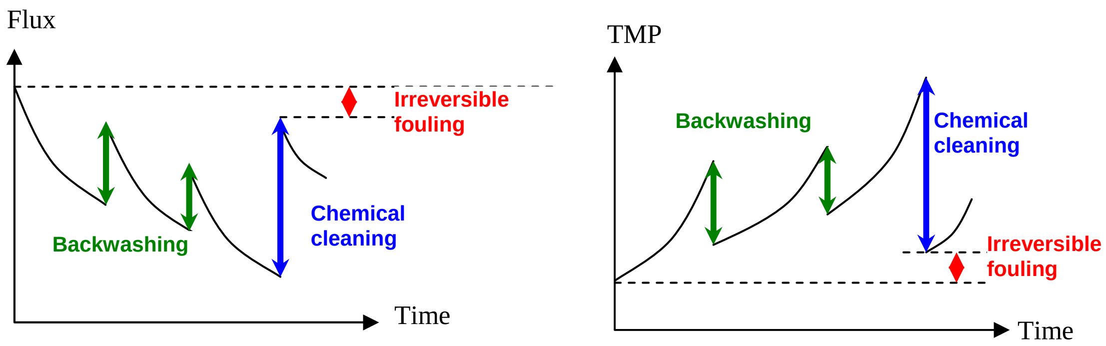


Figure 2.9 Schematic of partial restorations of transmembrane pressure by backwashing and chemical cleaning of MF membranes (Mallevialle et al, 1996)

2.3.2 Advantages and disadvantages of membrane filtration

Table 2.5 presents major advantages and disadvantages of membrane technology in practical situations. The noticeable advantages of the membranes are that they overcome many limitations of conventional technologies in water and wastewater works. The major disadvantage of membranes is fouling problem.

Table 2.5 Advantages and limitations of membrane filtration

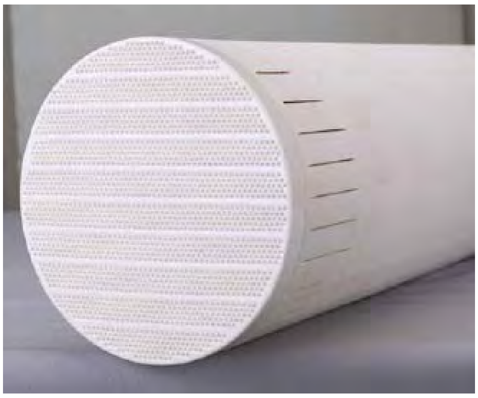
Advantages	Disadvantages
High pathogens removal rate	High capital cost
High natural organic mater removal rate (when enhanced by pre-treatment)	Complicated operation
Small area requirement (compact)	Skilled and trained human power requirement
Save chemical utilization	Pressure limitations
Low energy consumption (low membrane pressure)	Problems related to fouling

2.4 Ceramic microfiltration for surface water treatment

2.4.1 Development of the ceramic microfiltration for surface water treatment

Overcoming some problems generated from conventional water treatment system, the membrane technology has been being known as the good alternative. Membrane technologies have been developed in the recent decades. One of type of membrane material is ceramic. Ceramic membranes are made of mainly metal oxides like aluminum oxide α-Al_2O_3 and γ- Al_2O_3, titanium dioxide TiO_2, zirconium dioxide ZrO_2, silicon dioxide SiO_2, silicon carbide SiC, etc. By improvement of prescriptions, development of new concepts, use of new technologies like nanotechnology and increase of the production of ceramic membrane there is an enormous development. For large scale water treatment, the ceramic microfiltration is very interesting as pre-treatment step in the production of drinking water from surface water (Doeke et al., 2006)

Ceramic membrane has been applied in drinking water treatment for approximately 20 years (Milton et al., 2006). Although the ceramic membrane have just introduced since 1990s in Japan, it was applied effectively in the reality. Based on the mechanisms of the operation, as other membrane technologies, the ceramic membrane can be dived into two types: cross flow and dead-end. In the world, almost all of developed countries (USA, Norway, Turkey, etc.) use the cross flow technology. However, Japan uses not only this kind of ceramic membrane but also researched and designed many dead-end ceramic membrane system. This makes Japan be well-known in this technology.



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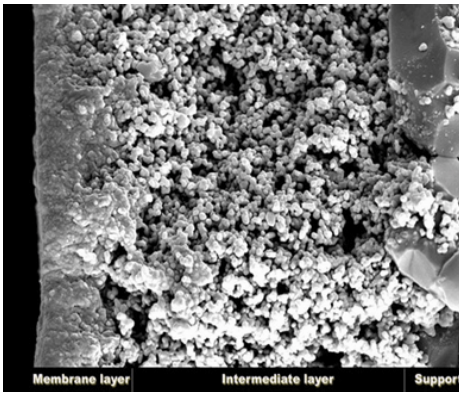


b)

Figure 2.10 Ceramic membrane products: a) Ceramic membrane element; b) The structure of ceramic membrane (Milton et al., 2006 and http://www.jiuwu.com, 2007)

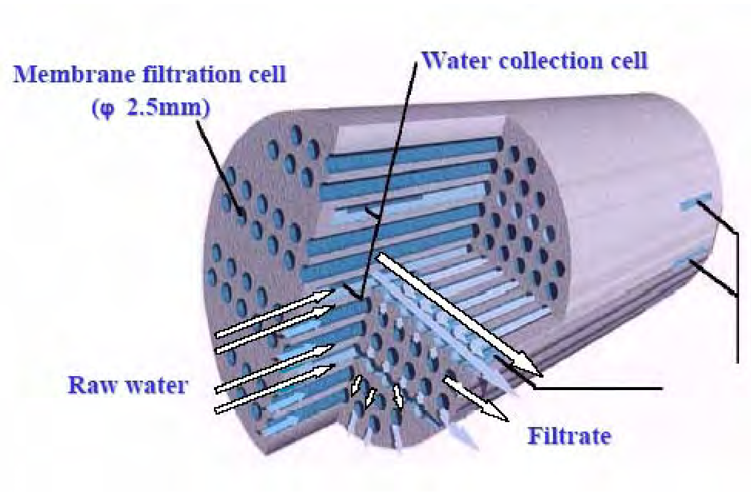


Figure 2.11 Structure of ceramic NGK membrane (NGK Insulators, Ltd., Japan, 2007)

2.4.2 Enhanced ceramic microfiltration for surface water treatment

Ceramic microfiltration is enhanced by coagulation:

Recent researches show that the hybrid coagulation/membrane system for water treatment has many advantages in term of the good quality of treated water: independence from the quality of raw water, organic matter removal including microbiological removal, particulates removal, etc. Beside, it also introduces other important advantages for feasibility in transferring technology such as fully automatic operation, small area requirement, and flexibility in system enlargement. In addition, this advanced technology helps to improve and stabilize both polymeric and membrane operation performance.

Andre Lerch, et al. (2004) conducted a study to determine the optimum conditions in coagulation for a hybrid system in which unit test was built. This pilot is a combination of a Jar test and a membrane filtration. The optimum conditions for coagulation of different coagulants such as dosage of coagulant, PH and energy consumption in the combination with the membrane were evaluated in the aspect of the influence on membrane operation performance. The experiment shows that the best coagulant dosage is 1.5 – 2 mg/L as Al^{3+} and 20 mg/L as PACl and the maximum permeability for the coagulated/flocculated Ruhr River Water is 80 L/m^2.h. The results were also mentioned as turbidity and particle removal versus time. A very high efficiency in turbidity removal (the turbidity of the filtrate is less than 0.004 NTU while this of feed water is more than 1 NTU), and 4 log removal rate in the size rang of bacteria was confirmed by this experiment. Based on the experiments, there are some recommendations for enhanced operation were proposed such as: overcoming the fouling by base chemical enhanced backwashing after normal backwashing and acid chemical enhanced backwashing, the design of mixing tank is important to distribute well coagulation for a better efficiency, the dosage of coagulation is also very important and need to be adjusted for removing organic pollutants better.

On the other hand, the influence of pH on coagulation/flocculation used for enhancing microfiltration was investigated by Meyn et al., 2006. The study has evaluated the removal of natural organic matter (NOM) and color of surface water as functions of coagulant dosage and the pH. In each train of the plant a different coagulant dosage as applied and kept constant for a period of the experiments. Polyaluminum chloride (PACl) was dosed in 5, 3 and 2 mg Al/L respectively. The pH value is fixed for one week of the experiment that mean the pilot was running with constant conditions for the duration of one week foe each examined pH value. Mixing conditions were constant during all experiments. A rapid mixing was applied at 192 rpm with the hydraulic retention time (HRT) of raw water of 6.7 minutes, and then a slow mixing is conducted at the speed of 53 rpm and the HRT of 20 minutes. The ceramic membrane used was operated in dead-end, inside-ouside mode with a pore size of 0.1 μm. The study pointed out that DOC removal greater than 80% at a pH value of 5.7 and dosage of 3.2 mg Al/L could achieved. DOC removal rate was achieved only at 50% if the dosage down to 2 mg Al/L at optimum pH value (Meyn et al., 2006).

Not only affecting to the pollutants removal rate, coagulation and flocculation conditions have had effects to the operation of the ceramic membrane. A lower pH range results in a higher rate of increase in TMP, but less TMP recovery after a hydraulic backwash. However, this problem dose not matter once a chemical cleaning could recover most of the membrane performance. Whereas, a higher pH resulted in a lower rate of TMP increase, but better TMP recovery that was at low pH (Milton et al., 2006).

Ceramic microfiltration is enhanced by powdered activated carbon (PAC) adsorption:

Further more, researches also pointed out the high removal rate of organic carbon by ceramic membrane enhanced by powered activated carbon (PAC). PAC added improves the efficiency of ceramic membrane. The turbidity also was improved by PAC added and shown that the satisfied removal with PAC addition less then 50 mg/L. Effects of PAC size to performance of the pilot were evaluated: PAC with the size of 1μm has higher removal rate in comparison with this of 10μm. And only 1/3 of PAC with size of 1μm is good enough to have the equivalent removal rate of PAC of 10μm. (Kanto et al., 2000).

In addition, researchers recently showed that the hybrid adsorption-membrane filtration processes are getting more attention because of its advantages such as high throughputs and low energy cost (Takizawa, et al, 2006). In order to get fully utilized adsorption capacity, a noble hybrid powdered activated carbon combined with ceramic microfiltration membranes (PAC-MF) was developed for advanced water treatment (Khan et al., 2002). A high concentration, i.e. 20 g/L, of PAC was suspended in the membrane separation reactor in order to maintain high DOC removal rates. In the previous study, a pilot-scale PAC-MF system had been operated for one year without withdrawal and replacement of PAC with an average DOC removal rate of about 80 percent (Kim et al., 2006; Oh et al., 2006). PAC cake layer fouling, however, was found to be a major problem while other types of membrane fouling, such as adsorption of organics on the membrane and membrane pore blocking, were significantly reduced because of very high removal rates of organic matter and metals from raw water (Zhao et al., 2005). The prevention of cake-layer formation was found to be very important to operate this process without replacement of PAC and membrane chemical cleaning. The effectiveness of air-scouring and backwashing on the prevention of cake-layer fouling was investigated using two PAC-MF pilot plants with different sizes of PAC. It was confirmed in previous experiments that the other kinds of resistance, e.g. pore blocking, were significantly lower than the PAC cake resistance (Takizawa, et al, 2006). Khan et al. (2002) conducted hybrid PAC-MF experiments, and revealed that PAC particle sizes decrease with time due to particle breakage caused by severe collision and friction, facilitating the cake formation.

Three factors affecting the membrane fouling in a hybrid PAC-membrane processes were previously reported; namely, natural organic matter, metal ions and particulate matter. Vernhet et al.(1997) reported that membrane pore blocking and cake layer may be caused by polar interaction and electrostatic forces between the membrane and PAC. Multivalent metals, such as Ca^{2+}, Mg^{2+}, Fe^{3+}, electrostatically attract and neutralize the negative charges of PAC particles and membrane surfaces, forming intra- and intermolecular interaction with organic molecules by bridging free functional groups, thus promoting aggregation and deposition of PAC cake layer (Yiantsios et al., 2001; Yuan et al., 1999). Fan et al. (2001) found that natural organic matter hardly adsorbable to PAC because of larger molecular weight (MW) or its hydrophilic nature may cause membrane fouling. Suspended solids, especially colloids and fine particles, are adsorbed not only on PAC, but on and within membrane surface, causing membrane pore blocking and cake layer (Pienta et al., 1998).

Ceramic microfiltration is enhanced by chemical backwashing (ECBW):

Although ceramic membrane filtration is already combined with pretreatments such as coagulation and PAC, the irreversible fouling still can not be eliminated completely. This reality requires a backwashing process. The strength of backwashing is very important to overcome fouling. With the same flux, shorter interval of backwashing makes a higher transmembrane pressure recovery (TMP). In addition, if the volume of water used for backwashing per unit of membrane surface area increase, TMP recovery will be increased. Using backwashing enhanced by acid, the volume required of backwashing water is reduced and the TMP was reached at high value (TMP = 99.2% in comparison with 98.5 % of normal backwashing) (Yonekawa et al., 2006).

In conclusion, the effectiveness of ceramic membrane filtration can be enhanced by pretreatment such as coagulation, PAC as well as by chemical backwashing. When enhanced, the hybrid ceramic membrane filtration will satisfy quality of treated water and technical conditions for operation.

2.5 Membrane technology for municipal wastewater reclamation

Membrane processes are regarded as key elements of advanced wastewater reclamation and reuse schemes and are implemented in a number of prominent schemes world-wide including artificial groundwater recharge, indirect potable reuse as well as industrial process water production.

There is a clear trend for new larger scale plants to use dual membrane processes and MBRs. Currently, membranes are applied to the treatment municipal wastewater mainly in MBRs and in MF/UF filtration of effluent, eventually followed by RO. An alternative to the "end of- pipe" treatment is the application of MBRs as a straight combination of biological treatment processes and biomass retention by MF or UF membranes. MF and UF employed in tertiary wastewater treatment are dedicated to remove suspended solids, organic matter, and for disinfection, recovering a high quality final effluent with various possible uses. MF and UF technologies both in effluent filtration as well as in MBRs are also suitable as pretreatment to NF or RO. Such physical barrier processes are attractive in wastewater treatment because any technology employed must be able to produce reused water of uniform quality, regardless of the normally wide variation in the concentrations or physicochemical properties of the wastewater influent (Metcalf & Eddy; Adin & Asano; E. Alonso et al., 1991, 1998, 2002) and the absence of chemicals addition is of economic and ecological benefit.

Conductivity and dissolved oxygen content remain unaffected by both MF and UF treatment. The decolouration due to UF is more noticeable than that due to MF. Elimination of detergent and phenol concentrations of 40% were achieved by filtration. Fe, Zn, AI, Cr, Cu and Mn can also be significantly eliminated by filtration, not only by direct precipitation as hydroxides or phosphates, but also through association of metals to suspended matter and macromolecules. It has been reported that microbial pollution is totally eliminated by MF and UF, explicable due to bacterial sizes being higher than pore the field of wastewater treatment, UF cannot be considered a complete barrier to bacteria. Positive coliform results were obtained when membrane systems were operating. The passage of bacteria across membranes may be attributable to the following: imperfections in the membrane surface; degradation of the membrane by bacterial enzymes or other materials; or inferior packing of membrane modules or elements. Another possible reason for the detection of bacteria in membrane filtrate is the introduction of bacteria from exterior sources such as contamination of the permeate tank. Also, because nutrients are not eliminated from the water, re-emergence is best avoided through a disinfection process (Bourgeous et al., 2001).

MF and UF are effective in eliminating many wastewater contaminants associated with suspended matter. Elimination of viruses and nematodes accompanies to some extent removal of suspended matter. It has been demonstrated that viruses (28 nm) can be effectively retained by a (0.2 µm nominal pore size) MF membrane. Virus retention is enhanced at lower TMP, in the presence of shear and in the presence of biomass/turbidity. The latter both provides extra surface area for adsorptive removal and forms a secondary filter-cake layer on the membrane.

Coupled with powdered activated carbon (PAC), UF can be used to treat water contaminated by dissolved organic matter and micro-pollutants. In PAC-membrane processes, PAC is added to the recirculation loop of the membrane systems. Contaminants (including natural disinfection byproduct precursors) are adsorbed onto the activated carbon particles, which are then separated from water by either UF or MF (Zhou & Smith, 2002). Because the quality of wastewater influent to MF and UF processes has a high influence on final effluent quality, permeated water might be suitable for unrestricted irrigation purposes, as it is high in nutrients (N and P practically insensitive to filtration), low micro-pollutant and microorganics content, and exhibits favourable inorganic ratios (Alonso et al., 2002).

MF may provide significant cost savings and water quality improvement when replacing conventional lime pre-treatment for RO (Lazarova et al., 2003). In addition, MF can reduce microbial contamination and thereby reduce the rate at which fouling and biofilm formation occurs in subsequent RO. Although are unlikely to pass through an RO membrane, leakage is possible (via glue strips or permeate seals) in spiral-wound elements. Thus, there is an incentive for virus removal at the pretreatment stage. Use of capillary membranes as a pre-treatment for RO feed has enabled operation of cellulose acetate membranes at lower feed pressure and the production of water of lower salinity (Wilf & Ait, 2000). Anti-scalant addition is intended to minimize chemical precipitation on the RO membrane surface. It has also been reported as deemed necessary that MF effluent be dosed with suiphuric acid for pH adjustment to minimize hydrolysis of cellulose acetate RO membranes. It is not uncommon for RO membranes in water reclamation applications to experience an average annual flux decline of 25-30%, even with frequent membrane cleanings. It should be noted that membrane rejection properties are susceptible to change after cleaning.

2.6 Advantages of hybrid ceramic membrane filtration

Compared with normal traditional filters and polymer or organic membranes, ceramic membrane filters has many unique advantages as the followings (Doeke et al, 2006):

- Excellent resistance to acid/alkaline and oxidation chemicals
- Solvent stability
- High permeate production at relative low pressure
- High thermal stability
- Fine separability with narrow pore size distribution
- Excellent mechanical and abrasive resistance
- Extremely long work life compared with polymeric membrane
- High recoveries
- Hydrophilic membrane surface
- Easy to be cleaned and sanitized with short backwash interval (with air flush) chemical cleaning

When a ceramic membrane filtration is enhanced by pre-treatment processes such as PAC adsorption and coagulation-flocculation, the system is called as a hybrid ceramic microfiltration. Not only the hybrid ceramic microfiltration has all above advantages of a ceramic membrane, but also it has some other special things such as very high quality of permeate, prolonged filtration cycle by reducing biological and colloidal fouling, etc.

Although the ceramic membrane can be applied in both surface water treatment and municipal wastewater reclamation, literatures on practical situations are very limited. In addition, in many papers they researched only on some specific feed waters with limited scenarios. The functions of PAC adsorption and coagulation-flocculation combined with CMF should be clarified more deeply, especially in ambient conditions. Based on gaps of recent researches and the need of application of the advanced technology, the study was conducted to contribute to achievement of a hybrid CMF system for treating surface water and reusing municipal wastewater. In conclusion, it was completely possible and important to investigate more attractive roles of a hybrid CMF system in the field of water and wastewater works.

Chapter 3

Methodology

3.1 Introduction

Based on the literature review and realities requirements, this study was conducted with ceramic membrane pilot in which dead-end mode of the microfiltration was used. The microfiltration using CMF would be enhanced by pre-treatment processes such as coagulation and adsorption depending on specifically operational scenario. The CMF pilot has major units that were made in Japan and almost all of processes of the pilot are controlled automatically. The study was divided into main stages including different experiments. Materials, experimental set–up, monitoring, and analytical methods are expressed in this chapter.

3.2 Materials

Materials for the study consist mainly of three parts, namely: (1) feed water including synthetic water, surface water, and municipal wastewater; (2) chemicals for operation and analysis and; (3) hybrid ceramic membrane filtration system.

3.2.1 Feed water

The study was carried out in two stages. The first stage was studied with synthetic water. Meanwhile, surface water (AIT pond water) and municipal wastewater (AIT wastewater) were used for the second stage.

Synthetic water:

Real surface water and wastewater have a variety of different components including inorganic and organic matters. This may causes many operational problems to the pilot system during experiments with these feed water sources. And, it is not easy to find out ways for solving operational problems within a limited time. Therefore, a buffer studying stage with synthetic water should be conducted before deploying any experiment with real surface water and municipal wastewater sources. The objective of this stage was to find out operationally generated problems of the CMF system and overcoming solutions. In addtion, by doing the first stage, it was very useful for next stage with surface water and municipal wastewater in terms of skilled working, time saving, problem avoiding and other experiences as well.

To achieve the mentioned objectives of the stage, characteristics of synthetic water were ensured for getting intermediate lessons. The useful conclusions from this experiment would be applied to avoid possible problems in treatment of surface water and municipal wastewater. Therefore, the synthetic water should have a similar characteristic on major components. The major components were not only pollutants interested in evaluating removal rate, but also elements could affect negatively to the treatment process. In addition, this similarity is not only about constitution but also on range of concentration of typical parameters. In the experiment, synthetic water was prepared using tap water and Kaoline clay. Compositions of the synthetic water were the followings:

Table 3.1 Major characteristics of synthetic water

Parameter	Unit	Value
pH	-	6.5 – 7.6
Temperature	°C	26.2 - 30.6
Conductivity	µs/cm	47.5 – 222
Turbidity	NTU	39.5 – 125
Micro-particle, 5-15 µm	Count/mL	33,100 – 339,040
Free Cl_2	mg/L	0.13 – 0.15
TS	mg/L	219 – 460
TSS	mg/L	148 – 304
TOC	mg/L	1.93 – 3.79
DOC	mg/L	1.07 – 1.86
Total Fe	mg/L	1.02 – 2.05
Total Mn	mg/L	0.010 – 0.185

Surface water (AIT pond water):

The AIT pond water was used as a surface water source for the study. The pond water was pretreated by a raw mesh screen, and then stored in a storage tank. This feed water was taken and analyzed to find out components before and during all experimental runs. The following table gives major characteristics of the AIT pond water used in the study.

Table 3.2 Major characteristics of AIT pond water

Parameter	Unit	Value
pH	-	6.5 - 8.2
Temperature	°C	26 – 31
Turbidity	NTU	5.18 – 23.1
Conductivity	µs/cm	259 – 505
Micro-particle, 5-15 µm	Count/mL	1,230 – 11,448
Free Cl_2	mg/L	0.00 – 0.01
TS	mg/L	198 – 315
TSS	mg/L	8 – 21
TOC	mg/L	10.05 – 12.5
DOC	mg/L	6.86 – 10.51
Total coliform	MPN/100 mL	190
Fecal coliform	MPN/100 mL	4 – 14
Total Fe	mg/L	0.02-0.09
Total Mn	mg/L	0.07-0.15

Municipal wastewater (AIT wastewater):

The domestic wastewater of AIT campus was used as a municipal wastewater source for the study. The municipal wastewater was also pretreated by a raw mesh screen before stored in the feed tank of the CMF system. Characteristics of the wastewater were analyzed in laboratory to find out components before and during every experiment The followings are major characteristics of AIT wastewater used in the study.

Table 3.3 Major characteristics of AIT wastewater

Parameter	Unit	Value
pH	-	6.0 – 7.8
Temperature	°C	24 - 32
Turbidity	NTU	83 - 92
Conductivity	µs/cm	546 - 572
TS	mg/L	198 - 315
TSS	mg/L	100 - 121
TOC	mg/L	55.1 – 62.5
DOC	mg/L	34.3 – 41.6
Total colifrom	MPN/100 mL	$4.4*10^6$
Fecal coliform	MPN/100 mL	$3.1*10^6$
BOD_5	mg/L	94 - 106
COD	mg/L	208 - 242

3.2.2 Hybrid ceramic microfiltration system

System set-up:

Main material of the study was a hybrid ceramic microfiltration system in which pre-coagulation process was combined to enhance efficiency of ceramic membrane filtration. In addition, backwashing equipment was an important unit accompanied to automatically clean fouling inside the channels of the membrane. Other sub-equipment such as feeding tank, chemical tanks, pumps, pressure gauge, and etc. were units constituting the pilot as well. The hybrid ceramic mirofiltration system is expressed in the figure 3.1 and figure 3.2.

Raw water was pumped to the system by a primary pump. After screened by the mesh screen, it came to the feed tank. Other pre-treatment processes could be used depending on each detailed experimental run. The raw water was continually pumped to the coagulation unit. In this unit, coagulant poly aluminum chloride (PACl) was supplied with an optimum dosage determined by the Jar test in part 3.7.2. After coagulated, raw water was pumped through flocculation tube before coming to the ceramic membrane. Inside the flocculation tube, flocculation occurred and the process helps to enhance pollutant removal efficiency of ceramic membrane filtration process. Coagulated - flocculated raw water then was transferred to inlet channels of the ceramic membrane, filtrate went to the pressurized tank before coming out to the filtrate tank. Backwashing process was operated automatically after each two hours (in synthetic and surface water treatment) or 40 minutes (in wastewater treatment) of filtration for reducing fouling. The backwashing process was conducted at 500 kPa using filtrate enhanced by NaClO. After that, air flushing at 200 Kpa was conducted also. Chemical cleaning process was done to overcome irreversible fouling when the transmembrane pressure (TMP) reached 100 to 120 kPa.

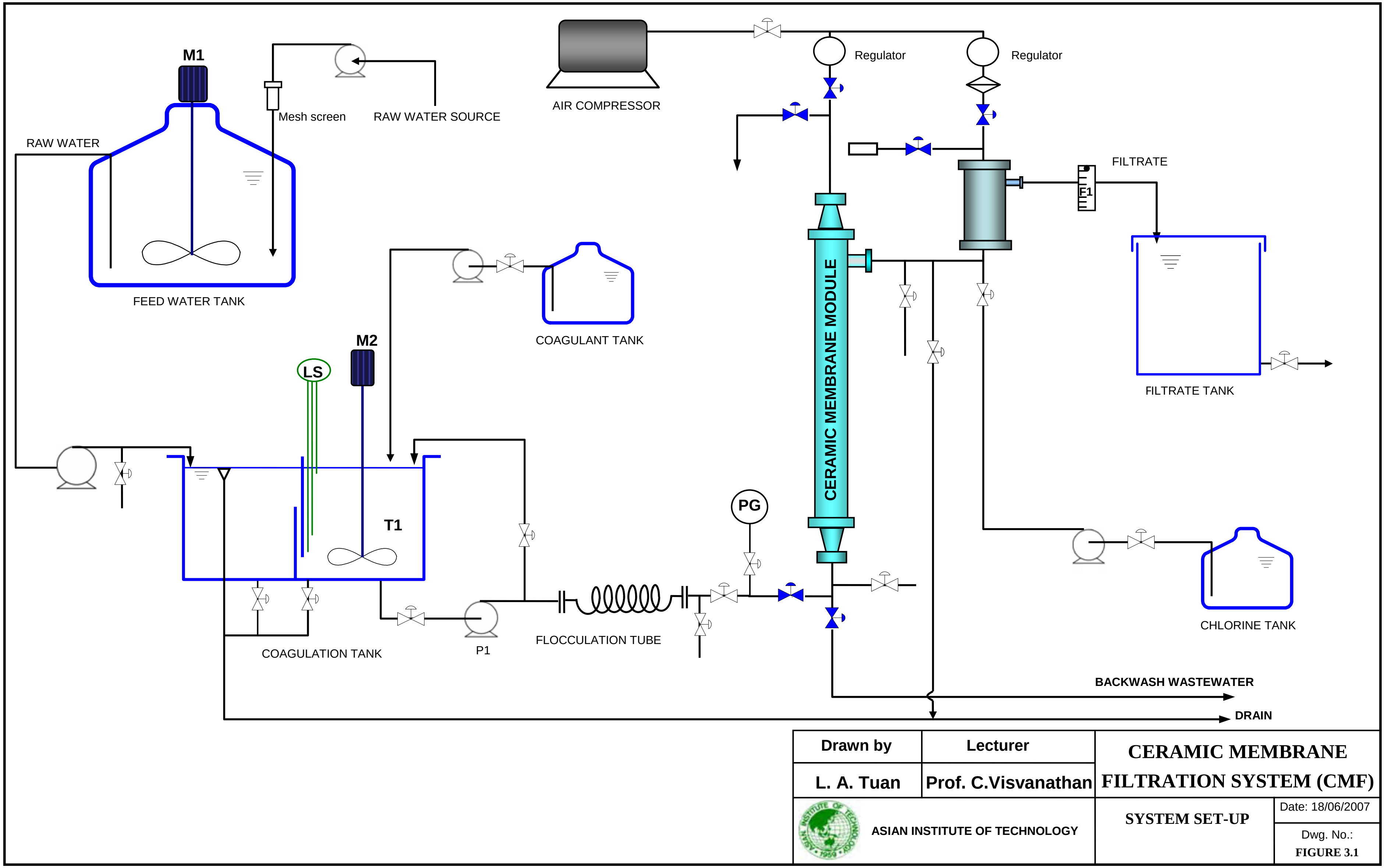


Figure 3.1 Diagram of the system set-up

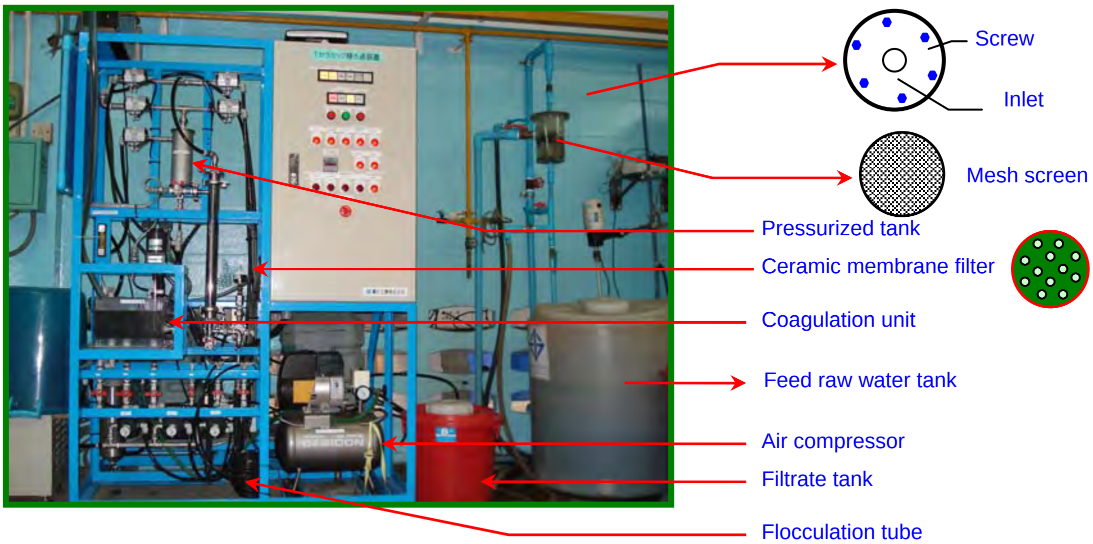


Figure 3.2 Microfiltration system

Each of equipment of the CMF system has some fixed specifications and functions in the treatment process. The followings are descriptions and specifications on major units of the pilot.

Coagulation unit:

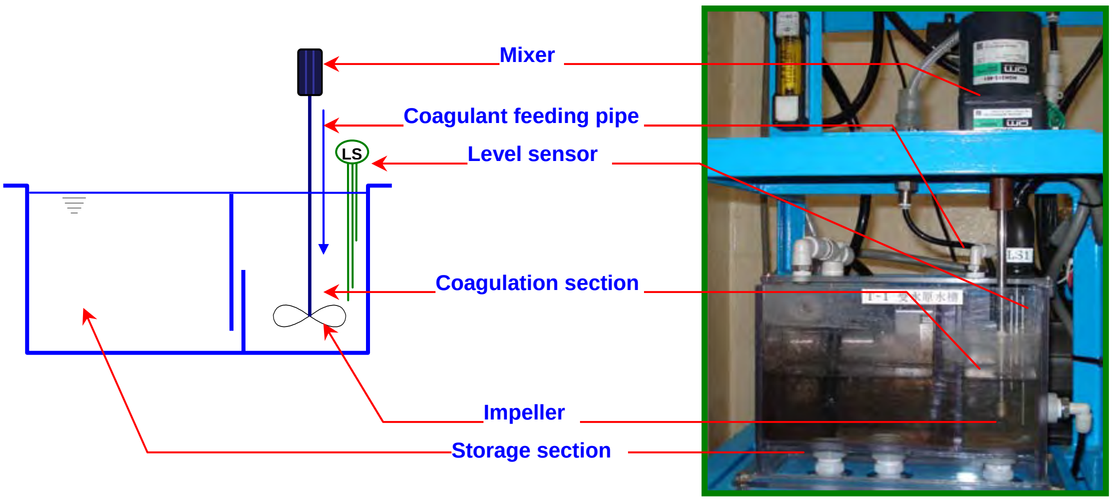


Figure 3.3 Coagulation unit

The coagulation unit severed as a pre-treatment process for enhancing pollutants removal rate, especially for removing more effectively natural organic matter in raw water. Effectiveness of the coagulation process depends upon some factors such as pH, coagulant type, and coagulant dosage. With a range of raw water is nearly neutral, and used coagulant is PACl, the coagulant dosage was the most important factor affecting to the pre-treatment process. Therefore, jar test was conducted frequently to find out optimum dosage for coagulation process, and this is expressed more clearly in part 3.7.2.

The coagulation unit was a rectangular tank including two compartments. The first compartment was to store raw water and equalize its flow rate, so it had an inlet pipe and two over flow drains. This compartment ensures the flow rate supplied to the next compartment (mixing section) was always stable. The coagulant PACl was added into the mixing section. The followings are some specifications of the coagulation unit:

Table 3.4 Specifications of the coagulation unit (NGK Insulators, Ltd.)

No.	Item	Specification	Material	Note
1	Storage tank volume	V = 0.8 L	PVC	Fixed
2	Mixing tank volume	V = 0.3 L	PVC	Fixed
3	Impeller	ϕ 44 mm	Stainless steel	Fixed
4	Mixer	AC100 V, 15 W		Fixed
5	Coagulant used	Solution 10 %	PACl	Commercial product
6	Coagulant dosing rate			Determined by Jart test
7	Retention time in mixing tank	3 minutes		When flux is 1.2 $m^3/m^2/d$
8	Coagulation mixing speed	400 rpm		Designed range: 300 – 450 rpm

Ceramic membrane filter module:

Being known as a feature unique to Japan, the most advanced dead-end type monolith ceramic membrane filtration system was developed in the early 1990s, and then it has been introduced in water purification since 1996. Nowadays, the type of ceramic membrane has been applied in more than thirty water treatment plants in Japan (Kanto, et al., 2000). Almost studies on membrane technologies for surface water treatment in Japan were conducted with ceramic membrane filtration. Likewise, in this study ceramic membrane module was the most important unit of the pilot and it was operated at dead-end mode.

In the study, ceramic membrane filter was fixed by a module casing (a stainless steel tube). The ceramic membrane has the pore size of 0.1 μm and it was installed vertically. The ceramic membrane has 55 channels and each channel has inner diameter of 2.5 mm. Raw water come into these channels and filtrate went outside. Raw water was pumped in the up flow from the bottom end of the ceramic membrane. Filtrate comes out from the upper end, concentrate flow is discharged downward through backwashing process after every two hours of filtration. When the membrane got fouling at 100-120 kPa of TMP, it was taken out from the module casing to carry out chemical cleaning process. Figure 3.4 is to describe more detail on structure of the ceramic membrane module, and specifications of the membrane are expressed in the table 3.4.

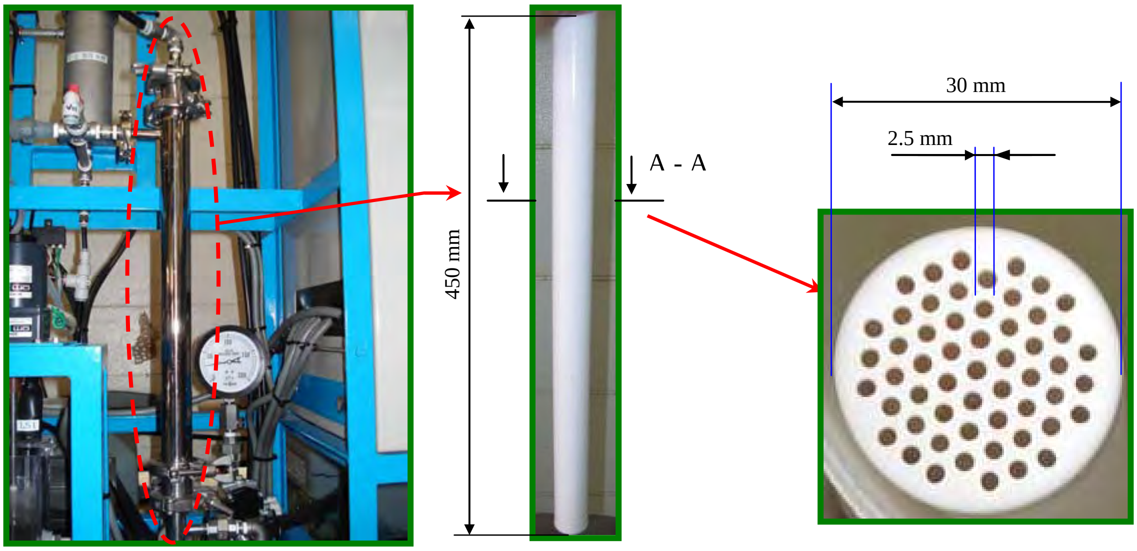


Figure 3.4 Ceramic membrane module

Table 3.5 Specifications of ceramic membrane unit (NGK Insulators, Ltd.)

No.	Item	Unit	Specification	Note
1	Membrane type		Monolith (multi-channel)	Dead-end mode, inside-outside flow
2	Material		Ceramic	
3	Dimension: D x H	mm	30 x 450	D: outer diameter, H: length
4	Channel number		55	Fixed
5	Channel diameter	mm	2.5	Fixed
6	Nominal pore size	μm	0.1	Fixed
7	Effective surface area	m^2	0.18	Fixed
8	Specific flux	$m^3/m^2/day$	1.2	Maximum: 2.1
9	Filtration flow rate	mL/min	150	Maximum: 280
10	Filtration time (backwash interval)	hours	2	1 - 3

Backwashing equipment:

Backwash was an important process to overcome fouling of the CMF system. It helps to limit the continuous accumulation of solids on the surface membrane area. Although the backwash process could be implemented manually or automatically, in this study, manual backwashing is used only in optional case and special cases such as after a few days that membrane filtration equipment has not been operated. The normal backwash process was carried out automatically using pressurized air combined with pressurized liquid. The backwash equipment includes two main parts: air compressor and pressurizing tank. The of operation of the process can be divided into two different stages, one is backwashing using pressurized filtrate combined with air in the pressurizing tank and another one is blow-down using pressurized air only. The maximum pressure of backwash was fixed as 500kPa and this one of blow-down was 200kPa. Pressure and flow of liquid and air were controlled by automatic valves.

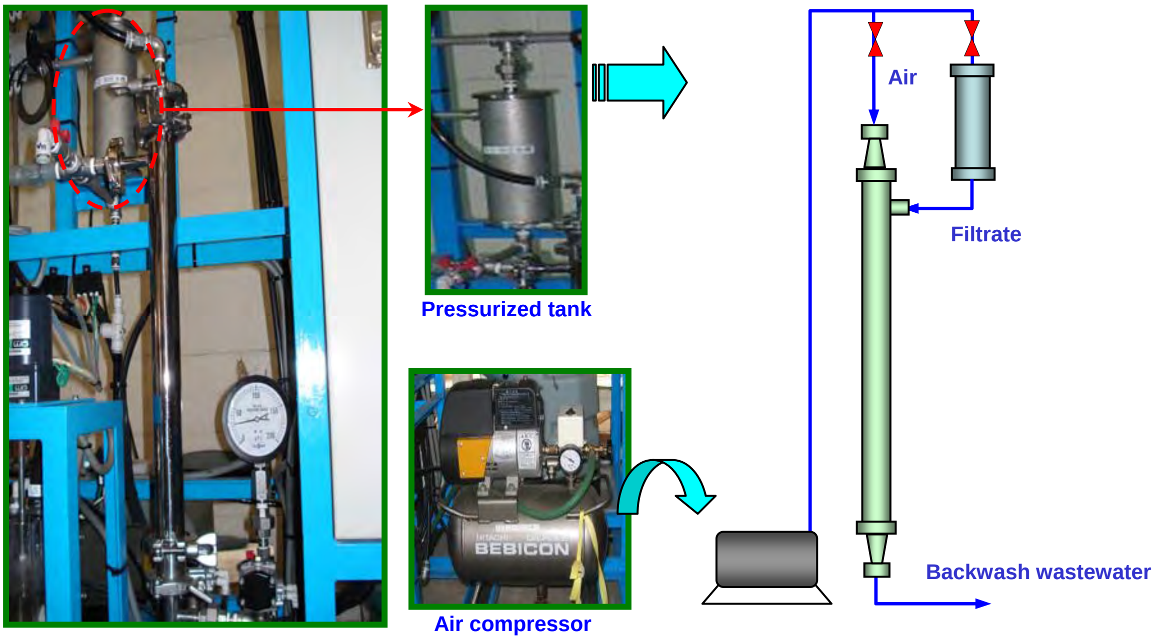


Figure 3.5 Equipment and illustrated flow diagram of backwash process

Table 3.6 Specifications of backwash unit (NGK Insulators, Ltd.)

No.	Item	Specification	Note
1	Air compressor	AC100V, 50Hz, 200W, 0.69 MPa (Max.)	Fixed
2	Pressurizing tank	V = 0.5 L	Stainless steel, fixed
3	Backwash interval	2 hours	Changeable
4	Backwash pressure	500 kPa	Fixed
5	Blow-down pressure	200 kPa	Fixed

Other equipment:

Other equipment such as feeding tank, chemical tanks, pumps, pressure gauge, and etc. are expressed in terms of their functions and technical characteristics as the following table.

Table 3.7 Specifications of sub-units of the CMF pilot (NGK Insulators, Ltd.)

No.	Item	Function	Specification	Material
1	Mesh screen	Removal of raw material of raw water source	Vertical flow direction	Mica, steal net
2	Raw water tank	Storage of raw water	V = 220 L	PVC
3	Feed pump	Supplies pre-coagulated water to the ceramic membrane	AC100 V, 50 Hz, 20 W, 38 L/min (max.), 1 MPa	Alumina
4	Coagulant pump	Supplies coagulant for coagulation process	AC100 V, 50 Hz, 20 W, 38l/min (max.), 1 MPa	PVC, etc.
5	Chlorine pump	Supplies chlorine solution for system	AC100 V, 50 Hz, 20 W, 38l/min (max.), 1 MPa	PVC, etc.
6	Level sensor	To feedback information on level for automatically controlling the operation	Electrode rod type	Stainless steel
7	Flow meter	To indicate flow rate of filtrate	Float type, 50-500 ml/min	Poly-amid
8	Pressure gauge	To indicate TMP of the membrane	Maximum level of 200 kPa	Stainless steel
9	Others: coagulant tank, chlorine tank, filtrate tank, PAC tank, control panel, valves, etc.	Sub-units of the system		PVC, stainless steel, etc.

3.2.3 Chemicals preparation for experiment

Chemical agents for coagulation process:

Coagulant for experiment was Poly Aluminum Chloride (PACl). The efficiency of coagulation is highly affected by dilution and dosage of coagulant. With the commercial PACl solution 10%, the maximum efficiency of coagulation would be achieved at dilution factor of 100 times (NGK Insulator, Ltd. Japan, 2006). For the experiment, dilution and dosage of coagulant were calculated and prepared carefully, and then setting up dosing pump was taken care as well. After preparing 25 liters of coagulant PACl solution by diluting the initially commercial product 100 times, the prepared PACl solution was used within one week at the optimum dosage that had been being determined by Jar test.

- *Coagulant dosage:*

As above, after diluted 100 times, the prepared coagulant solution had concentration of 1.0 g/L (1000 mg/L). The prepared coagulant solution was added into coagulation tank by a dosing pump, and the calculation for setting-up the pump and at what level is as the following:

- PACl dosage that would be used is x mg/L (determined from Jar test, part 3.7.2).
- 1 m L of the prepared coagulant solution had 10 mg PACl.

- Flow rate of permeate: Q_2 = 150 ml/min.

- Q_1 (mL/min) is the flow rate of PACl added in order to get the above concentration:

$Q_1*C_1 = Q_2*C_2 \Rightarrow Q1 *1000$ mg/L = 150 ml/min *x mg/L

$\Rightarrow Q_1 = 150*x/1000$ (ml/min)

In short, with coagulant concentration of 1000 mg/L and dosage of x mg/L, the flow rate of dosing pump needed is Q1 (was calculated as above), and then pump configuration (with stroke length of 80) would be set to have the pump flow rate of Q1.

• *Procedure for coagulant preparation:*

The procedure for coagulant preparation was as the following, and the prepared coagulant solution was used within one week after preparation.

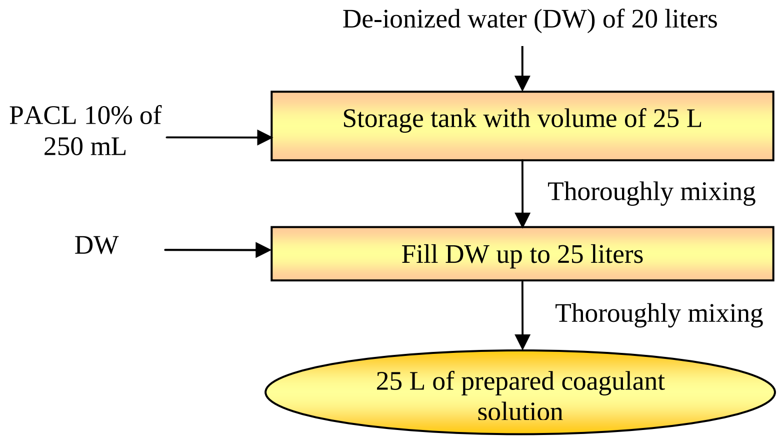


Figure 3.6 Procedure for coagulant preparation

Chemical agents for chemical enhanced backwashing process:

In the study, NaClO solution was used for enhancement of backwasing. The followings are about preparation of the solution for the process.

• *Choosing dosage for the pump:*

- The NaClO x % solution has 1000*x mg of PACl in each liter
- NaClO dosage that will be used is 10 mg/L.
- Flow rate of permeate: Q_2 = 150 ml/min.
- Q1 (mL/min) is flow rate of NaClO added in order to get the above concentration:

  $Q1*C1 = Q2*C2 \Rightarrow Q1 *1000*x$ mg/L = 150 ml/min *10 mg/L

  $\Rightarrow Q1 = 1500/(1000*x) = y$ (ml/min)

Based on the relationship between flow rate and stroke rate of the pump that was fixed by the producer, y = 5 (ml/min) was chosen with the stroke rate of 50. Therefore, x = 0.03, and it is needed to prepare NaClO 0.03 % solution.

• *NaOCl solution 0.03%:*

Prepare one liter NaOCl solution 0.03% (300 mg/L) from a commercial NaOCl solution 10% (100,000 mg/L) by following equation:

C1*V1 = C2*V2
⇒ V1 (L) * 100,000 (mg/L) = 300 (mg/L) * 1 (L)
⇒ V1 = 0.003 L = 3 mL.

⇒ To prepare NaOCl solution 0.03%, take 3 mL of commercial NaOCl solution 10% and adding distilled water (DW) up to one liter to have one liter of NaOCl solution 0.03%.

⇒ For operation of the pilot, taking 75 mL of commercial NaOCl solution 10% and adding distilled water up to 25 liters to have 25 liters of NaOCl solution 0.03%.

Chemicals preparation for chemical cleaning process of the membrane:

When the ceramic membrane filter was fouled in which the pressure gauge indicated at 100 - 120 kPa, it was required to take out the ceramic membrane for chemical cleaning process. To do the process, a preparation for chemical solutions was carried out before conducting soaking. The followings are procedures for preparing needed solutions:

• *Preparation of citric acid solution 1%:*

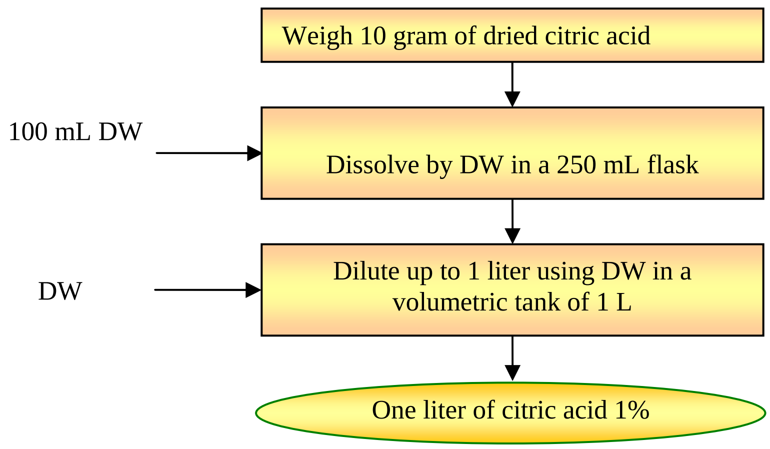


Figure 3.7 Procedure for preparation of 1%citric acid solution

• *NaOCl solution 0.3%:*

Preparing one liter NaOCl solution 0.3% (3000 mg/L) from commercial NaOCl solution 10% (100,000 mg/L) by following equation:

C1*V1 = C2*V2
⇒ V1 (L) * 100,000 (mg/L) = 3000 (mg/L) * 1 (L)
⇒ V1 = 0.03 L = 30 mL.

⇒ Taking 30 mL of commercial NaOCl solution 10% and adding distilled water up to one liter to have one liter NaOCl solution 0.3%.

• *H_2SO_4 solution 0.05M, pH = 1.5:*

Preparing H_2SO_4 solution 0.05M from H_2SO_4 solution of 96% by using calculation:

H_2SO_4 solution 96%: 960 gram H_2SO_4 in one liter of the solution
⇒ 960/98 = 9.796 mole H_2SO_4 in 1000 milliliters of the solution
⇒ 0.05 mole of H_2SO_4 in 0.05x1000/9.796 = 5.1 mL H_2SO_4 solution 96%.

Procedure for preparation of the solution was as the following figure:

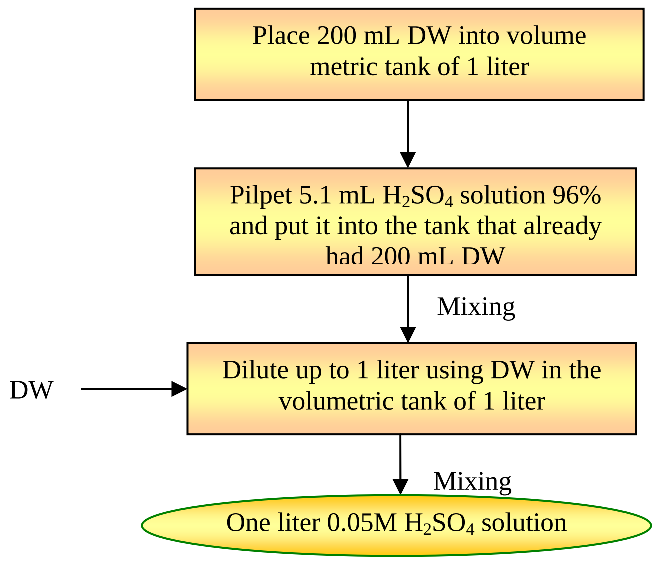


Figure 3.8 Procedure to preparation of 0.05M H_2SO_4 solution

3.3 Experimental set-up

To achieve the proposed objectives of the study, three seniors were used for setting-up experiment as table 3.8. Parameters shown in table 3.9 were monitored and analyzed. Simplified flow diagrams and technical diagrams of the scenarios are drawn in figures 3.9 and 3.10.

Table 3.8 Experimental set-up for differently operational scenarios

Operational scenarios	Objectives	Operational descriptions	Note
Scenario 1:			
Direct CMF and backwashing enhanced by NaClO. Chemical cleaning by citric acid solution 1% (for 24 hrs) and NaClO 0.3% (four 24 hrs)	To evaluate the direct filtration of the ceramic membrane and compare results gained between the scenario and other scenarios. To investigate operational problems and ways to overcome them.	Raw water comes to the ceramic membrane filter directly. Filtrate goes to the filtrate tank. Back washing interval of 2 hours (in synthetic and surface water treatment) or 40 minutes (in municipal wastewater treatment) was set up automatically. The backwashing enhanced using NaClO with dosage of 10 mg/L (in synthetic and surface water treatment) or 15 mg/L (in MWW). When TMP reached at 100-120 kPa, CMF fouling would be solved by chemical cleaning process.	This scenario is very important to evaluate non-enhanced CMF system (not hybrid CMF system) on removing pollutants and it is the basis to propose whether a hybrid system is necessary.
Scenario 2:			
Coagulation and Flocculation + CMF. Backwashing enhanced by NaClO. Chemical cleaning by citric acid solution 1% (for 24 hrs) and NaClO 0.3% (four 24 hrs)	To evaluate effectives of a hybrid CMF system where the CMF system was enhanced by coagulation and flocculation process. To investigate the effectiveness of the coagulation and flocculation on the enhancement.	Raw water goes to the coagulation unit. PACl coagulant is added at an optimum dosage (determined from Jart test) under mixing condition of 400 rpm. After coagulation, coagulated water goes through flocculation tube for forming bigger size of flocs, and then it comes to the CMF. After 2 hours (SWT) or 40 minutes (in MWWT) of filtration, backwashing using filtrate water enhanced by NaClO dosage of 10 mg/L (in SWT) or 15 mg/L (in MWWT) and air-blow was operated automatically. Chemical cleaning process were conducted when TMP reached at 100 – 120 kPa.	Coagulation and flocculation help to enhance effectively system on pollutants removal, especially organic matters.
Scenario 3:			
PAC adsorption + Coagulation and Flocculation + CMF. Backwashing enhanced by NaClO. Chemical cleaning by citric acid solution 1% (for 24 hrs) and NaClO 0.3% (four 24 hrs)	To investigate effects of pre-treatment by PAC adsorption beside coagulation and flocculation processes.	Raw water has been firstly pre-treated by PAC adsorption, and then it goes to the coagulation unit using PACl coagulant. Coagulated-raw water goes through flocculation tube, and then comes to the CMF. Filtrate goes to the filtrate tank. After 2 hours (in SFT) or 40 minutes (in MWWT) of filtration, backwashing by filtrate water enhanced by 10 mg/L (in SWT) or 15 mg/L NaClO (in MWWT) and air-blow were operated automatically. Chemical cleaning process was conducted when TMP reached at 100 – 120 kPa.	Pre-treatment by PAC is to enhance organic removal rate, especially remained DOC that could not removed by coagulation and flocculation processes. After adsorbing DOC, PAC would be coagulated together with other pollutants and removed by CMF.

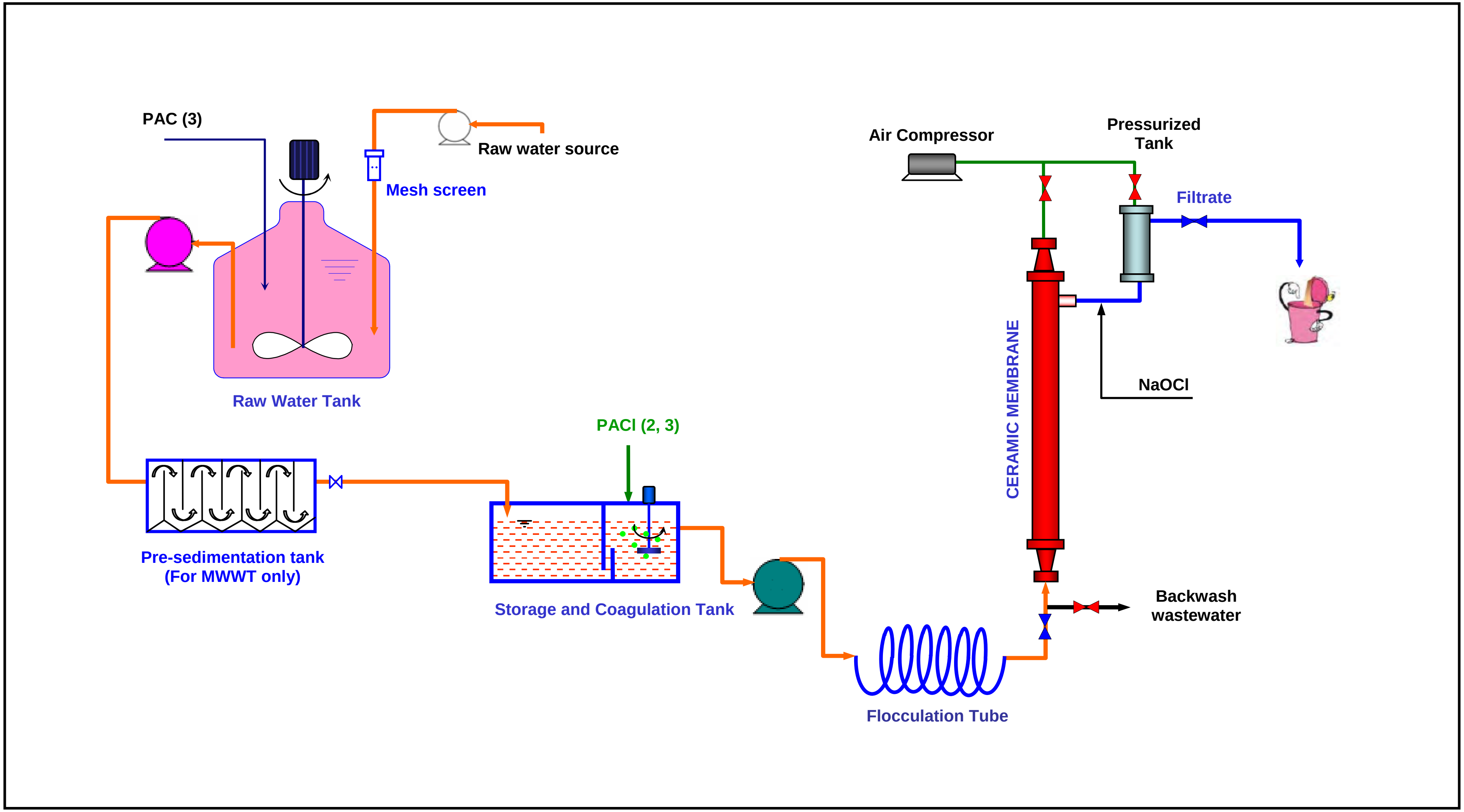
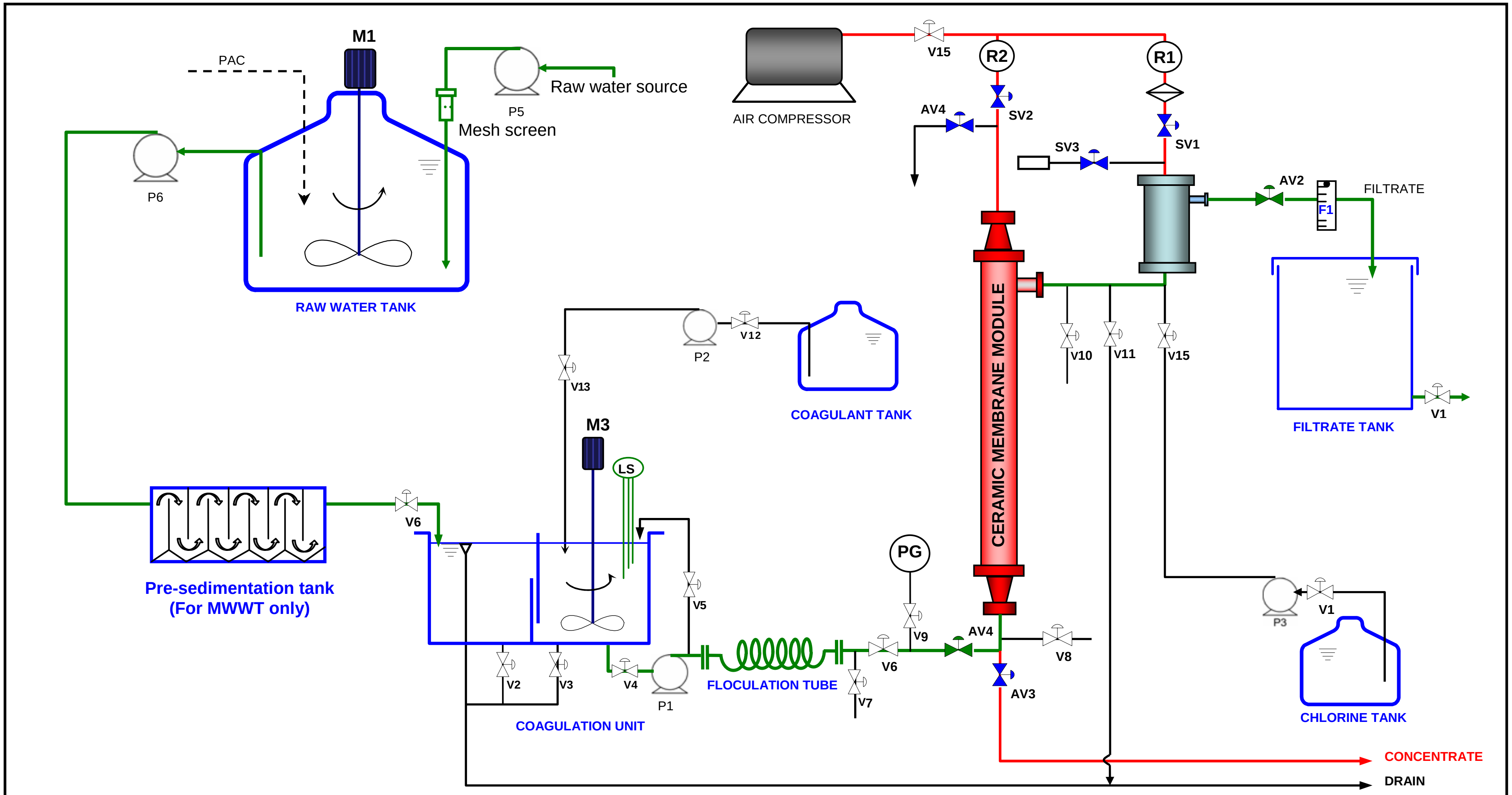


Figure 3.9 Simplified flow diagram of the CMF system for the operational scenarios:
PACl (2, 3): coagulant PACl is used for scenarios 2 and 3; PAC (3): powered activated carbon is used for the scenario 3



Note:
- Scenario 1: Adsorption (PAC) and coagulation-flocculation (PACl) processes were not included
- Scenario 2: No adsorption process included
- Scenario 3: All processes were included as the full figure

Drawn by	Lecturer	CERAMIC MEMBRANE FILTRATION SYSTEM (CMF)	
L. A. Tuan	Prof. C.Visvanathan		
ASIAN INSTITUTE OF TECHNOLOGY		CMF FOR SCENARIOS	Date: 08/08/2007
			Dwg. No.: Figure 3.10

Figure 3.10 Technical diagram for the operational scenarios

3.4 Overall experiment

The experiment of the study was divided into two main stages: the first stage was carried out with synthetic water and; the second stage was conducted using AIT pond water and AIT wastewater as the raw water sources. Major objectives of the first stage were to find out problems generated while operating and solution for solving them as well as for getting skilled work and analysis in the laboratory. Beside, inter-evaluations and optimization of the system would be achieved for experiment runs in the second stage. The second stage was the main part of the study and all results gained from the stage allowed us to have an actual evaluation of the system on the treatment of surface water and municipal wastewater. Each scenario of real waters was repeated for two cycles of membrane fouling.

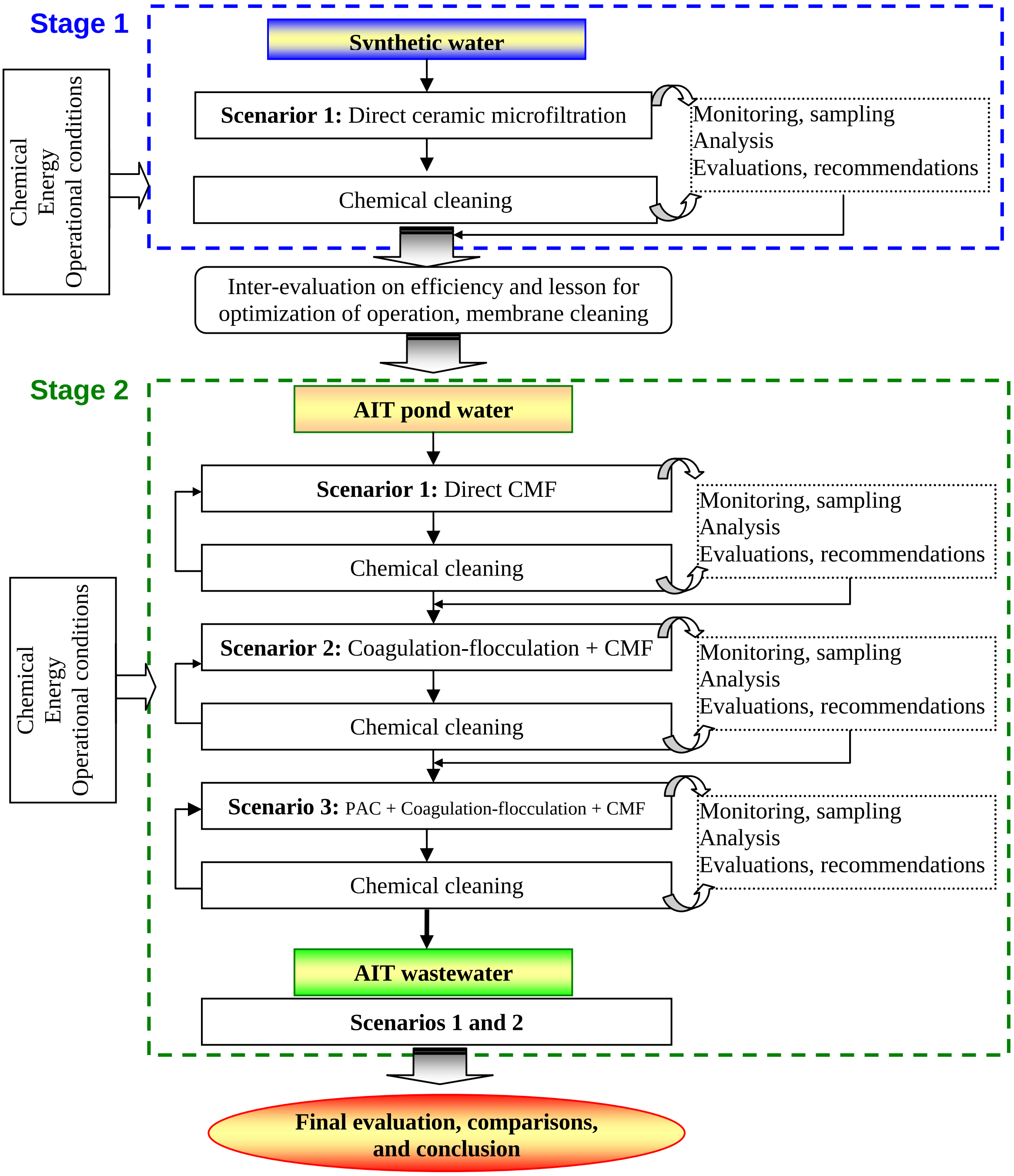


Figure 3.11 Overall experiment

3.5 Operational conditions

All equipment of the ceramic membrane systems were designed for indoor use only, with electricity power of 220V. To achieve the best results on operation, major operation conditions were set in ranges as recommended by producer. In addition, based on previous researches on this type of the membrane, the operation was carried out in some specific conditions to get high efficiency of water treatment. In short, main operation conditions are expressed in the following table:

Table 3.9 Major operational conditions of the CMF system

Items	Setting Value
Effective membrane area	$0.18m^2$
Membrane flux	$1.2m^3/m^2$/day
Membrane filtration rate	$0.2m^3$/day (150 ml/min)
Filtration time (backwash interval)	2 hours
Backwash pressure	500kPa
Blow-down pressure	200kPa
Coagulant	PACl
Coagulant dosing rate	Determined by jar test
Coagulation Mixing Speed	400 rpm

3.6 Chemical cleaning procedure for the membrane

3.6.1 Chemical cleaning procedure for normal clogging

Regular backwashing is very effective for removing a significant portion of contaminants retained on the feed channels of membrane. However, a faction of contaminants remains persistently on the surface or embedded inside the membrane, so a periodic chemical cleanings would be required to overcome fouling not recovered during normal backwashing sequences. Chemical cleaning procedure varies with membrane manufacturer, membrane configuration, membrane material, type of suspected foulant, and degree of foulant (WEF Press, 2006). The following is the procedure for chemical cleaning of the study:

- Take out the ceramic membrane from the system
- Soak the ceramic membrane 1% in citric acid solution for 24 hours
- Take out the ceramic membrane and rinse it with tap water
- Take out the membrane and dip in 0.3% NaOCl solution for 24 hrs
- Take out the membrane and wash it by tap water
- Use air flow pressurized by external air compressor to push out remained foulants.
- If the ceramic membrane was already cleaned, fix it in the system and observe the recovery on transmembrane pressure (TMP).

3.6.2 Chemical cleaning procedure for serious clogging

In cases that fouling was solved by the chemical cleaning procedure for normal clogging as above, a chemical cleaning process could be used as the following:

- Soak the Ceramic membrane H_2SO_4 solution 0.05M, pH = 1.5

- Soaking time is around six to twenty four hours, depending upon the fouling status
- Take out the membrane and wash it by tap water
- Use air flow pressurized by external air compressor to push remained solid out.
- Fix the ceramic membrane in the system and observe TMP recovery.

3.7 Monitoring and analyzing methods

3.7.1 Monitored and analyzed parameters

All measurements were based on standard methods for examination of water and wastewater and the frequency, methods, and sampling location for analyzing were depended on specific parameters. Detail monitoring and analyzing for the hybrid CMF system are expressed in table 3.10.

Table 3.10 Parameters for monitoring and analyzing

No.	Parameter	Sampling location		Minimum test frequency	Methods/analyzing equipment	Interference
		Feed	Permeate			
1	Temperature	X	X	Daily	Thermometer	
2	pH	X	X	Daily	pH meter	-
3	TMP	X		Daily	Pressure gauge	
4	TMP recovery	X		Three times/run	Pressure gauge	
5	Alkalinity	X	X	Once per week	APHA, 1998: Titration	
6	Turbidity	X	X	Daily	HACH 2100N Turbidimeter	-
7	Conductivity	X	X	Daily	Conductivity meter/WTW-330i	
8	TOC	X	X	Twice a week	APHA, 1998 Shimazu TOC-5000	Acids, Alkalis, Salts
9	DOC	X	X	Twice a week	APHA, 1998 Shimazu TOC-5000	Acids, Alkalis, Salts
10	TS	X	X	Twice a week	APHA, 1998	
11	TSS	X	X	Twice a week	APHA, 1998	
12	Total Fe	X	X	Twice a week	Atomic absorption spectrophotomer (AAS) Z-8230	Oxidizing agents, PO_4^-, heavy metals, Nitrite
13	Dissolved Fe	X	X	Twice a week	Atomic absorption spectrophotomer (AAS) Z-8230	
14	Total Mn	X	X	Twice a week	Atomic absorption spectrophotomer (AAS) Z-8230	Chloride, Organic matters
15	Dissolved Mn	X	X	Twice a week	Atomic absorption spectrophotomer (AAS) Z-8230	
16	Free chlorine	X	X	Twice a week	APHA, 1998	Chromate, ferric, sulfite
17[a]	Total coliform	X	X	Twice a week	APHA, 1998	
18[a]	Fecal coliform	X	X	Twice a week	APHA, 1998	

19[a]	Particle number; Giardia & Cryptosporidium	X	X	Twice a week	Particle counter MLC-7P
20	COD	X	X	Once a week	APHA, 1998
21	BOD_5	X	X	Once a week	APHA, 1998
22	Jar test	X		Twice a run	Jart test equipment

Note:
- (a): Wash and sterilize the filtrate side before sampling.
- Feed: water in raw water tank
- Filtrate: sampling directly in filtrate after ceramic membrane filtration
- Examinations base on Standard methods for the examination of water and wastewater (APHA, 1998).

3.7.2 Jar test for optimization of coagulant-flocculation

Jar test ws conducted twice a run to verify the optimum dose of coagulant. According to the given PACl solution concentration is 10%. The dilution factor is very important to achieve effectiveness of coagulation, with PACl coagulant at optimum dosage, the highest effectiveness of coagulation is achieved at dilution factor of 100 times (NGK Insulators, Ltd.). After diluted 100 times as calculated above, the PACl solution has concentration of 1000 mg/L or 1000 mg/1000 mL.

⇒ 1 mg of PACl in 1 mL of the diluted solution, the concentration and dosage respectively that were used for Jar test are the followings:

Table 3.11 Concentration and dosage of coagulation for Jar test

Concentration of PACl (mg/l)	Dosage (ml)
0	0
5	5
10	10
15	15
20	20
25	25
30	30
35	35
40	40
45	45

Adding coagulant as above into 1000 mL of water and operating jart test as the following procedure:

- Rapid mixing at 125 rpm for 1-2 minutes
- Slow mixing at 30 – 40 rpm for 20 minutes
- Settling for 30 minutes

3.7.3 Determination of micro-particles, Giadia and Cryptosporidium (protozoa)

As mentioned in the chapter 2, protozoa are the microbial pathogens in water and waste water works, and they have size ranges are from 2 to 15 µm. In these pathogens, Giadia and Cryptosporidium are the most common protozoa pathogens with the body size of 5 to 15 µm (American Water Works Association, 1999). The two major pathogens were measured relatively using micro-particle counter machine MLC-7P (made in Japan). The size range of particles that can be measured by the counter was 1 to 25µm.

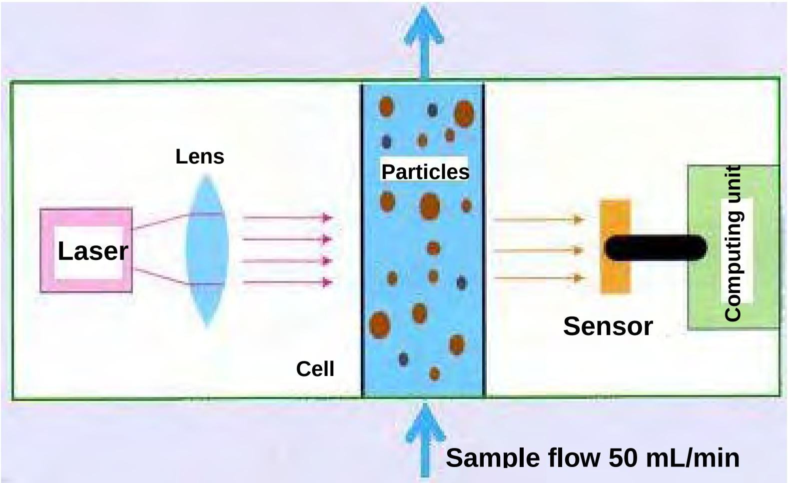


Figure 3.12 Working principle of particle counter MLC-7P

a. Set-up equipment:

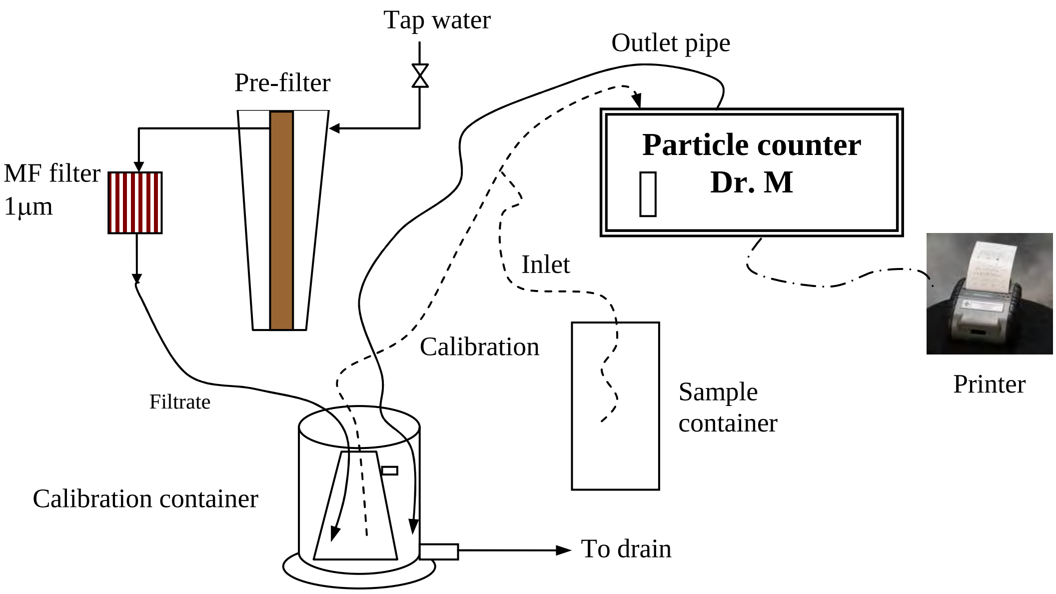


Figure 3.13 Experimental set-up of particle counter MLC-7P

b. Sample preparation:

- Filter sample using screen with pore size of 53 μm;
- Dilute sample if necessary;
- Check all connections correctly (refer to the figure 3.13).

c. Calibration and measurement:

Calibration:

- Open tap water valve and wait until having in overflow gate of the filtrate tank for 3-4 minutes;
- Switch on the main power and the pump of the particle counter;
- Open the flow valve to the maximum value to eliminate air bubble in the tubes;
- Adjust the flow rate to 50 mL/min;
- Press the "confirm" button in the function buttons;
- Wait until the machine is stabilized when umber of particle of the filtered water is near zero (or less than 50).

Sample measurement:

- When machine is stable, put inlet tube into the filtered sample container instantly.
- Open the flow valve to the maximum value to eliminate air bubble for few minutes;
- Adjust the flow rate to 50 mL/min;
- Switch on the printer;
- After getting five repetitive results;
- Change to the next sample if any;
- After measurement, deep the inlet tube to the calibration container to clean the instrument for 5-10 minutes; switch off the pump and the main power.

Note: the measurement is not correctly done if particles in sample are too highly concentrated. Measurement limit of this machine is 10,000 (alarm level). Results over measurement limit are not reliable. In this case, sample should be diluted using filtered water of micro-filter 1μm.

3.7.4 Determination of total and dissolved organic carbon (TOC and DOC)

Both total organic carbon (TOC) and dissolved organic carbon (DOC) were determined. TOC and DOC are very important in detecting contaminants included in water. DOC is defined as organic carbon remaining after 0.45 μm filtration, the DOC is determined by TOC analyzer (Jarusuthirak, et al. 2007). TOC is an important parameter because of its possible effects on the environment, human health, and TOC is of interest in the field of potable water purification due to disinfection of byproducts. In addition, normally surface water and wastewater are contaminated with organic compound, so TOC removal is the most important factor to evaluate efficiency of the ceramic membrane filtration system on treatment of surface water and wastewater. Especially, when enhanced with other process such as pre-coagulation and adsorption using powered activated carbon, the efficiency of a hybrid ceramic microfiltration on TOC removal was very high. The TOC and DOC parameters were analyzed using Shimazu TOC-5000 machine.

Chapter 4

Results and Discussions

The study was implemented in two stages as mentioned in the chapter 3. In more detail, in terms of experimental works, the results of the study could be divided into four parts: pre-experiments in which operational conditions such as preparation of synthetic water and results of jar test for the pilot were found out, and experimental results with synthetic water, surface water, and municipal wastewater respectively. Therefore, the experimental results and discussions of the study are also arranged in four parts. In addition, the investigation of operational problems generated during study of the dead-end ceramic microfiltration system and solutions are presented in the fifth section of this chapter.

4.1 Results of pre-experiments

4.1.1 Preparation of synthetic water

The synthetic water was prepared from tap water (in the ambient lab of EEM, AIT) and Kaolin clay. Composition of tap water and detailed data of the preparation are presented in tables B.1 and B.2, appendix B, and the graphical results are shown in figure 4.1.

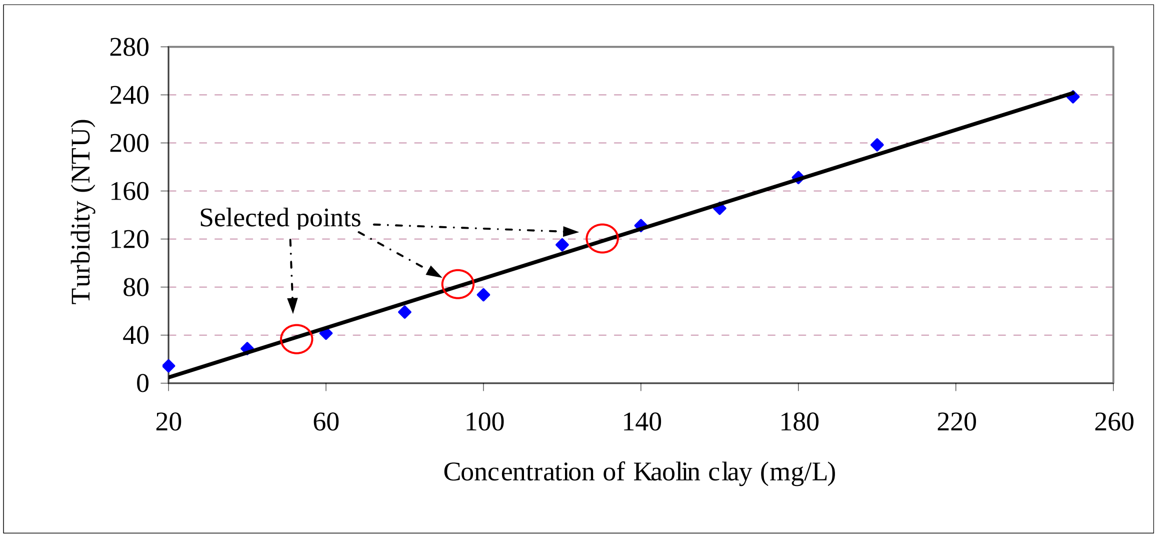


Figure 4.1 Variation of turbidity with Kaolin clay concentration

Based on turbidities of real water sources that would be used for the pilot (AIT pond water and AIT wastewater) and the relationship drawn in figure 4.1, synthetic water was prepared in three different levels of turbidity as the followings:

- Turbidity level 1 (low turbidity, slightly higher than maximum turbidity of AIT Pond water): Turbidity of 40 NTU with Kaolin clay concentration of 55 mg/L

- Turbidity level 2 (average turbidity as minimum turbidity of AIT wastewater): Turbidity of 80 NTU with Kaolin clay concentration of 95 mg/L

- Turbidity level 3 (high turbidity, higher than maximum turbidity of AIT wastewater): Turbidity of 120 NTU with Kaolin clay concentration of 137 mg/L

4.1.2 Jar test

a. Jar test for surface water (AIT pond water)

- ***Jar test with coagulation-flocculation process by PACl:***

Figure 4.2 is graphical result of the jar test and table B.3, appendix B, presents the detailed results.

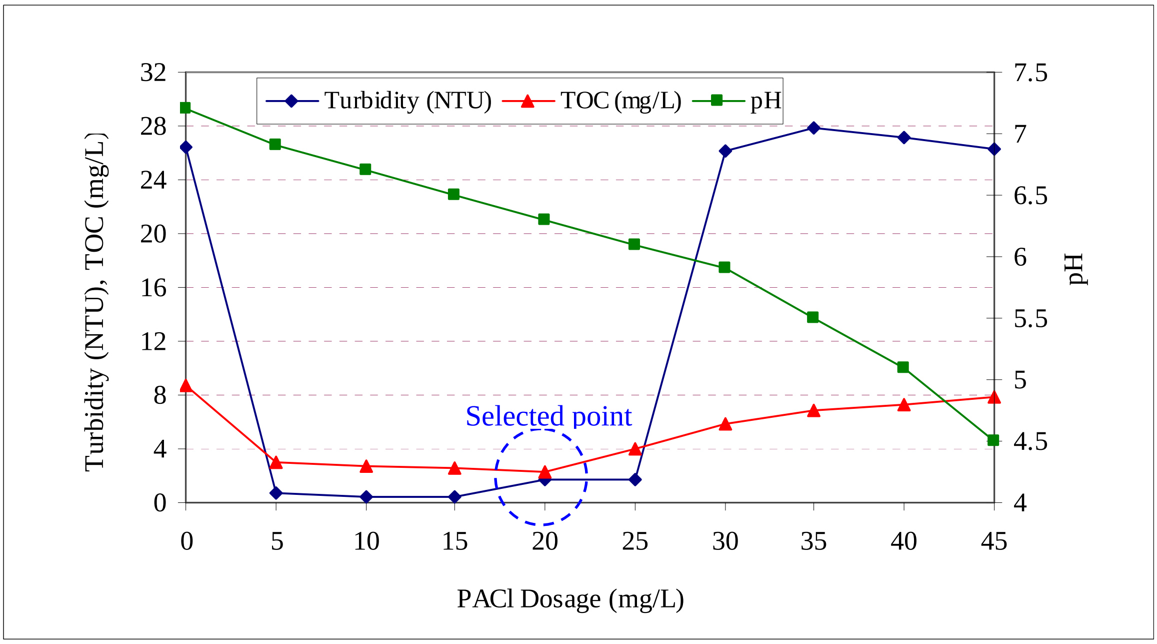


Figure 4.2 Variations of turbidity and pH of supernatant with coagulant dosage

In terms of turbidity removal, optimum dosage of PACl was 15 mg/L, turbidity was 0.39 NTU and TOC was 2.55 mg/L. In terms of TOC removal, it was found out that optimum dosage of PACl was 20 mg/L, turbidity is 1.67 NTU and TOC is 2.29 mg/L. Because turbidity is not an issue with CMF (when running with synthetic water, turbidity removal of direct ceramic microfiltration was very high: turbidity of permeate was always around 0.065 NTU compared with 40, 80, or 120 NTU of feed) and the major purpose of the experiment was to remove TOC as high as possible, the selected optimum coagulant dosage was 20 mg PACl/L (equal to 2 mg/L as Al^{3+}), and pH of supernatant was at 6.3. This selected optimum dosage was used for experimental scenario of the hybrid CMF system enhanced by coagulation-flocculation with AIT pond water.

- ***Jar test with adsorption process by PAC:***

The quality of supernatant was analyzed, and the figure 4.3 shows the main results for choosing PAC dosage, and table B.4 (appendix B) presents the detailed resuts.

TOC removal of PAC adsorption was quite low. With the dosage of 50 mg/L, TOC removal rate was 31% (remained TOC is 7.5 mg/L compared with 10.8 mg/L of TOC of

AIT pond water). Remained TOC decreased slowly with the increase of PAC dosage and until PAC dosage of 250 mg/L, TOC reduction of 55.56 % (TOC remained is 6 mg/L). Although PAC dosage was increased from 50 mg/L to 250 mg/L, the removals of color and TOC were not increased notably. This changing tendency of efficiency of the PAC adsorption can be explained clearly that PAC can adsorb only small molecules of organic matters and therefore it could not remove all TOC in very small dissolved form (DOC).

Because PAC was used to enhance coagulation-flocculation process in terms of TOC removal and also help to reduce fouling. The combination among the above results of jar test, economic aspect of using PAC, and literature review made a decision to choose the dosage of PAC of 20 mg/L. In this point, although 13.9% of TOC was removed by PAC, it was expected that the remained TOC would be removed more effectively by accumulation of PAC inside membrane during filtering and coagulation-flocculation process followed.

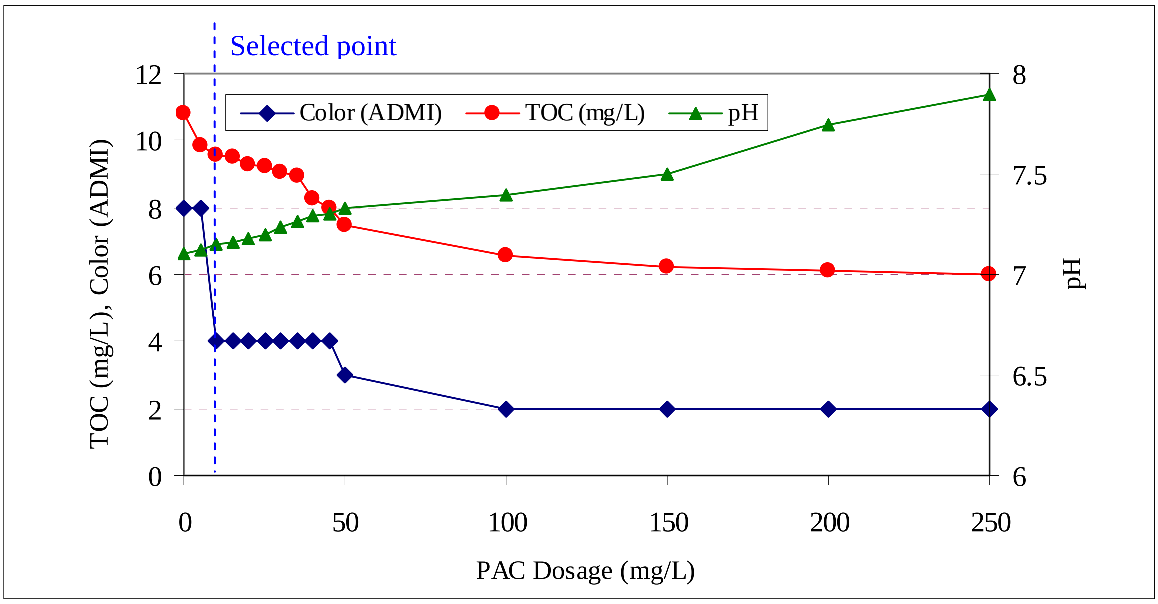


Figure 4.3 Variations of TOC and color of supernatant with PAC dosage

- ***Jar test with the combination of adsorption and coagulation-flocculation processes:***

As selected in the jar test with PAC adsorption, PAC dosage of 20 mg/L was used for enhancement of TOC removal of the hybrid CMF system. Thus, in this combined jar test, all beakers were supplied with the same PAC absorbent dosage of 20 mg/L and only PACl coagulant dosage was altered.

Graphical result of this jar test is presented in figure 4.4, and table B.5 (appendix B) shows analyzed data in more detail. The graphical result shows that remaining TOC and turbidity of supernatant were decreased rapidly with the increase of PACl dosage from 0-20 mg/L. After the point of 20 mg/L PACl, the TOC and turbidity removal were not changed notably and the remaining values were almost kept at the same values compared with those at PACl dosage of 20 mg/L. Beside, with increase of PACl, pH was degreased, and in practical situation we do not want to have a too low pH after coagulation-flocculation to avoid possible metallic corrosion of equipment. Therefore, the optimum coagulant dosage chosen is 20 mg PACl/L (2 mg/L as Al^{3+}), with TOC removal of 56% (remaining TOC of 4.27 mg/L), and pH of supernatant was at 6.97.

In conclusion, selected adsorbent and coagulant dosages were 20 mg/L PAC and 20mg/L PACl, and used for experimental scenario of the hybrid CMF system enhanced by adsorption and coagulation-flocculation with AIT pond water.

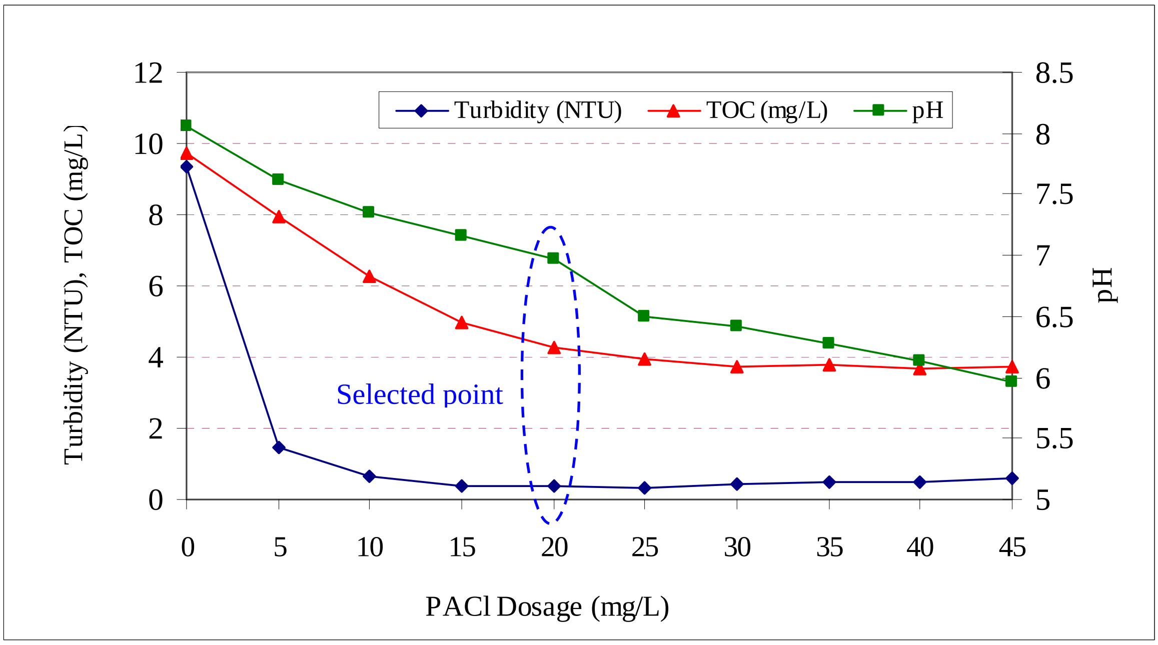


Figure 4.4 Variations of turbidity and pH of supernatant with coagulant dosage

b. Jar test for municipal waste water (AIT wastewater)

- ***Jar test with coagulation-flocculation process by PACl:***

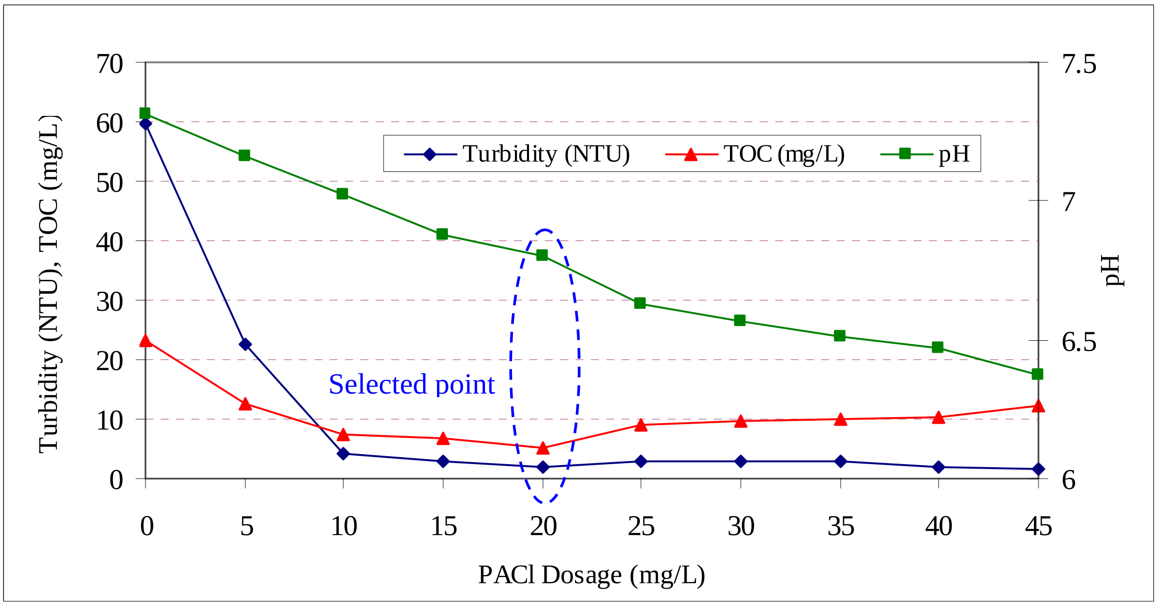


Figure 4.5 Variations of turbidity and pH of supernatant with coagulant dosage

The results are presented on the above graph, and numerical results are given in table B.6, appendix B.

The optimum dosage of PACl was chosen as 20 mg/L. In this point, the lowest remaining concentrations of TOC and turbidity of supernatant were achieved, and at pH of 6.8.

- ***Jar test with adsorption process by PAC:***

The quality of supernatant was analyzed, and the figure 4.6 shows the main results for choosing PAC dosage. Table B.7, appendix B, presents detailed results .

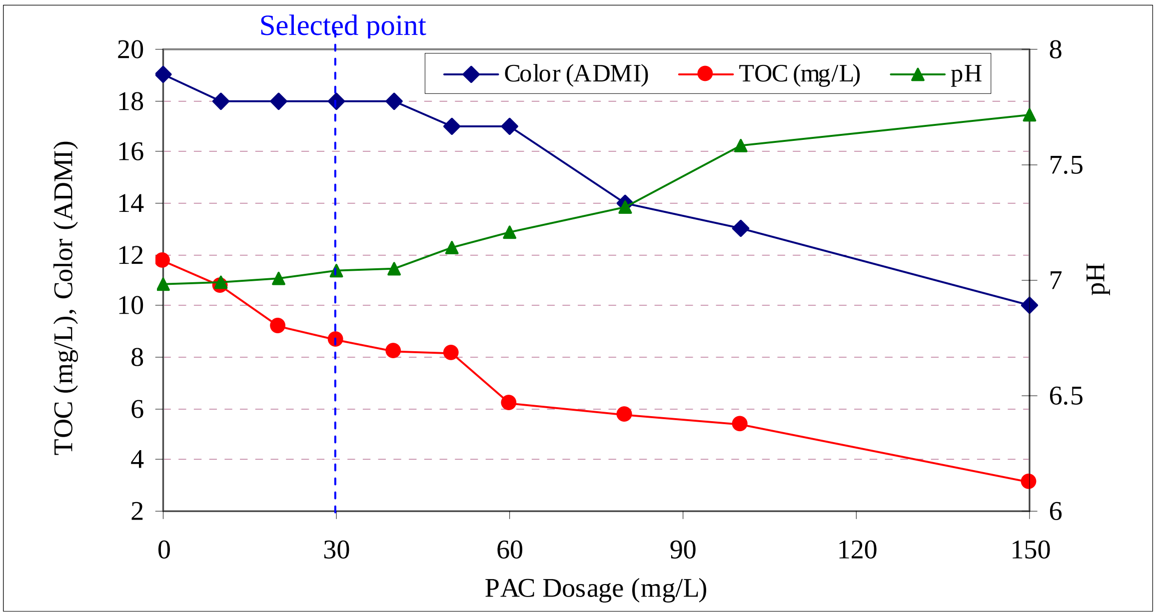


Figure 4.6 Variations of TOC and color of supernatant with PAC dosage

When PAC dosage increased, the TOC removal also was increased. However, from 30 to 50 mg/L of PAC dosage, the TOC removal rate was not increased rapidly. In addition, when used in the CMF system, PAC not only enhances coagulation-flocculation process in terms of TOC removal, but it also helps to reduce fouling of the ceramic membrane. The combination among the above results of jar test, economic aspect of using PAC, and literature review made a decision to choose the dosage of PAC of 30 mg/L. In this point, 26 % of TOC was removed by PAC and it was expected that the remained TOC would be removed more effectively by accumulation of PAC inside membrane during filtering and the combined coagulation-flocculation process.

- ***Jar test with the combination of adsorption and coagulation-flocculation processes:***

In the combined jar test, all beakers were supplied with the same PAC absorbent dosage of 30 mg/L and only PACl coagulant dosage was altered.

Figure 4.7 presents graphical result of the jar test, and table B.8 (appendix B) shows analyzed data in more detail. The graphical result shows that remaining TOC and turbidity of supernatant were decreased rapidly with the increase of PACl dosage from 0 to 20 mg/L. After the point of 20 mg/L PACl, the TOC and turbidity removal were slightly decreased and the remaining values were higher than the TOC and turbidity values at PACl dosage of 20 mg/L. Beside, with increase of PACl, the pH was decreased, and in practical situation it is unwanted to have a too low pH after coagulation-flocculation due to possible metallic corrosion of equipment. Therefore, the optimum coagulant dosage chosen is 20 mg PACl/L (2 mg/L as Al^{3+}), with TOC removal of 52.4 % (remaining TOC of 4.52 mg/L), and pH of supernatant was at 6.63.

In conclusion, selected adsorbent and coagulant dosages were 30 mg/L PAC and 20mg/L PACl, and used for experimental scenario of the hybrid CMF system enhanced by adsorption and coagulation-flocculation with AIT wastewater.

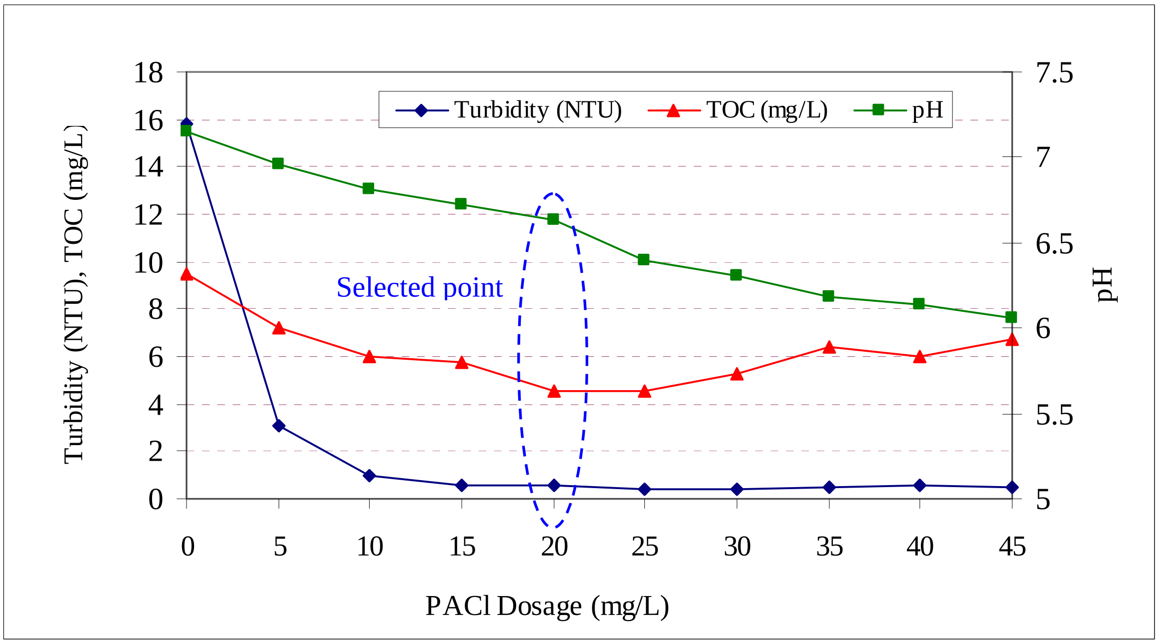


Figure 4.7 Variation of turbidity and pH of supernatant with coagulant dosage

4.2 Experimental run with synthetic water

In this experiment, prepared synthetic water was used as feed water for the pilot. The pilot system was set-up and operated with the scenario 1 as mentioned in the chapter 3.

4.2.1 Results and discussions

a. Transmembrane pressure (TMP)

Figure 4.8 gives changes of TMP and turbidity of feed water with filtration time. The TMP was being increased day by day until the 11^{th} day of the operation. After adding chlorine using NaClO with dosage of 10 mg/L, the TMP was decreased, and then after 17 days of treatment TMP was at 43 kPa. It was expected that the CMF would have to be cleaned by chemical cleaning in which TMP of 100 kPa.

Due to the decrease of TMP after adding NaClO to backwashing, it was decided to increase the turbidity of feed water up to 80 NTU but the TMP still was going down to 30 kPa. After turbidity of feed water was increased to 120 NTU, the TMP was increased slightly but it was kept almost at the constant TMP of 40 kPa. The characteristic of feed water was inorganic, and the foulants here almost are inorganic particles (kaolin clay), so the membrane was easily cleaned by BW, and TMP was recovered highly.

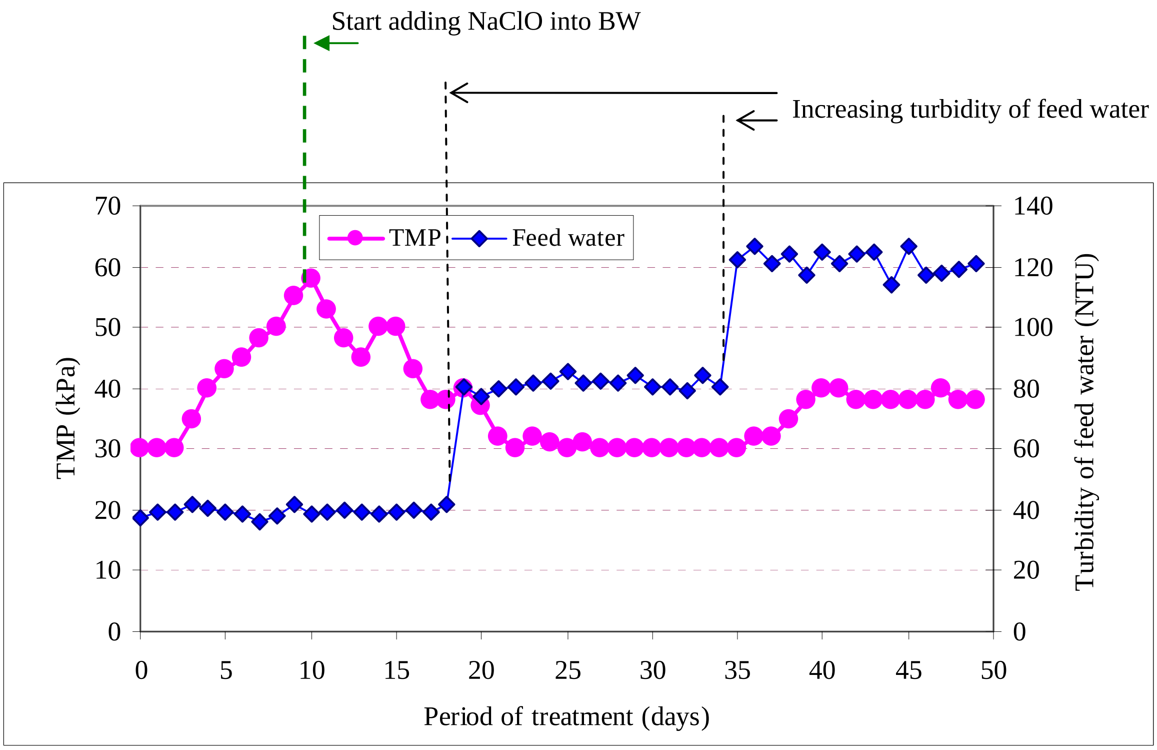


Figure 4.8 Variations of TMP and turbidity of feed water with period of treatment

b. Performance of the system in terms of turbidity removal

Figure 4.9 shows graphical changes of turbidities with time duration of the operation. (Refer to table B.11, appendix B, for detailed data).

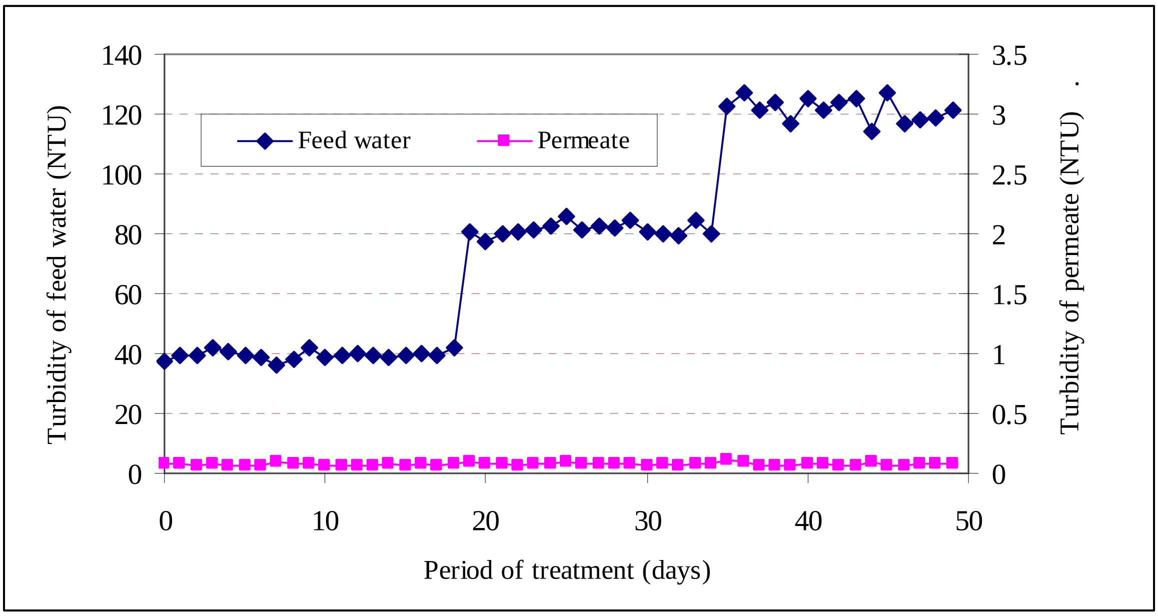


Figure 4.9 Changes of turbidity, turbidity removal with filtration time

The turbidity of permeate was very low (less than 0.1 NTU) even that of feed water was very high (40, 80, and 120 NTU). Although turbidity of the feed water was increased from 40 NTU to around 80 NTU and then up to around 120 NTU, the turbidity of the permeate was kept constantly. Therefore, the efficiency of the direct CMF system for the synthetic water treatment in terms of turbidity removal was dependent from the turbidity of feed water. The log removal of turbidity was from 2.56 – 3.28 and the removal rate was 99.73 – 99. 95%. The most visible evidence explaining clearly such a high performance is that kaolin clay had the size range from 100- 235 μm and it was easily removed by the ceramic membrane with pore size of 1 μm.

c. Observations of pH, temperature and conductivity

The numerical results of all the parameters are given in table B.9, appendix B. The pH of feed water and permeate water were neutral from 6.9 to 8. Because NaClO was added into permeate (for enhancing backwashing process), the remaining NaClO made a slightly higher pH of the permeate compared with that of the feed water. Figure B.4, appendix B, presents this difference in detail.

The temperature of permeate was always higher than the temperature of feed water, but the difference was not remarkable (0.1 – 1.5 ^{o}C). The increase of temperature of water after filtered can be caused by the effect of friction when feed water passed to the so small pores of the membrane. The changes of the temperature are presented in figure B.5, appendix B.

At the beginning stage, in which feed water has turbidity of 40 NTU, conductivity of permeate were little smaller than that of the feed water (conductivity of the synthetic water was around 47 – 51 μS/cm meanwhile this of the permeate was 47 – 50 μS/cm). But after adding NaClO into filtrate tank (for enhancement of backwashing), the conductivity of the permeate was increased and higher than that of the feed water. The phenomena could be explained by the existing of ions released from NaClO compound. The variety of conductivity is shown in the figure B.6, appendix B.

d. Performance in terms of TOC removal

Figure 4.10 presnts the results on TOC removal efficiency and TOC concentrations in the feed water and the permeate. (Refer to table B.12, appendix B, for more detail).

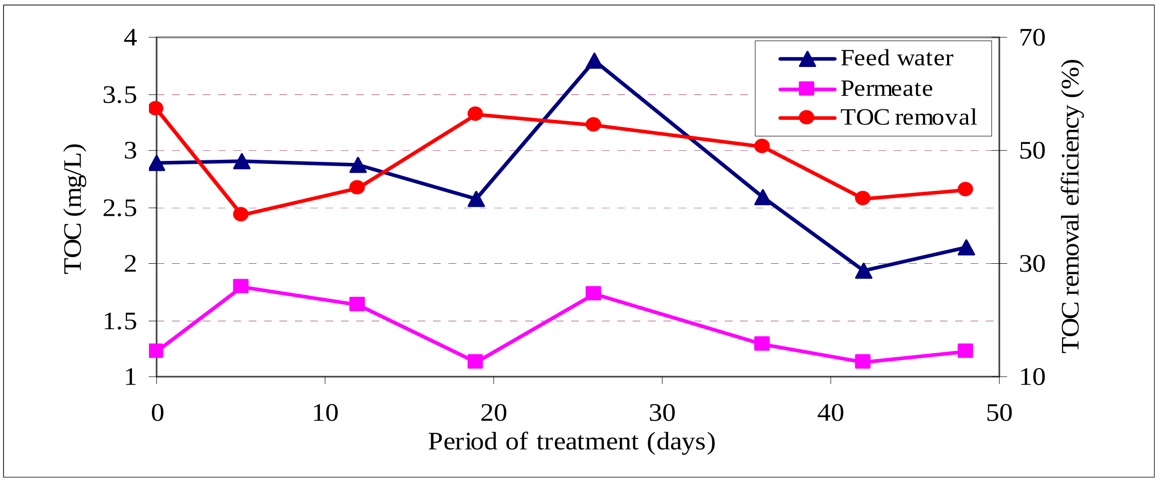


Figure 4.10 Changes of TOC and TOC removal efficiency with period of treatment

TOC of the synthetic water was from 1.43 to 3.79 mg/L, and permeate had lower TOC (1.12 – 2.08 mg/L). The TOC efficiency of the direct CMF system for the synthetic water treatment in terms was relatively low, from 38 to 57 %. It pointed out that without pre-treatments for enhancement of TOC removal such as coagulation-flocculation, adsorption, and etc., the experimental scenario could not remove effectively TOC. All most al of removed TOC here was particles (DOC may be adsorbed in kaolin clay particles), and the remained TOC was colloidal form that passed through the pores of the ceramic membrane.

e. Performance in terms of DOC removal

DOC removal efficiency, DOC concentrations of the feed water and the permeate are shown in figure 4.11. (Refer to table B.12, appendix B, for more detailed information).

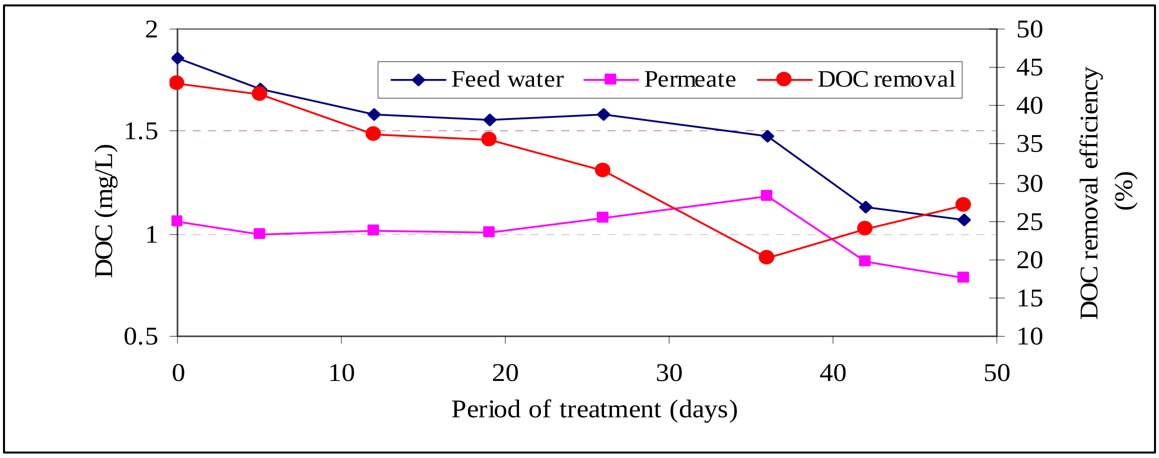


Figure 4.11 Changes of DOC and DOC removal with period of treatment

DOC of the synthetic water was low (1.07 – 1.859 mg/L), and permeate had lower DOC concentration (0.78 – 1.18 mg/L). The DOC removal efficiency of the direct CMF system for the synthetic water treatment was low, from 20 to 43 %. The reason explaining this low performance is the same as the above mentioned discussion for the TOC removal.

f. Performance in terms of total Fe removal

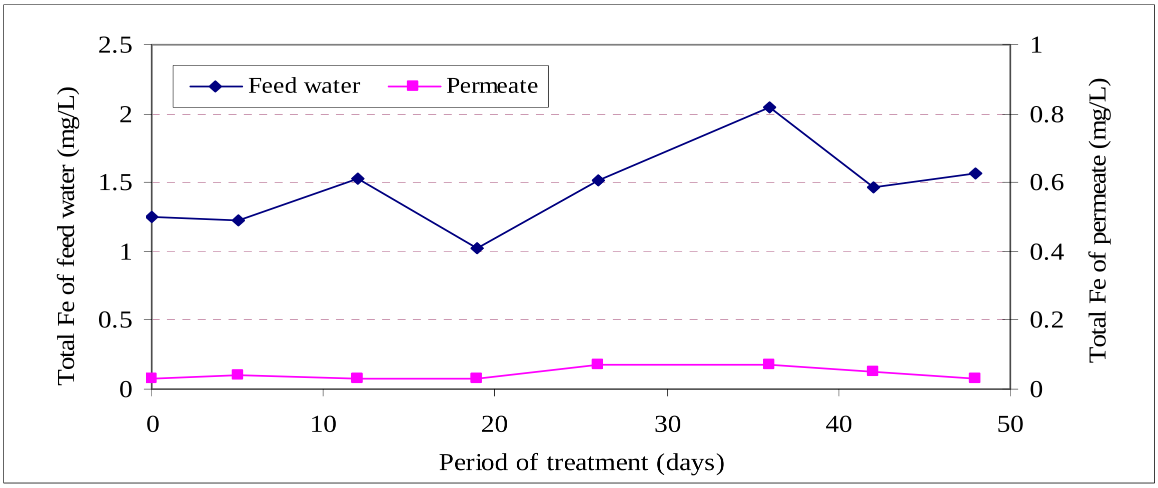


Figure 4.12 Variation of Fe with period of treatment

Total Fe concentrations of the permeate were very low (0.02 – 0.04 mg/L) compared with those of feed water (1.02 – 2.05 mg/L). The efficiency of the direct CMF system for the synthetic water treatment in terms of Fe removal was reached highly of 98 %. Fe of the synthetic water came from tap water and the kaolin clay. Through observation, it was seen that light yellow-brown color of Fe^{3+} form in the tap water which was used for preparing the synthetic water. In addition, the kaolin clay had the size range of 100- 235 μm, so almost all of removed Fe was un-dissolved Fe (Fe^{3+}). The supposition also was ensured when the color of membrane after running was yellow brown color.

g. Performance in terms of Mn removal

Both Mn concentrations of the feed water and the permeate were very low. The permeate had lower Mn concentration (0 – 10 μg/L) compared with those of the feed water (10 – 185 μg/L). The efficiency of the direct CMF system for the synthetic water treatment in terms of Mn removal was from 70 to 100 %. The mechanism of Mn removal can be explained as Fe removal as well. That means removed Mn from feed water was in un-dissolved form existing in kaolin clay and a part of tap water.

Figure B.7, appendix B, shows the changes of Mn in the feed water and the permeate. After 26 days of operation, Mn content of the permeate was none detected although the Mn still existed in the feed water. This could be caused by the accumulation of foulant inside pores of the ceramic membrane that helped to remove Mn more effectively.

h. Performance on micro-particle removal

The number of micro-particles was measured twice a week. Figure 4.13 presents the graphical results on removing micro-particle with size range from 5 to 15 μm. Table B.13, appendix B, gives detailed measurement on micro-particles.

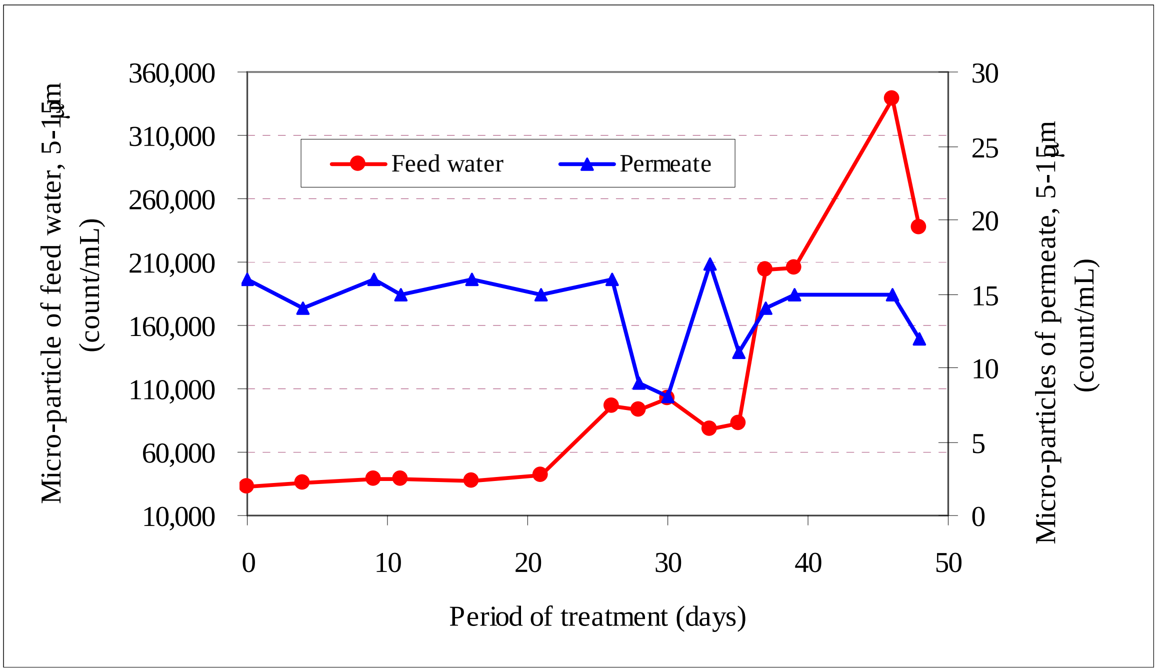


Figure 4.13 Micro-particles of the feed and the permeate water

The results pointed out micro-particles (5 – 15 μm) or Giadia and Crypto removal efficiency of the direct CMF system was very high, 99.95 - 99.99%. The log micro-particle removal (5 – 15 μm) was from 3.28 – 4.21. Compared with a research conducted by Arika et al. (2006), researched in Cambodia with a ceramic membrane having pore size of 0.1 μm, the micro-particles of permeate was 130 count/mL, the direct CMF system running at AIT was much more effective.

The measurement of the micro-particles could not tell exactly the number of microbiological particles with synthetic water, but it relatively could tell performance of the CMF system for Giadia and Cryptosporidium removals in experiments with real water sources.

i. Performance on TSS and TS removal

Quality of the feed water and the permeate, and the removal efficincy in terms of TSS and TST is established in table B.12, appendix B.

The direct microfiltration system had a very high TSS removal efficiency, 99 - 100%, with the TSS of permeate was from 0 to 0.5 mg/L. TSS almost existed in the kaolin clay (particle form), so it was effectively removed by the ceramic membrane with pore size of 0.1 μm.

On the other hand, TS removal efficiency was achieved from 44-70%. This pointed out the direct CMF could not remove completely dissolved solid matter of tap water (a component constituting the synthetic water). Beside, injecting NaClO with dosage of 10 mg/l to filtrate tank for enhancement of backwashing is another reason that made the high remained total solid in the permeate.

4.2.2 Conclusion

After 50 day of the operation with the synthetic water, the ceramic membrane filter was not fouled even the turbidity of synthetic water was very high (120 NTU). In addition, the quality of the permeate was very good. Therefore, the experimental run with synthetic water was stopped and no further experiment with pre-treatments conducted. For next experimental runs with real water sources, the membrane was taken out from the casing and chemically cleaned by citric acid solution 1%, and then NaClO 0.3%.

In this experimental run, the feed water used was the synthetic water prepared from tap water and kaolin clay. The feed water had the inorganic characteristics, so the pollutants were also inorganic matters. The inorganic pollutants made inorganic foulants to the membrane. These inorganic foulants were easily removed by backwashing using air scouring and filtrate flushing. However, when the feed water used is surface water or wastewater, foulants would be both inorganic and organic matters. Therefore, experimental runs with surface water (AIT pond water) and municipal wastewater (AIT wastewater) would have to include backwashing enhanced by NaClO.

4.3 Experimental runs with surface water

4.3.1 Scenario 1: Direct ceramic microfiltration

With this scenario, two experimental runs were conducted and the results are summarized in the following section.

a. Transmembrane pressure (TMP)

Figure 4.14 presents graphical results on TMP and turbidity changing tendencies of two different runs with AIT pond water using direct microfiltration scenario. Table B.15 and B.20, appendix B, show detailed results.

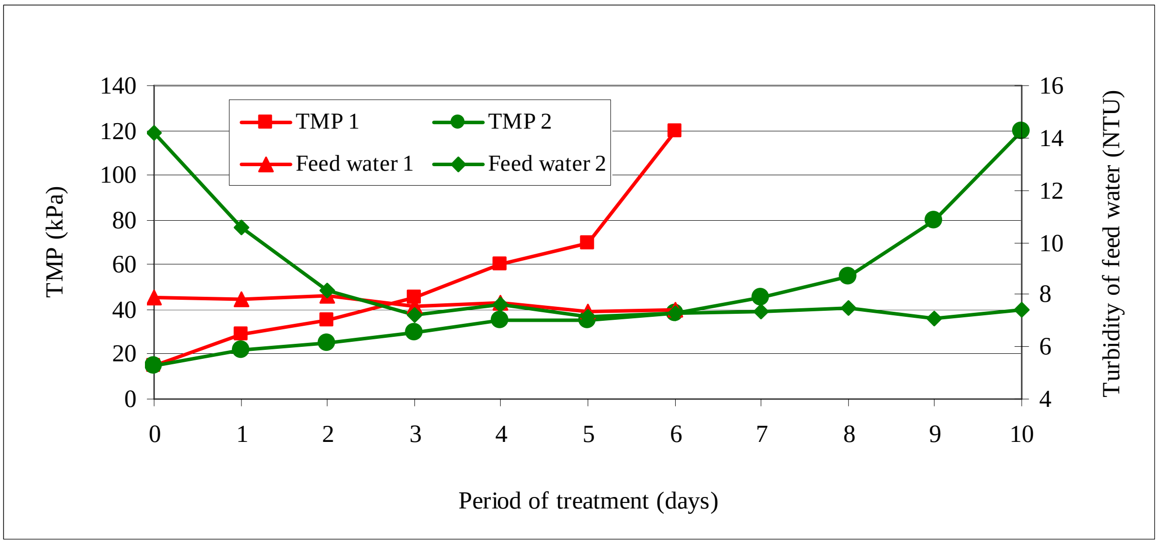


Figure 4.14 Changes of TMP and turbidity of feed water with period of treatment

In the first experimental run, the fouling with TMP of 120 kPa was achieved on the 7th day of operation. Meanwhile, in the second run, the starting TMP was the same as this of the first run (15kPa), but it got 11 days for getting fouling at TMP of 120 kPa. The difference of time duration for occurring fouling between the two experimental runs is explained by the difference between the qualities of the feed waters. The turbidity of the feed water 1 (7.38 – 7.94 NTU) was slightly higher than that of the feed water 2 (7.07 – 7.62) since the third day of the operation, this prolonged time filtration of the run 2 compared with that of the run 1.

Further more, through observation during backwashing process, TPM recovery by backwashing in both runs was from 20 – 50 kPa. TMP recoveries by chemical cleaning using acid citric 1% solution and NaClO 0.3% solution respectively were 60 kPa (TMP was reduced from 120 kPa down to 60 Kpa after 24 hours of soaking) and 45 kPa (TMP was reduced from 60 Kpa to 15 Kpa after 24hours of soaking).

b. Performance of the system in terms of turbidity removal

Figure 4.15 gives graphical changing tendency and relationship among turbidity, time duration of the operation, and efficiency of the system on turbidity removal for the two runs with the same scenario direct CMF with surface water. (Refer to tables B.15 and B.20, appendix B).

In both the experimental runs, the turbidity of permeate was the highest value on the first day of operation. This phenomenon is explained by the proportional increase of foulant accumulation with period of treatment. On the starting day of each run, membrane was pure after chemical cleaning of the last run, so its pore size was large and the turbidity of permeate therefore was high. Day by day, foulants were accumulated inside pores and on surface of feed channels and they helped to remove more effectively turbidity of feed water.

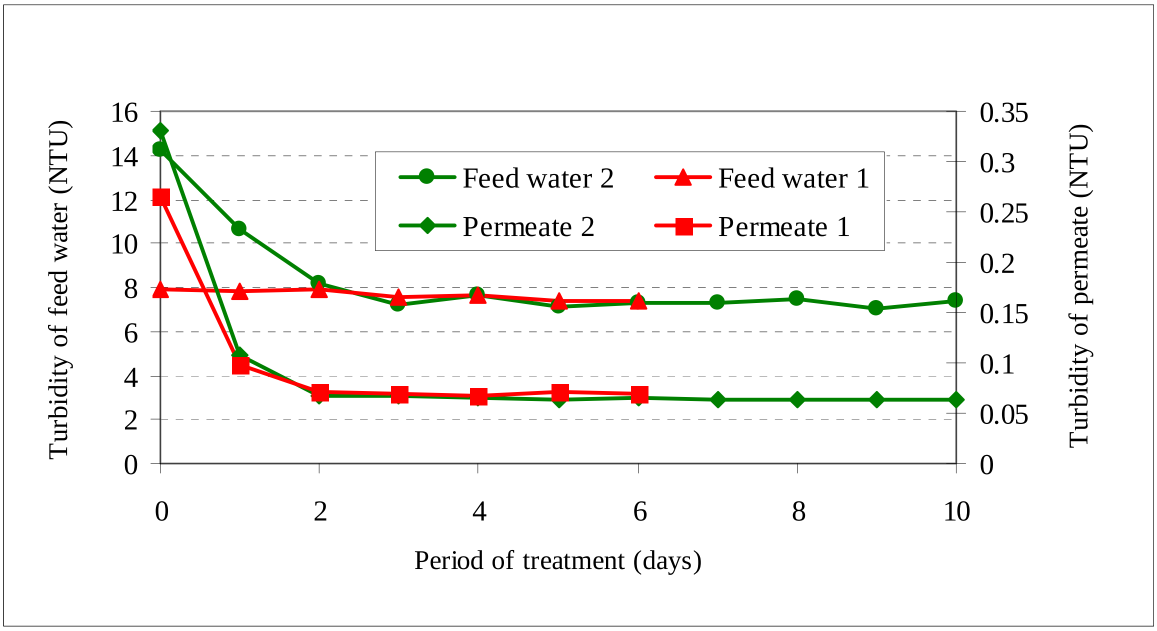


Figure 4.15 Changes of turbidity with period of treatment

From the 3rd day of operation, the operation of the system was stable. This made turbidity of permeate was kept constantly and steadily from 0.064 to 0.071 NTU in both two experimental runs. The turbidity removal efficiency was 99.02 – 99. 16%.

c. Performance in terms of TOC and DOC removals

Figures 4.16 and 4.17 show the removals and concentrations of TOC and DOC. The numerical concentrations are given in tables B.16 and B.21, appendix B.

In the first run, with time duration for getting fouling of 7 days, TOC of feed water was 10.05 – 12.1 mg/L, and permeate had lower TOC concentrations, 7.46 – 8.30 mg/L. The TOC removal efficiency of the direct CMF system for the surface water treatment was 18.8 – 26.1 %. DOC of feed water was from 9.15 – 10.51 mg/L and higher than this of permeate, 7.01 – 7.81 mg/L. DOC removal rate of this run was 15 – 31%.

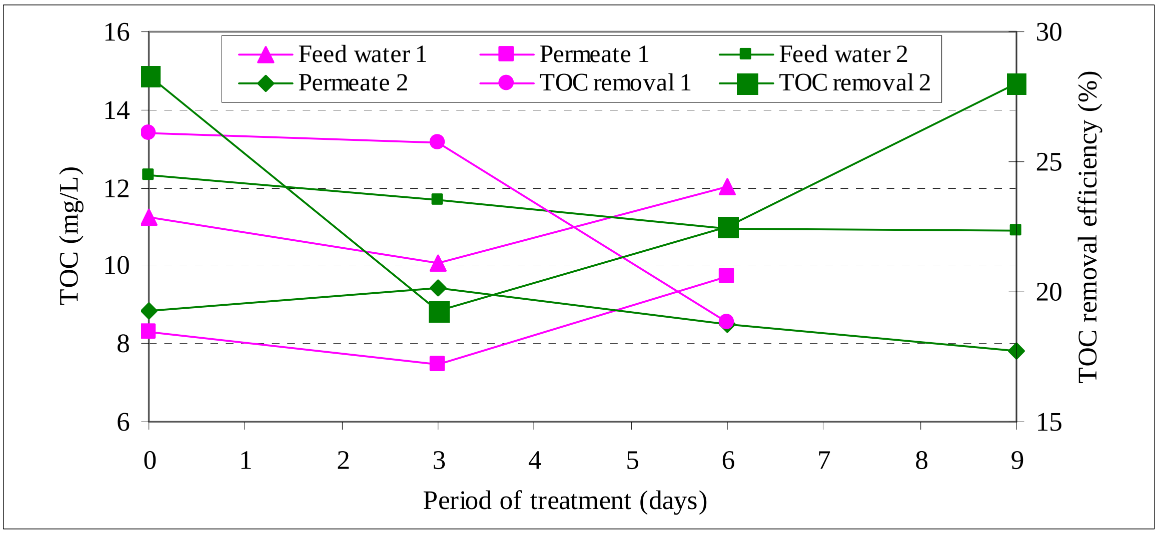


Figure 4.16 Changes of TOC and TOC removal efficiency with period of treatment

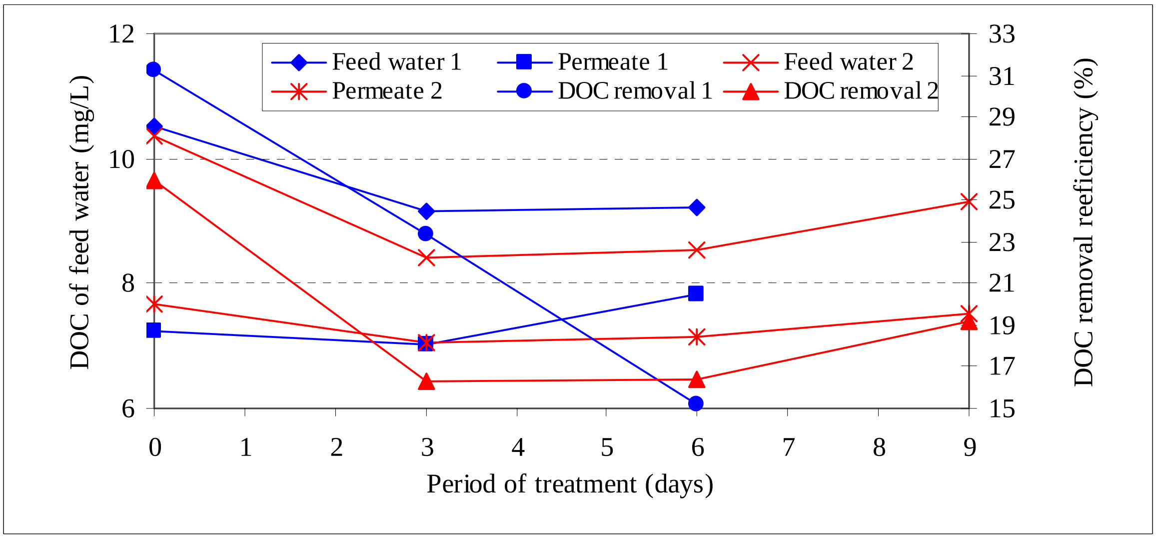


Figure 4.17 Changes of DOC and DOC removal efficiency with period of treatment

In the second run, with period of treatment for getting fouling of 11 days, TOC of feed water was 10.88 to 12.34 mg/L, and permeate had lower TOC concentrations, 7.836 to 9.42 mg/L. TOC removal efficiency of the direct CMF system for the surface water treatment was 19.3 to 28.3 %. DOC of the feed water was from 8.42 – 10.37 mg/L and higher than that of the permeate, 7.05 – 7.68 mg/L. DOC removal efficiency of this run was 16.3 – 25.9%.

In conclusion, the TOC and DOC efficiencies of the two different runs were relatively low. It was found out from this experiment that the direct ceramic microfiltration was not effectively for treatment of highly organic contaminated surface water. Without pre-treatments such as coagulation-flocculation, adsorption, and etc., the organic pollutants removal efficiencies were very low. High remained TOC and DOC are really issues for a water treatment plant to choose disinfection methods. If such organic contaminated permeate is disinfected by chlorine, THMs will exist as by-disinfection products leading to harmful effects to human health (potentials of cancer diseases). Therefore, it is really necessary to include pre-treatment processes such as coagulation-flocculation and powder activated carbon adsorption to enhance TOC and DOC removals of the ceramic membrane.

d. Performance on micro-particle removal

Figures 4.18 and 4.19 give the graphical results on removing micro-particle with size range from 5 to 15 μm. Tables B.18 and B.23, appendix B, shows detailed measurement on the micro-particles.

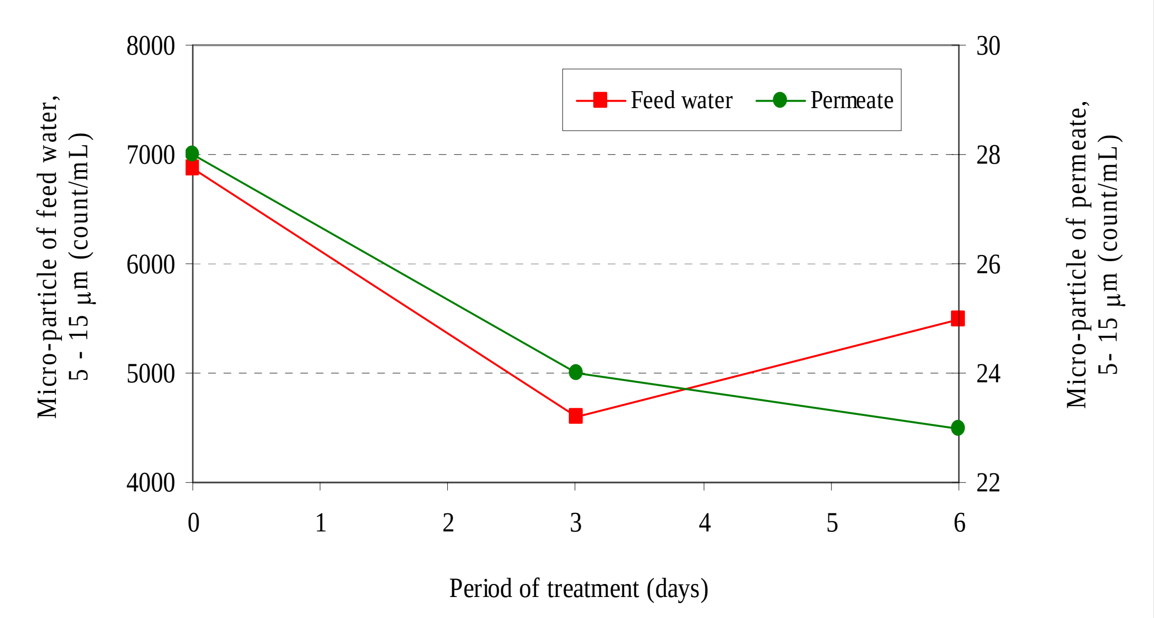


Figure 4.18 Change of number of micro-particle with period of treatment of run 1

In the experimental run 1, removal efficiency on micro-particles with the same size range of Giadia and Crypto was 99.48 - 99.59%, and log micro-particle removal was 2.28 – 2.39. The feed water had 4592 – 6872 particles/mL, and permeate had 23-28 particles/mL with size of 5 – 15 μm. The number of the micro-particles of permeate was decreased with the increase of period of treatment. This can be explained by increasing thickness of fouling inside membrane with time, and it enhanced the particle removal through cake filtration mechanisms.

In the experimental run 2, removal efficiency on micro-particles with same size range of Giadia and Crypto was 99.59 - 99.78 %, and log micro-particle removal was 2.39 – 2.66. The feed water had 4680 – 11488 particles/mL, and permeate had 19-30 particles/mL. The number of the micro-particles of permeate was also decreased with the increase of period of treatment. This is caused by foulant accumulation inside membrane that enhanced the particle removal through cake filtration mechanisms.

In summary, the results pointed out removal efficiency of the direct CMF system in terms of micro-particles (5 – 15 μm) or Giadia and Crypto was 99.48 - 99.78 %. The log micro-particle removal (5 – 15 μm) was from 2.28 – 2.66. The measurement of the micro-particle number indirectly and relatively told number of parasite pathogens, Crypto and Giadia that exist in the feed and permeate, and performance of the direct CMF system for removing the microbiological pollutants.

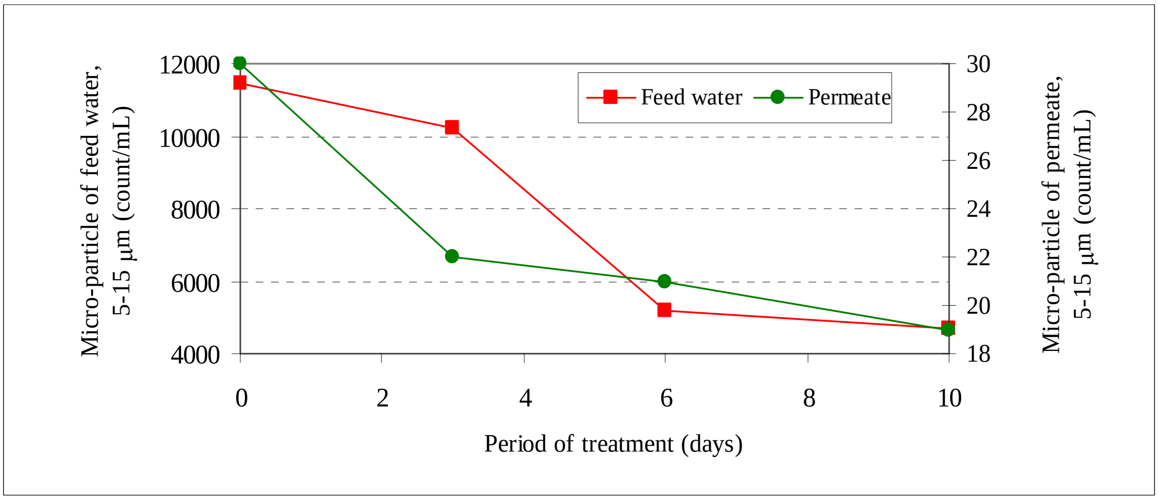


Figure 4.19 Change of number of micro-particle with period of treatment of run 2

e. Performance on TSS and TS removal

Tables B.16 and B.21, appendix B, present the quality of the feed water and the permeate and the removal efficiencies in terms of TSS and TS of the two different runs.

On the first day of operation, TSS of permeate was 0.5 mg/L and the removal efficiency was 95.5-97.7 % for the run 1 and run 2 respectively. After three days of operation, the system worked steadily and TSS of permeate was zero with the TSS removal efficiency of 100 %.

TS of the permeate was slightly lower than that of the feed water. Although when TSS removal was 100 %, TS of the permeate was still very high and TS removal efficiency was very low, less than 10 %. This can be explained by the adding NaClO into filtrate tank, and the NaClO contribute to TS increase of the permeate. TS of the permeate was 188 - 204 mg/L and 308 – 312 mg/L in run 1 and run 2, respectively.

f. Performance on removal of other pollutants: Fe, Mn, total coliform, fecal coliform, free Cl_2 residual and total alkalinity.

Tables B.17 and B.22, appendix B, show results on measurement of total Fe, dissolved Fe, total Mn, and dissolved Mn on two experiments. Total Fe of the feed water was 0.39 – 0.75 mg/L, and total Fe of the permeate was 0.03 – 0.06 mg/L. Dissolved Fe of the feed water was 0.15 – 0.3 mg/L, and that of the permeate was 0 – 0.07 mg/L. Total Mn of feed water was 30 – 114 µg/L and that of permeate was 5 – 107 µg/L. Dissolved Mn of the feed and permeate was 0- 5 µg/L and 0 µg/L respectively. The results show that Fe and Mn of both the feed water and the permeate were very low, almost zero.

Total coliform and fecal coliform of the feed water were 190 – 438 MPN/100mL and 4 – 14 MPN/100mL respectively. Both total colifrom and fecal coliform of the permeate were none-detected. This means the direct CMF removed 100% total coliform and fecal coliform.

The feed water had no free chlorine, but the permeate had free Cl_2 residual of 3.65 – 4.1 mg/L due to adding continuously NaClO to filtrate tank for enhancement of the backwash.

Alkalinity of the feed water was 59 – 62 mg/L as $CaCO_3$ and this of the permeate was 66 – 70 mg/L as $CaCO_3$. The difference between alkalinities of the feed water and the permeate also was caused by the used NaClO. NaClO made pH of water increases leading to higher total alkalinity of treated water compared with total alkalinity of the feed water.

4.3.2 Scenario 2: Coagulation-flocculation and CMF

Based on the results of the pre-experiment on jar test that was mentioned in the section 4.1.2.a, coagulant dosage of 20 mg PACl /L was selected for coagulation process. Two experimental runs were conducted with AIT pond water using hybrid ceramic microfiltration system in which a pre-treatment by coagulation-flocculation was used. Results of these two runs are summarized in the following section.

a. Transmembrane pressure (TMP)

Figure 4.20 presents changes of TMP and turbidity of the feed water, and tables B.25 and B.30, appendix B, give numerical results.

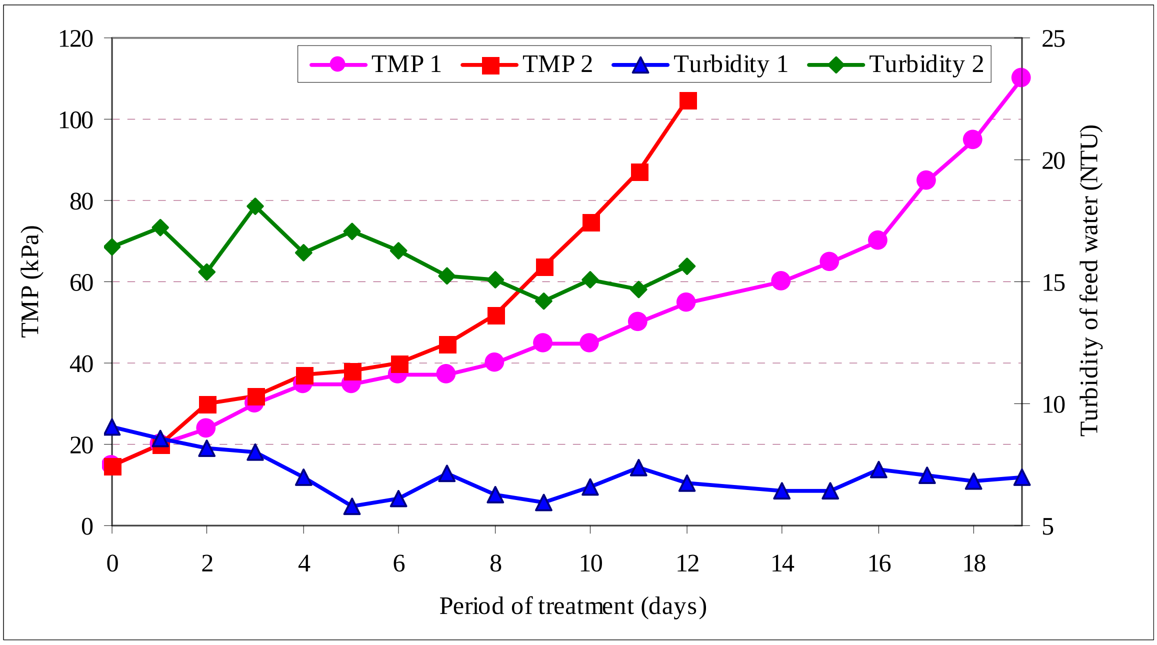


Figure 4.20 Changes of TMP, turbidity of feed water and period of treatment

In the first experimental run, the fouling with TMP of 105 kPa was achieved on the 13^{th} day of the operation. In the second run, fouling at TMP of 120 kPa was achieved after 20 days of the treatment. The difference between time durations of occurring fouling can be reasoned by the different qualities of the feed waters. The quality of AIT pond water which was used as surface water source could be changed by time. The run 1 was conducted in the different time with the run 2. The turbidity of the feed water 1 (14.2 – 18.1 NTU) was much higher than that of the feed water 2 (5.76 – 9.02). This made the run 2 had the longer filtration time compared with run 1.

Through observation, TMP of this scenario did not increased rapidly as that of the scenario without coagulation-flocculation. But TMP from 5 – 7 kPa recovered by each time of backwashing process of this hybrid scenario was lower. It was found out that, after coagulated and flocculated, the particle and colloidal contents of the feed water were reduced highly. A small amount remained colloidal of the feed water made the low TMP increase due to colloidal fouling. Then this fouling was removed by the EBW. This finding is the reason for the lower TMP increase and TMP recovery by EBW as well. TMP recoveries by chemical cleaning using acid citric 1% solution and NaClO 0.3% solution were 80 - 85 kPa (TMP was reduced from 105-110 kPa down to 25 Kpa after 24 hours of soaking) and 10 - 12 kPa (TMP was reduced from 25 Kpa to 13 - 15 Kpa after 24hours of soaking), respectively.

b. Performance of the system in terms of turbidity removal

Figure 4.21 presents graphical changes of turbidities of the system in the two experi,ental runs. Tables B.25 and B.30, appendix B, give detailed data

On the first day of operation, when foulants were not accumulated notably inside pores of the membrane, the turbidity of permeate was the highest value. However, the difference between turbidities on the first day and second days was very small, 0.003 – 0.01 NTU. This difference was lower than that of the scenario without coagulation-flocculation, 0.17-0.26 NTU. This pointed out that the formation of big flocs due to coagulation-flocculation helped to remove more effectively turbidity even on the first day of operation when the ceramic membrane had very clean pores.

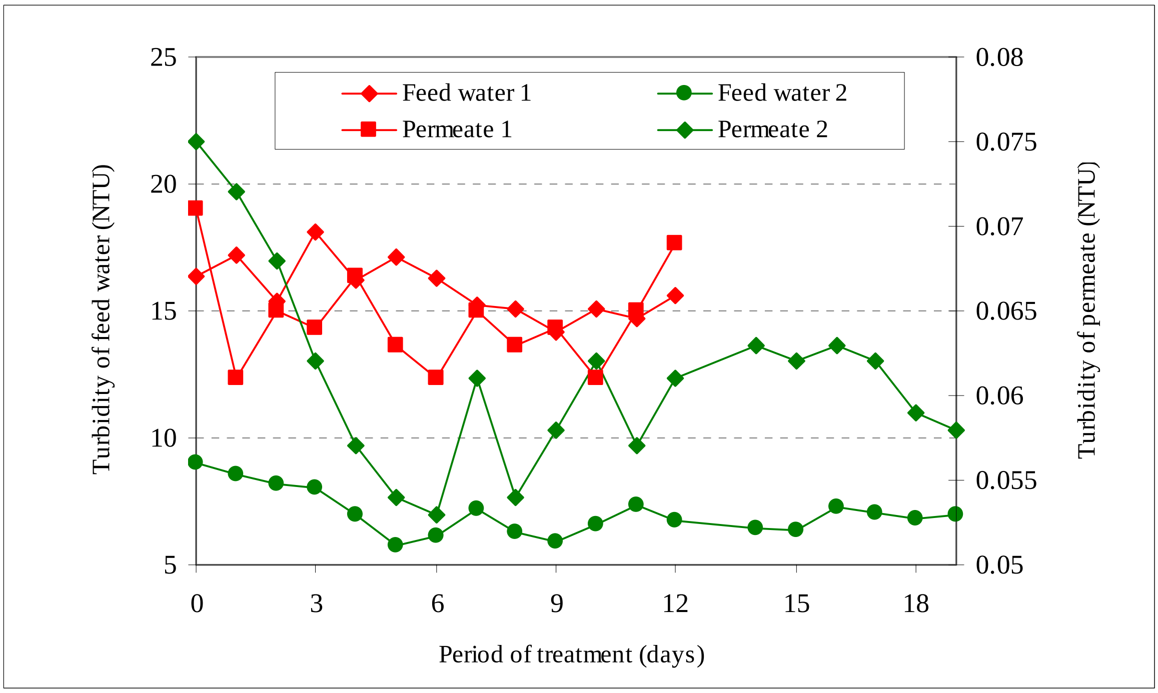


Figure 4.21 Change of turbidity with period of treatment

In the first run, after 1 days of operation, a steady state on removing turbidity was achieved. From this time, turbidity of the permeate was kept stably from 0.061 to 0.069 NTU with turbidity removal efficiency of 99.55 – 99.65%. Meanwhile, in the second run, after 2 days of operation, the performance of the system was stable. In this steady state turbidity of the permeate also was 0.053 to 0.068 NTU. The turbidity removal efficiency was 99.02 – 99. 23%. This points out that lower turbidity of feed water prolonged time duration of the hybrid system, but it took longer period of treatment for getting steady performance and fouling.

c. Performance in terms of TOC and DOC removals

Figures 4.22 and 4.23 present TOC, DOC removal efficiencies and concentrations in the feed water and the permeate of the two experimental runs. The numerical concentrations are given in tables B.26 and B.31, appendix B.

In the first run, with the fouling cycle of 13 days, TOC of the feed water was 10.97 to 11.45 mg/L, and that of the permeate was 2.69 – 2.97 mg/L. TOC removal efficiency of the PACl + CMF hybrid system for the surface water treatment was 72.59 to 75.63 %. Compared with the scenario without pretreatment by coagulation-flocculation, this scenario with pre-treatment by coagulation-flocculation is very highly effective on TOC removal. The coagulation-flocculation enhanced strongly both period of treatment and TOC removal. In addition, DOC of feed water was from 6.86 – 7.87 mg/L and higher than this of permeate, 2.28 – 2.52 mg/L. DOC removal rate of this run was 63.4 – 69.5%, very high compared with this of the scenario without coagulation-flocculation (15 – 31%).

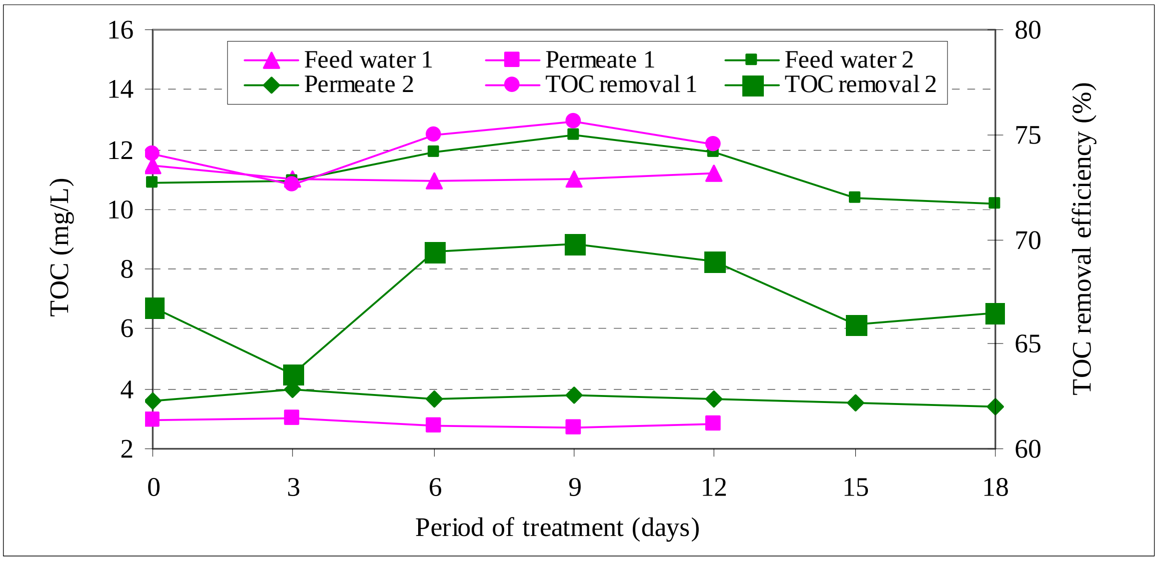


Figure 4.22 TOC and TOC removal rate with period of treatment

In the second run, period of treatment for getting fouling of 19 days, TOC of the feed water and the permeate was 10.18 to 12.5 mg/L and 3.41 – 3.98 mg/L, respectively. The TOC removal efficiency of the hybrid CMF system for the surface water treatment in terms of was 63.6 – 69.7 %. In addition, DOC of feed water was from 8.11 – 9.74 mg/L and higher than this of permeate, 3.28 – 3.80 mg/L. DOC removal efficiency of this run was 57.66 – 63.23 %. The TOC and DOC removal efficiencies of the run were much higher compared with the scenario without coagulation-flocculation process.

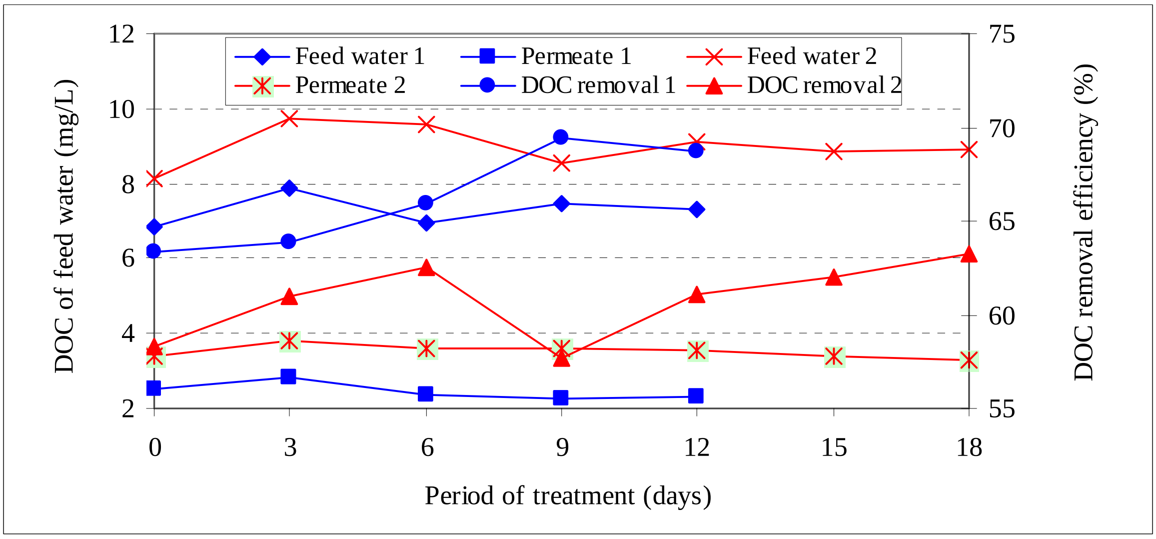


Figure 4.23 DOC and DOC removal rate with period of treatment

In conclusion, the efficiencies on removing both TOC and DOC of the two different runs with the same scenario were relatively high compared with the last experiment without coagulation-flocculation. In addition, this experiment pointed out clearly that when combined with pre-treatment by coagulation-flocculation process to have the hybrid ceramic microfiltration system, for treatment of surface water with high organic, the time duration for getting fouling was prolonged from 7-11 days up to 13-20 days removal rates for removing organic pollutants were very low. Enhanced by PACl coagulation-flocculation, TOC and DOC removal efficiency could be improved up to 63.6 – 75.63 % and 57.66 – 69.5 %, respectively.

However, remained TOC and DOC are still higher than 2 and 3 mg/L in run 1 and run 2, respectively, and it is really necessary to conduct study on powder activated carbon adsorption that is used as one more pre-treatment process to enhance TOC and DOC removals of the ceramic membrane.

d. Performance on micro-particle removal

Figures 4.24 and 4.25 present the graphical results on removing micro-particle with size range from 5 to 15 μm, and tables B.28 and B.33, appendix B, give detailed measurement on the micro-particles.

In the experimental run 1, on micro-particles removal efficiency with size range of Giadia and Crypto was 99.69 - 99.80 %. Log micro-particles removal was 2.51 – 2.70. The feed water had 5918 – 7266 particles/mL, and permeate had 13-21 particles/mL with size of 5 – 15 μm.

The number of the micro-particles of permeate was decreased with the increase of filtration time. This can be explained by increasing thickness of fouling inside membrane with time. The foulants accumulation enhanced the particle removal through cake filtration mechanisms.

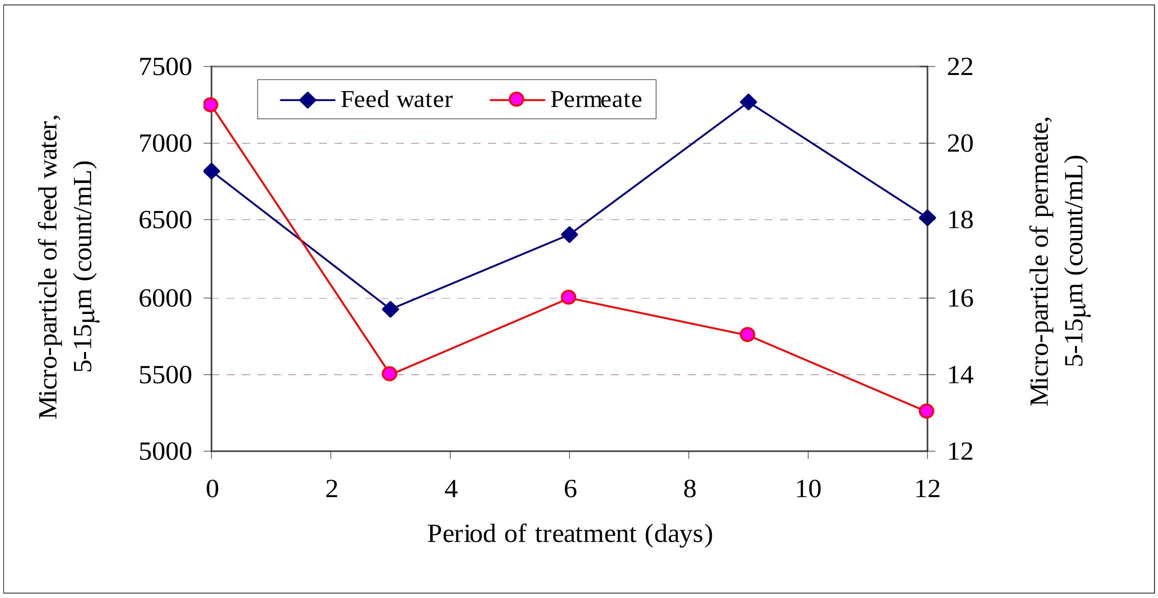


Figure 4.24 Number of micro-particle and period of treatment of run 1

In the experimental run 2, Giadia and Crypto were removed at 99.68 - 99.84 %, and log removal of 2.52 – 2.70. The feed water had 5890 – 7511 particles/mL, and the permeate had 12-20 particles/mL. The number of the micro-particles of the permeate was also decreased with the increase of the period of treatment. This again shows role of foulant accumulation inside membrane that enhanced the particle removal through cake filtration.

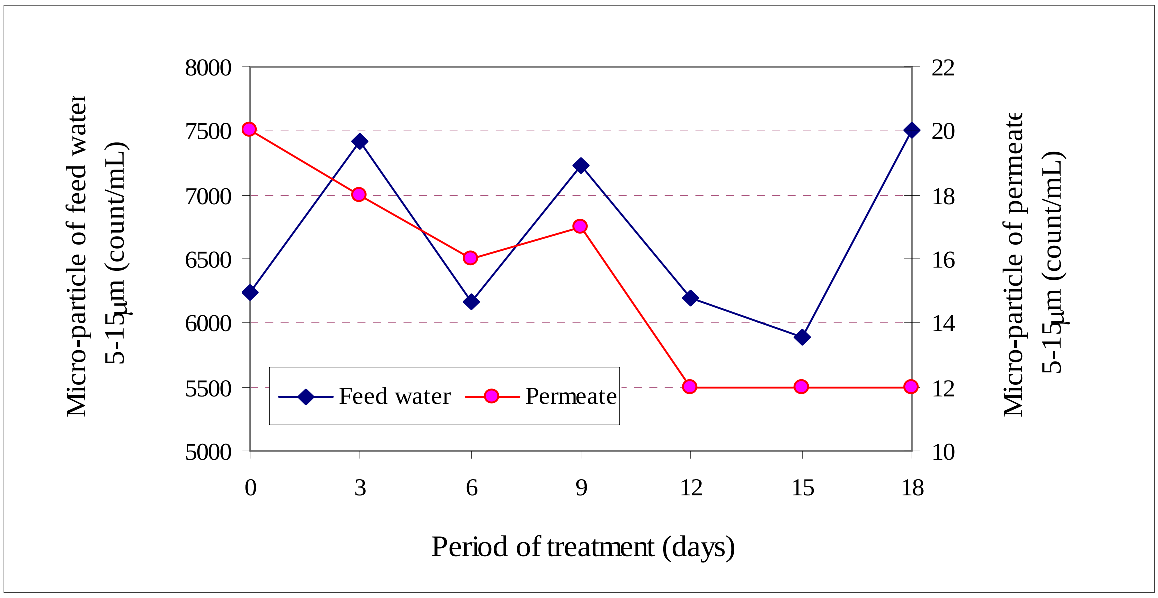


Figure 4.25 Number of micro-particle and period of treatment of run 2

In summary, the measurement indirectly and relatively told the number of parasite pathogens, Crypto and Giadia existing in the feed and the permeate, and the performance of the PACl + CMF hybrid system. The results pointed out that the hybrid CMF system enhanced by coagulation-flocculation remove much more effectively Giadia and Crypto (5 – 15 μm), 99.69 – 99.84% compared with 99.48 - 99.78 % of direct CMF. The log micro-particles removal was 2.51 to 2.70.

4.3.3 Scenario 3: Adsorption, coagulation-flocculation, and CMF

a. Transmembrane pressure (TMP)

Figure 4.26 presents changes of turbidity of feed water and TMP, and table B.35 gives detailed results.

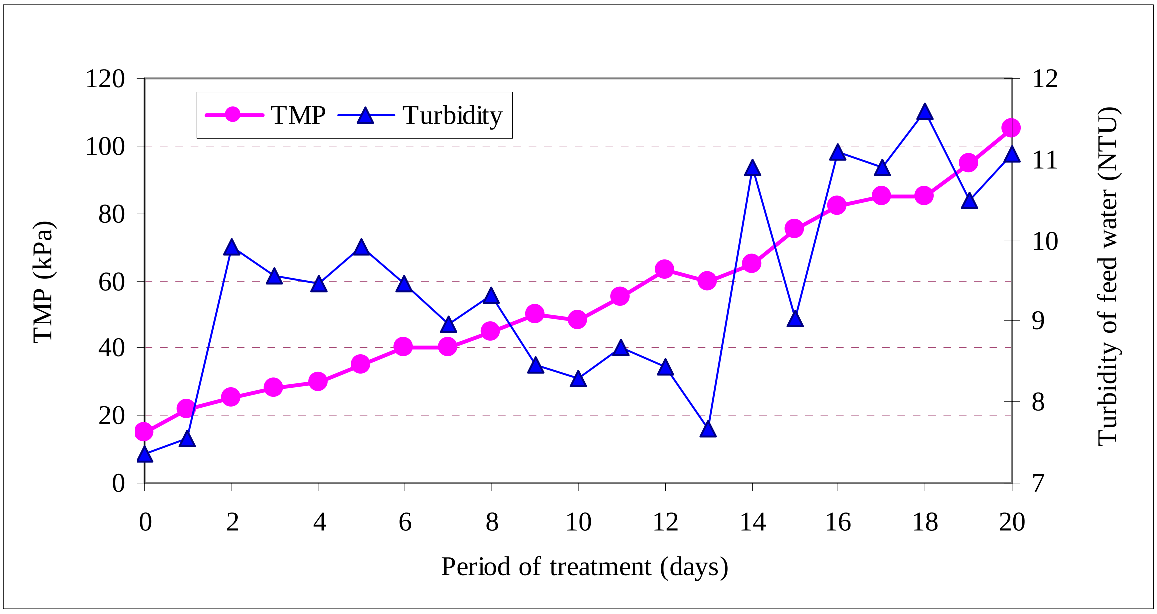


Figure 4.26 Changes of TMP and turbidity of feed water with period of treatment

The fouling with TMP of 105 kPa was achieved on the 21th day of operation. Compared with the last runs without adsorption, this run had a longer filtration time. The feed water had turbidity of 7.35 - 11.6 NTU.

The TMP did not increased rapidly as the situation of scenarios without the PAC adsorption. TMP recovered by each time of backwashing was around 5 kPa and less than other scenarios. TMP recoveries by chemical cleaning using acid citric 1% solution and NaClO 0.3% solution were 85 kPa (TMP was reduced from 105 kPa down to 20 Kpa after 24 hours of soaking) and 5 kPa (TMP was reduced from 20 Kpa to 15 Kpa after 24hours of soaking), respectively.

b. Performance of the system in terms of turbidity removal

Figure 4.27 gives graphical changes of turbidity and turbidity removal efficiency of the experimental run. (Refer to table B.35, appendix B, for numerical data).

On the first day of operation, when foulants were not accumulated notably inside pores of the membrane, the turbidity of the permeate was the highest value of 0.18 NTU. From the 3rd day, a steady state on removing turbidity was achieved. In this state, turbidity of the permeate was kept stably of 0.053 – 0.066 NTU, with turbidity removal efficiency of 99.44 – 99.53 %. Compared with last runs without PAC adsorption, the permeate of this run is clearer than the others.

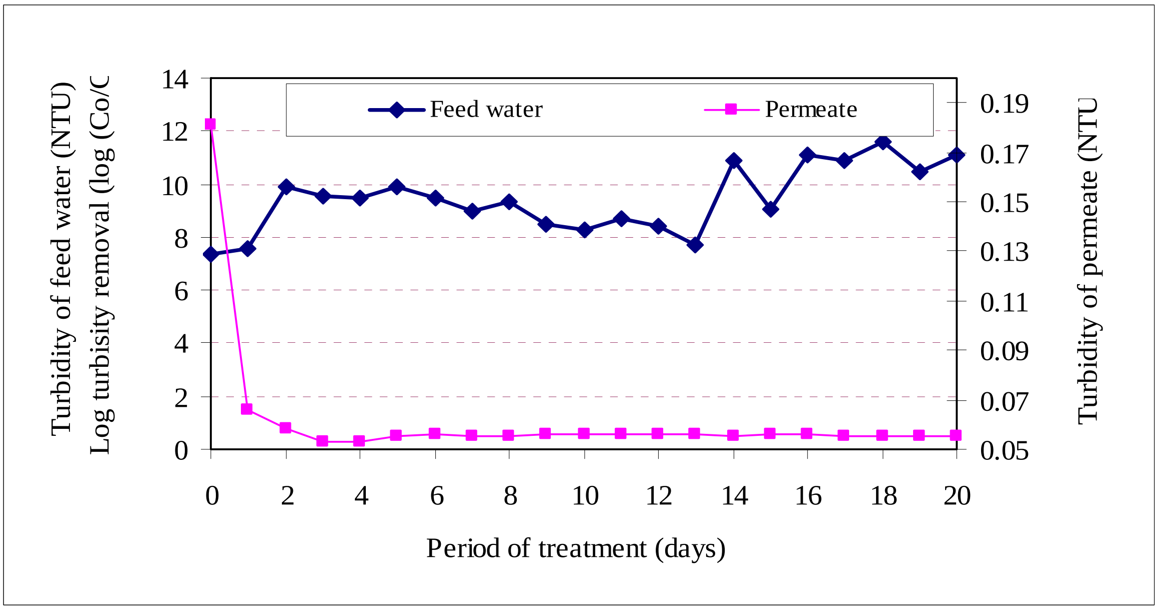


Figure 4.27 Relationship between turbidity and period of treatment

c. Performance in terms of TOC and DOC removals

Figures 4.28 and 4.29 give removal efficiencies and concentrations of TOC and DOC in the feed water and the permeate. The numerical values are given in table B.36, appendix B.

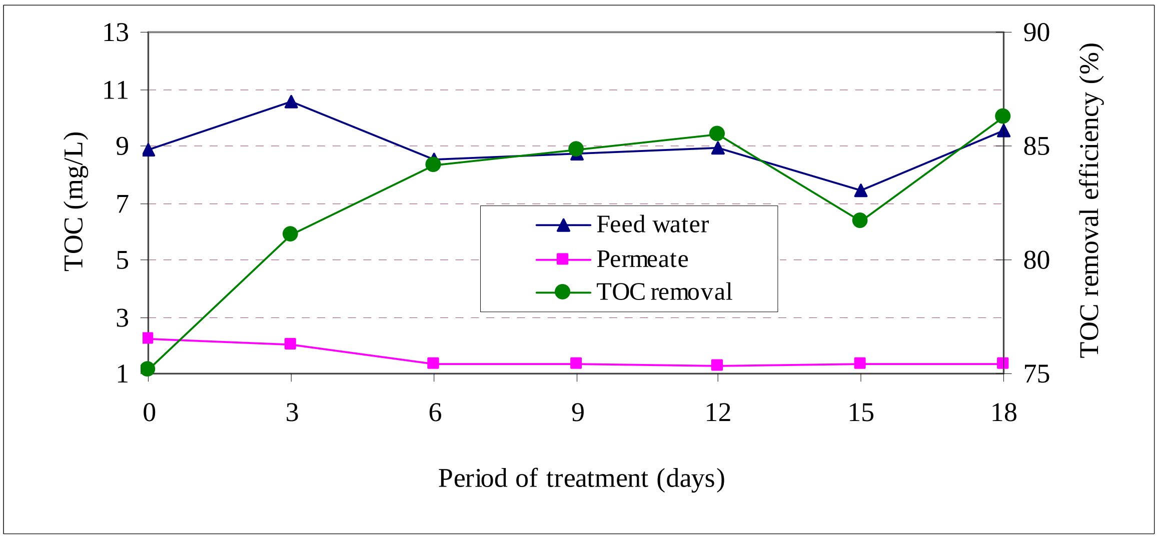


Figure 4.28 TOC and TOC removal rate with period of treatment

TOC of the feed water was 8.54 – 10.54 mg/L, and that of the permeate was 1.29 – 2.2 mg/L. TOC removal efficiency of the PAC + PACl + CMF hybrid system was 75.14 – 86.30 %. Compared with this of scenarios without coagulation-flocculation, 18.8 – 26.1 %, and without PAC adsorption, 72.59 – 75.63 %, the scenario with pre-treatment by both PAC and PACl was much more effective on TOC removal. In addition, the PAC adsorption and coagulation-flocculation also prolonged the filtration time of the membrane.

DOC of the feed water was 6.26 to 7.31 mg/L and higher than this of the permeate, 1.11 – 1.83 mg/L. Meanwhile, the last experiment without PAC adsorption had the remaining DOC in permeate of 2.28 – 2.52 mg/L. This comparison clarifies important role of PAC on removing DOC composition in the feed water. DOC removal efficiency of the PAC + PACl + CMF hybrid system was 76.56 – 82.26 %. This value was very high the DOC removal efficiencies of the other scenarios (without PAC: 63.4 – 69.5%, and without both PAC and PACl: 15 – 31%).

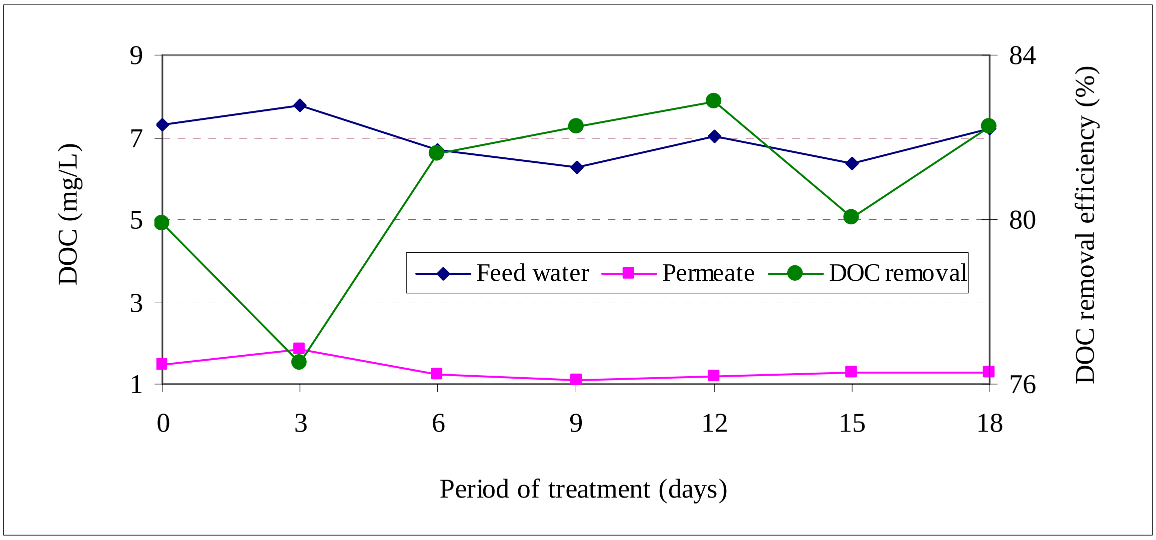


Figure 4.29 DOC and DOC removal rate with period of treatment

d. Performance on micro-particle removal

Figures 4.30 gives the graphical results on removing micro-particle with range size from 5-15 μm. Table B.38, appendix B, presents detailed measurement on the micro-particles.

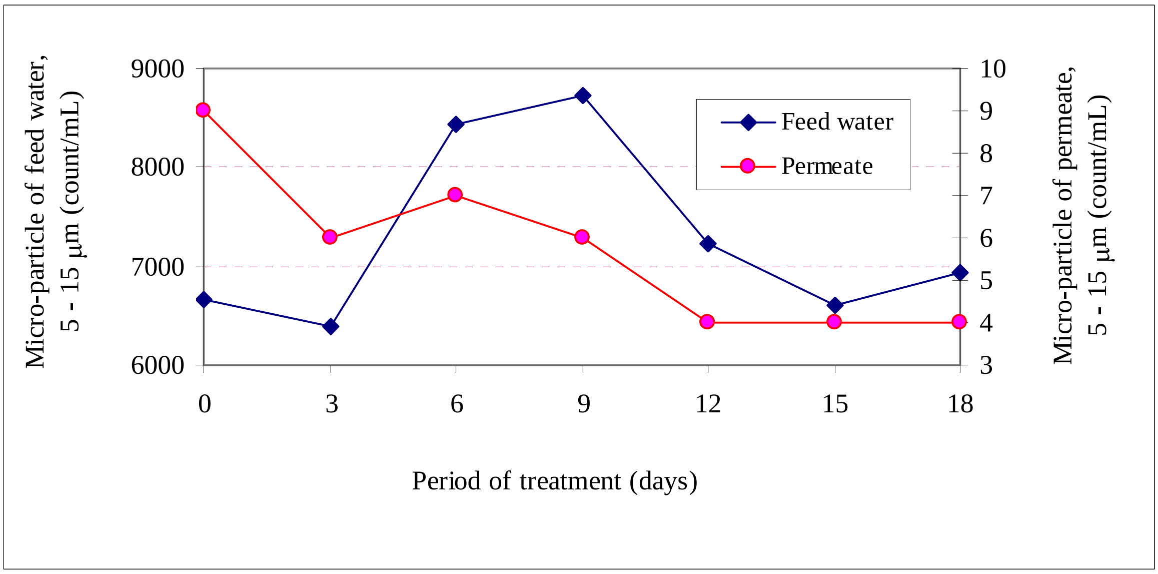


Figure 4.30 Number of micro-particle and period of treatment of the PAC + PACl + CMF hybrid system

Removal efficiency on micro-particles with same range size of Giadia and Crypto was 99.86 - 99.94 %, and log micro-particles removal was 2.87 – 3.26. The feed water had 6607 – 8726 particles/mL, and the permeate had 4 - 9 particles/mL with size of 5 – 15 μm.

The number of the micro-particles of the permeate was decreased with the increase of treatment duration due to accumulation of foulants.

4.3.4 Comparison of results

a. Filtration time, TMP, and TMP recovery

Figure 4.31 presents changes of TMP with filtration time in the different scenarios. Through the graph, the experiment runs with direct ceramic microfiltration had the shortest filtration durations, 7 and 11 days. When combined with pre-treatment by PACl coagulation-flocculation, the hybrid CMF system had longer filtration times, 13 and 19 days. Moreover, pre-treatment by adsorption using PAC helped to increase period of treatment up to 21 days. The results pointed out the advantages of hybrid CMF systems compared with direct CMF system. With the hybrid systems, increase of filtration time and lower TMP increase were found out.

The pre-treatment processes including coagulation-flocculation, and adsorption reduced effectively colloidal-organic matters. Therefore, they helped the hybrid systems to reduce irreversible fouling caused by the colloidal materials inside the membrane pores. These results indicate lower increase of TMP with time of the hybrid scenarios compared with that of other runs of the direct CMF scenario.

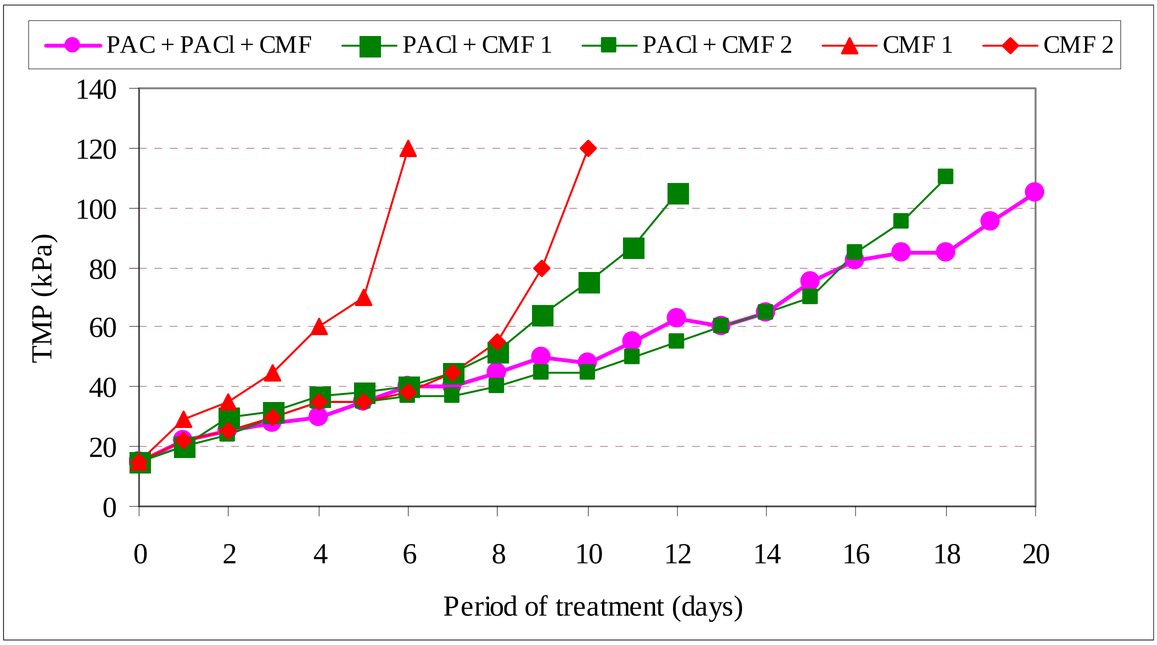


Figure 4.31 Changes of TMP with filtration time

In the direct CMF system, the TMP increased quickly, and the average TMP recovery by each time of backwashing also was the highest. This was caused by high particle content in the feed water and no pretreatment for reducing them prior to the membrane. In contrast, TMP of the hybrid systems increased slowly with time and the average TMP recovery by backwashing was also smaller. The figure 4.31 and 4.32 point out that more hybridized system, lower TMP increase with time and smaller TMP recovery by backwashing also.

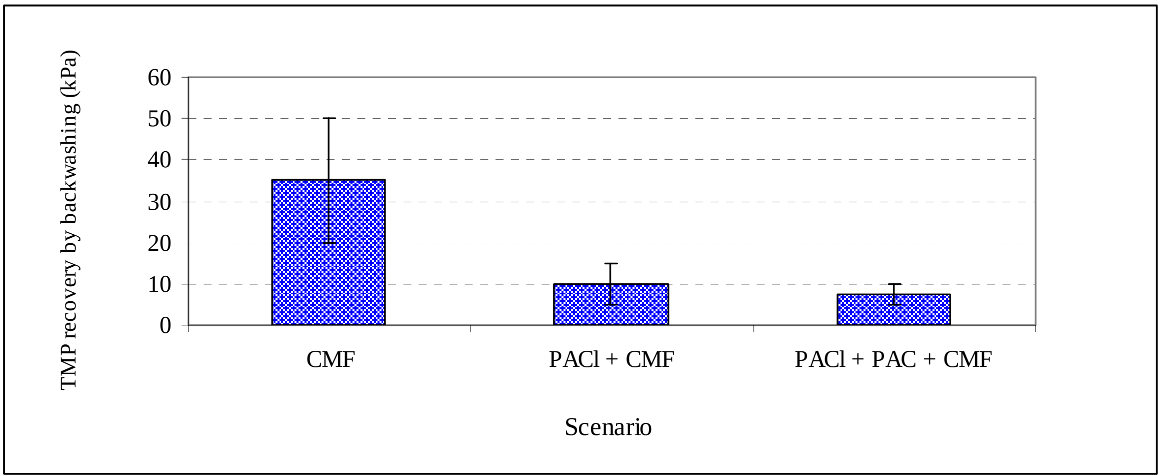


Figure 4.32 Recovery of TMP by each time of backwashing

Table 4.1 presents TMP recovery by steps of chemical cleaning procedure. Based on the results, more enhanced by pre-treatment, the ceramic membrane was cleaned better by the first step using citric acid solution. Citric acid has the function for dissolving inorganic matters existed in both inorganic and inorganic-organic complexes such as ion-organic compound. Pretreated by coagulation-flocculation and adsorption, a notable amount of ions and colloid was constituted into the flocs or adsorbed in the PAC particles. This flocs then were removed effectively by backwashing. These processes reduced ions and colloidal fouling, so the effectiveness of citric acid on cleaning was enhanced with the increase of the pretreatment levels.

Table 4.1 TMP recovery by chemical cleaning

Scenarios	TMP with tap water (kPa) at flux of 50 $L/m^2.h$			
	Before run	After run	After washed by citric acid 1 %	After washed by NaClO 0.3 %
Direct CMF	15	120	60	15
PACl + CMF	15	105	25	15
PAC + PACl + CMF	15	105	20	15

b. Pollutant removal and quality of treated water

Figure 4.33 is the summarized comparison on removing main pollutants of the different scenarios, and table B.39, appendix B, presents detailed comparative results. In both direct CMF and hybrid systems, total coliform, fecal coliform, and TSS were removed completely in the steady states of the operations. With the pore size of 0.1 μm, the ceramic membrane was very attractive to remove the bacteria and TSS. Moreover, adding NaClO into the filtrate tank for enhancing backwashing also contributed to the disinfection of the bacteria in the filtrate if any.

Figure 4.33 also clarified important roles of the pre-treatment processes. Without pre-treatment, the direct CMF system had lower pollutants removal efficiencies. Both TOC and DOC were not removed well by the direct filtration, less than 25%. But in the hybrid systems, they were removed more than 60% by coagulation-floccualtion combined with the CMF. In the other hand, PAC adsorption also played an important role through increasing significantly pollutants removal efficiencies including DOC, more than 80 %.

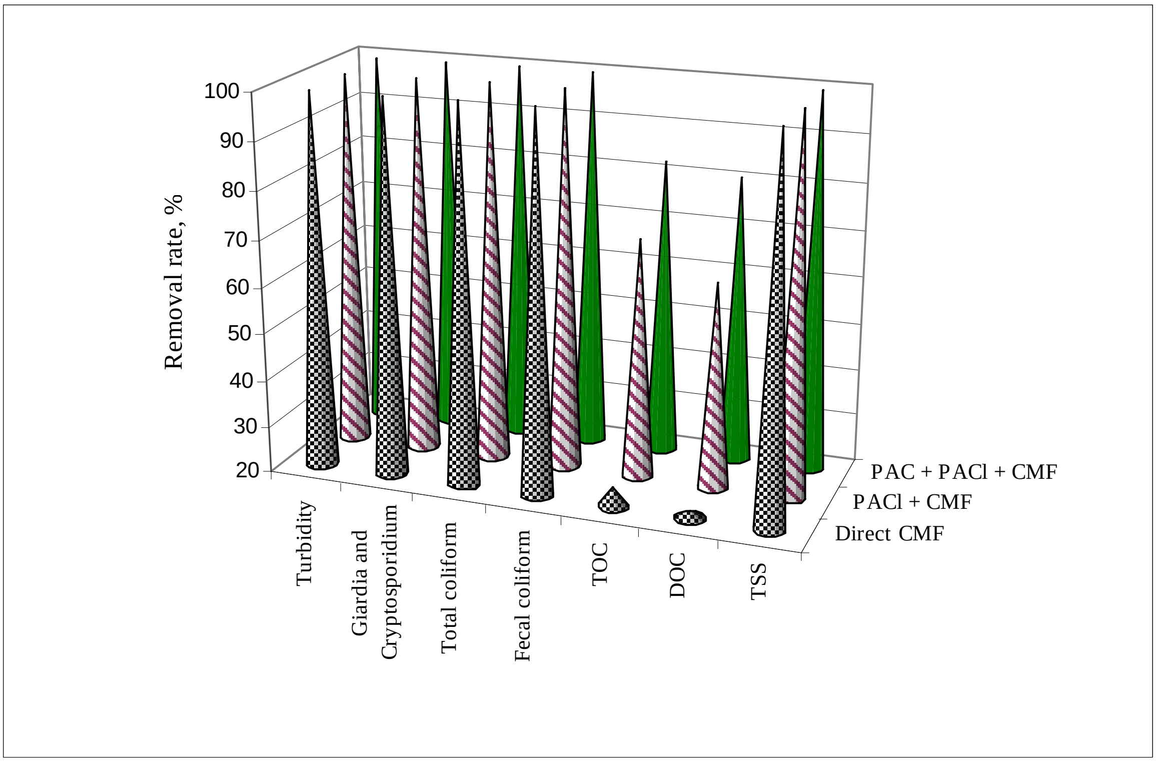


Figure 4.33 Comparison among scenarios on removals of major pollutants

Two currently available standard systems were used for evaluation of the treated water. They are given in table 4.2. From the table, compliances were achieved at all scenarios if the permeate is used for domestic supply water in Vietnam, a developing country located on Mekong river delta. For drinking purposes in the USA, only the permeate of the hybrid system that all PAC, PACl, and CMF were constituted complied fully the standard. With other systems including direct CMF and hybrid CMF enhanced by PACl, permeate also met the USA standard for almost all of parameters except percentage requirement on Giardia and Cryptosporidium removals.

Table 4.2 Quality of treated water and standards

Parameters	Unit	Permeate of scenario			Standard	
		Direct CMF	PACl + CMF	PAC + PACl + CMF	Vietnam[a]	USA[b]
pH	-	7.5 – 8.1	6.5 - 7	6.8 – 7.2	6.5 – 8.5	6.5 – 8.5
Turbidity	NTU	0.066	0.064	0.055	5	1
Giardia and Cryptosporidium	% removed	99.61	99.77	99.92	-	99.9
Total coliform	MPN/100mL	0	0	0	2.2	0
Fecal coliform	MPN/100mL	0	0	0	0	0
TDS	mg/L	312	214	204	1000	500
Total Fe	mg/L	0.06	0.01	ND	0.5	0.3
Total Mn	mg/L	0.01	ND	ND	0.5	0.05
NH_3 - N	mg/L	0.49	0.03	ND	3	-

[a] *Vietnamese national standards TCVN 5502:2003 - Domestic supply water*
[b] *National secondary drinking water standards, EPA, USA- The maximum permissible level of a contaminant in water which is delivered to any user of a public water system*

4.4 Experimental runs with municipal wastewater

In these experiments, AIT wastewater was used as a municipal wastewater source, which had the seriously polluted characteristics presented in the table 3.3. Therefore, pre-sedimentation tank were added to reduce TSS of the feed water that made rapid clogging to the membrane. In addition, operational conditions for experiments also were adjusted in comparison with the last experiments with surface water. Backwashing interval of the CFM system used for wastewater treatment was 40 minutes instead of 2 hours as used for surface water treatment. NaClO solution with dosage of 15 mg/L also was used for enhancement backwashing process. The experimental results are summarized as the followings.

4.4.1 Scenario 1: Direct ceramic microfiltration

a. Transmembrane pressure (TMP)

Figure 4.34 presents graphical results on TMP and turbidity changing tendencies of the scenario, and table B.41, appendix B, shows detailed results.

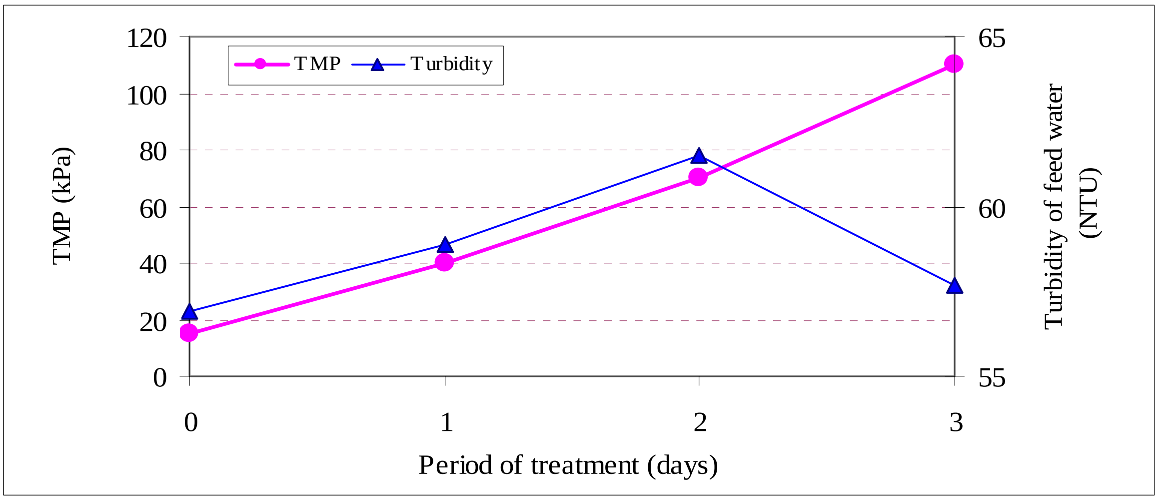


Figure 4.34 Changes of TMP and turbidity of feed water with period of treatment

The fouling with TMP of 120 kPa was achieved on the 4^{th} day of the treatmento. Although turbidity of feed water was kept stably from 56.9 to 61.5 NTU, the TMP of the system was increased rapidly day by day. Compared with the same scenario used for treatment of surface water (turbidity of 7.06-7.62 NTU, BW interval of 2 hours and filtration time of 11 days), the experiment had much shorter filtration time although BW interval was shortened down to 40 mintues. This pointed out clearly that in wastewater treatment, the filtration cycle for getting fouling is much smaller than that in surface water treatment.

TPM recovery by each time of backwashing was 10 to 15 kPa. TMP recoveries by chemical cleaning using acid citric 1% solution and NaClO 0.3% solution respectively were 45 kPa (TMP was reduced from 110 kPa down to 65 Kpa after 24 hours of soaking) and 50 kPa (TMP was reduced from 65 Kpa to 15 Kpa after 24hours of soaking), respectively.

b. Performance of the system in terms of turbidity removal

Figure 4.35 presents graphical changes of turbidities with filtration time. For more detailed data, refer to table B.41, appendix B.

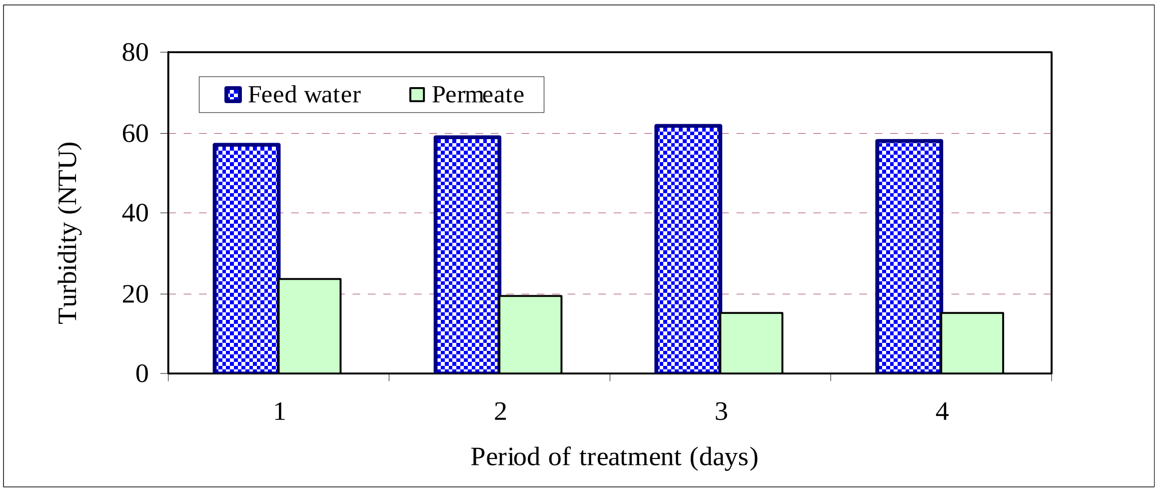


Figure 4.35 Changes of turbidity of feed water and permeate with time

Due to the accumulation of foulants, a steady state was achieved on the 3rd day of the operation. In this case, turbidity of permeate was kept constantly around 15 NTU with the turbidity removal efficiency of 75 %. This efficiency was lower than that of the surface water treatment. The phenomenon can be explained by the higher colloidal fraction in wastewater (refer to the DOC concentrations on the tables 3.2 and 3.3). In addition, a part of DOC fraction passed to pores of ceramic membrane without pre-treatment such as coagulation or adsorption.

d. Performance on micro-particle removal

Figures 4.36 gives graphical results on removing micro-particles within the size range of 5 to 15 μm (refer to table B.42, appendix B).

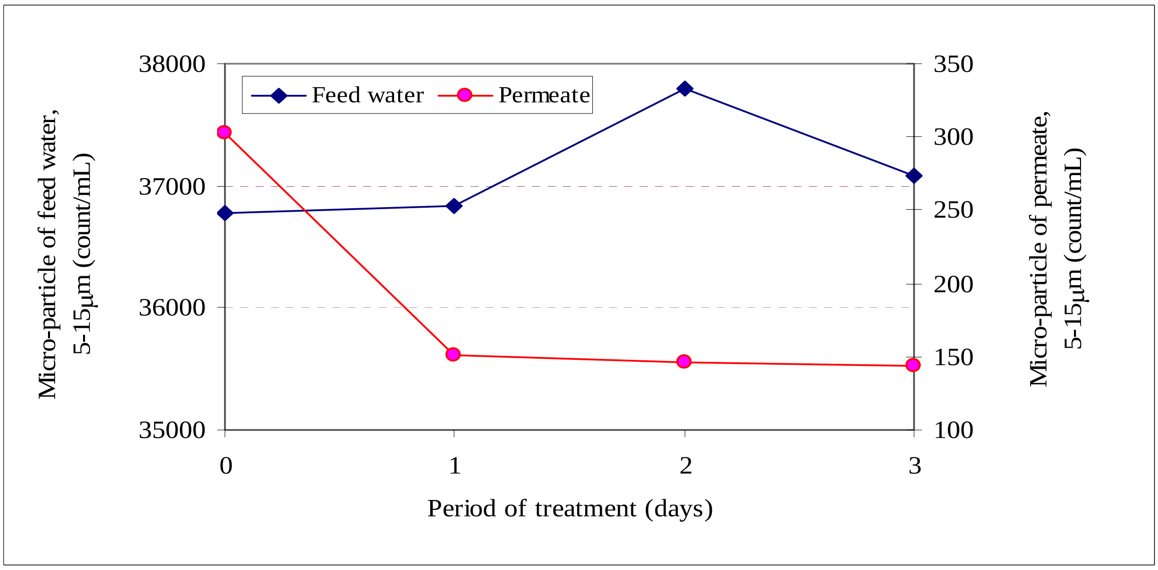


Figure 4.36 Number of micro-particle and period of treatment of the direct CMF system

Micro-particles removal efficiency (Giadia and Crypto removal efficicncy) was 99.17 - 99.61 %, and log micro-particles removal was 2.08 – 2.41. The feed water had 36780 – 37080 particles/mL, and the permeate had 144-303 particles/mL with size of 5 – 15 μm. When the operation was steady, the micro-particles removal was stable with the removal efficiency of 99.61 % and the permeate had 144 particles/mL.

c. Performance in removing other pollutants: TOC, BOD, COD, total coliform, and fecal colifrom.

Figure 4.37 summarizes performance of the direct CMF system on removing major pollutants when the system was operated at the steady state. Table B.43, appendix B, presents detailed analytical results.

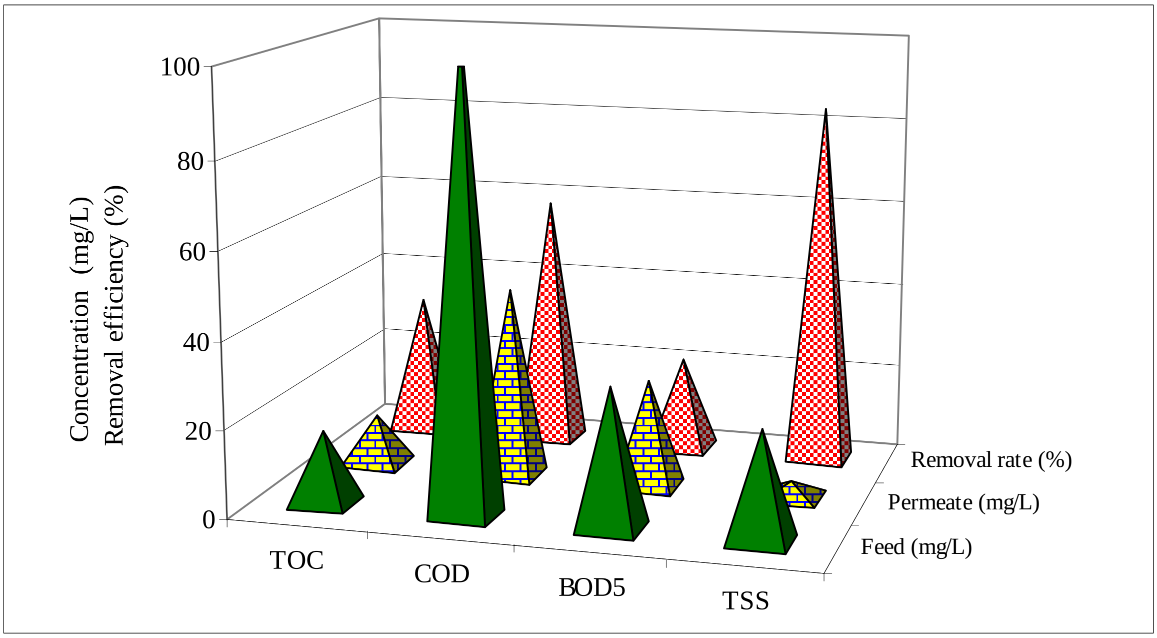


Figure 4.37 Removals of pollutants by the direct CMF system

TOC of the permeate was 11.4 mg/L, and smaller than the value of the feed water, 16.9 mg/L. TOC removal efficiency was 32.5 %. Compared with the direct CMF for surface water treatment, TOC removal of 28.3 %, the higher TOC removal efficiency was achieved in the treatment of municipal wastewater. This result can be explained through the difference between TSS of wastewater and surface water. After pre-treated by mesh screen and pre-sedimentation tank, the wastewater had TSS of 25 mg/L (figure 4.38). This value was higher than TSS of the surface (table 3.2). Once organic TSS was removed, TOC also was removed. Therefore, the TOC removal efficiency of wastewater reclamation was higher that of surface water treatment.

COD of the feed water was 106 mg/L. The treated wastewater had 44 mg COD/L with the removal efficiency of the system of 58.5 %. BOD_5 removal efficiency was 21.9 %, with BOD_5 of the feed water and the permeate was 32 mg/L and 25 mg/L respectively.

Total coliform and fecal coliform in feed water was $4.4*10^6$ MPN/100mL and $3.1*10^6$ MPN/100mL respectively. Both total colifrom and fecal coliform of permeate were none-detected. This means the direct CMF removed completely total coliform and fecal coliform.

4.4.2 Scenario 2: Coagulation-flocculation and CMF

a. Transmembrane pressure (TMP)

Figure 4.38 presents graphical results on TMP and turbidity changing tendencies of the scenario. Table B.45, appendix B, shows detailed results.

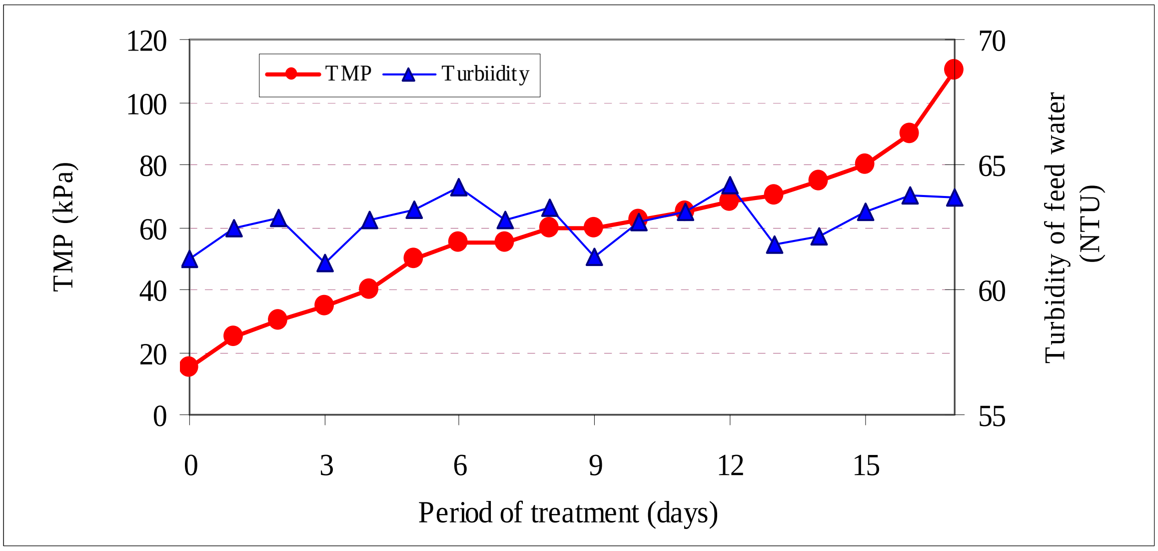


Figure 4.38 Changes of TMP and turbidity of feed water with period of treatment

In the experiment, a fouling with TMP of 110 kPa was achieved on the 15th day of the operation. Compared with the last experimental run without coagulation that had only 4 days of a filtration cycle, the run with enhancement by coagulation-flocculation using PACl had a much longer filtration time. Considering the feed water, after pre-sedimentation tank, it had the almost same characteristics including turbidity compared with that used for the last run without coagulation. Therefore, the important role of primary coagulation-flocculation on prolonging filtration time was also confirmed strongly again.

TMP did not increase rapidly as it did in the scenario without coagulation-flocculation. Each time of backwashing TMP recovery was from 5 to 10 kPa. Total TMP recovery rate by chemical cleaning was 100 %, with 75 kPa and 25 kPa recovered by acid citric solution 1% and by NaClO solution 0.3%, respectively.

b. Performance of the system in terms of turbidity removal

Figure 4.39 gives graphical changes of turbidities with filtration time. Table B.45, appendix B, points out analytical results and performance of the hybrid system in removing turbidity.

Turbidity of the feed water was fluctuated slightly from 60 to 65 NTU. On the 1st day of the treatment, turbidity of permeate was 3.68 NTU. This value was decreased with time to 1.12 and 0.43 NTU on the 2nd and 3rd day due to foulants accumulation. A steady state in term of turbidity removal was started on the 4th day. In this state, turbidity of permeate was 0.18 - 0.23 NTU. Compared with the run without coagulation-flocculation, permeate had turbidity of 15 NTU, the PACl + PAC run had much higher quality of permeate in terms of turbidity. The turbidity removal efficiency of the hybrid scenario was 99.65%.

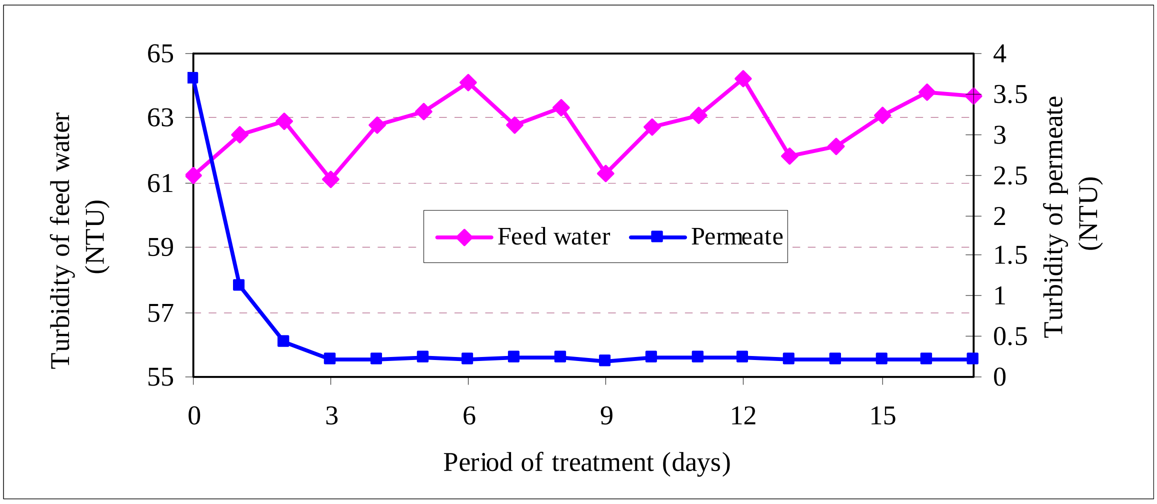


Figure 4.39 Changes of turbidity of feed water and permeate with time

d. Performance on micro-particle removal

Figures 4.40 presents results on removing micro-particle (Giardia and Cryptoporidium) of the hybrid CMF system. Table B.46, appendix B, gives detailed micro-particles measurement of the experiment.

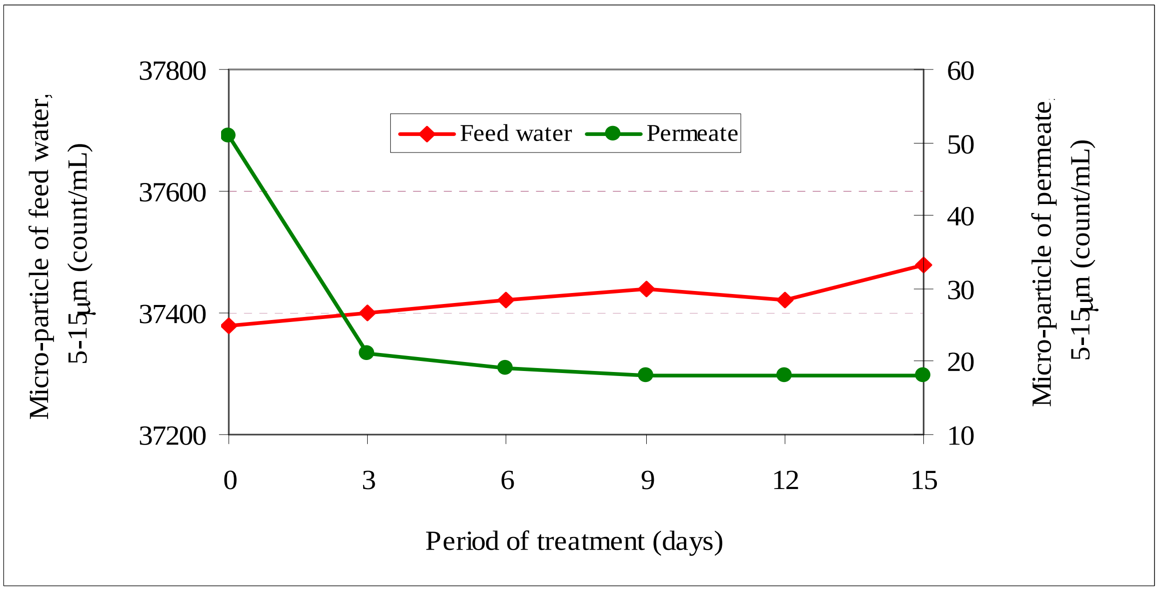


Figure 4.40 Number of micro-particle and period of treatment of the PACl + CMF hybrid system

Compared with the last experiment on direct CMF, this scenario had a higher performance in removing micro-particles. Removal efficiency on micro-particles with same range size of Giadia and Crypto was 99.86 - 99.95 %. Log micro-particle removal was 2.86 – 3.32. The feed water had 37380 – 37480 particles/mL, and permeate had 18 - 51 particles/mL with size of 5 – 15 μm (18 particles/mL in the steady state). The number of the micro-particles of permeate was decreased with the increase of period of treatment due to accumulation of foulants. In the steady state, the average removal efficiency and log removal was 99.95% and 3.2 respectively.

c. Performance in removing other pollutants: TOC, BOD, COD, total coliform, and fecal colifrom.

Figures 4.41 gives summarized results on performance of the hybrid PACl + CMF system on removing major pollutants when it was operated in steady state. Table B.48, appendix B, presents detailed analytical results.

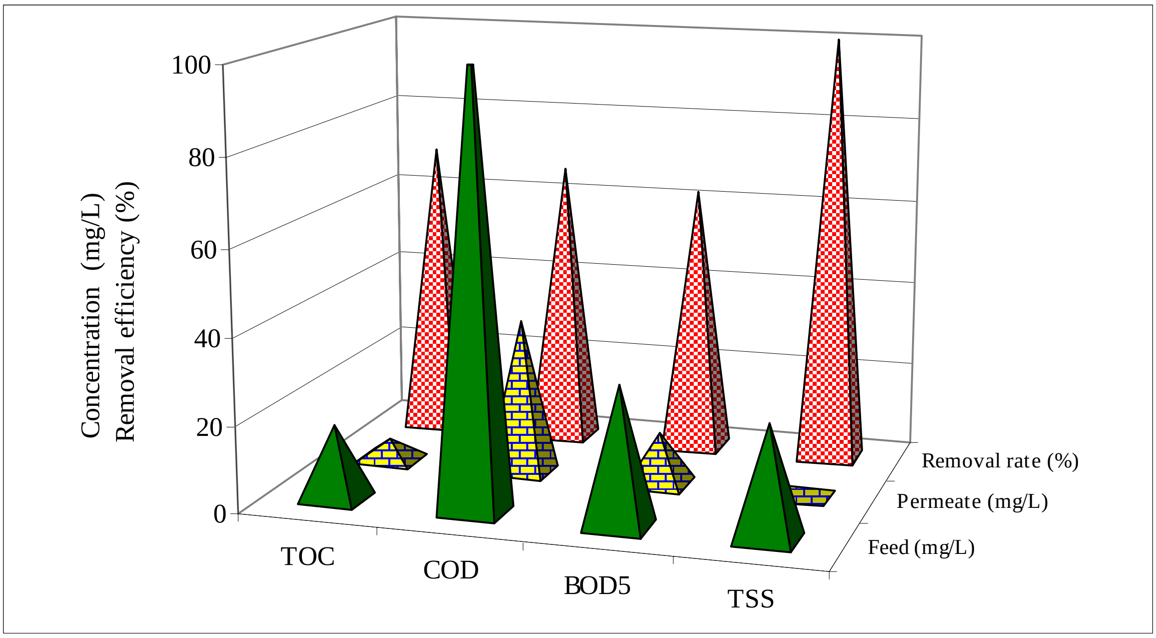


Figure 4.41 Removals of pollutants by the PACl + CMF hybrid system

Average TOC of the feed water was 17.3 mg/L, and this of the permeate was 5.22 mg/L. TOC removal efficiency was 68.83 % and very high when compared with the direct CMF (TOC removal efficiency of 32.5 % only). This result presents the important role of coagulation-flocculation for enhancing the ceramic membrane on TOC removal.

COD of feed water was 108 mg/L and this of permeate was 44 mg COD/L present COD removal rate of the hybrid system of 66.67%, slightly higher than the removal of the direct CMF system, 58.5 %. BOD removal rate of 62.5 % also was higher than BOD removal rate of the last scenario without coagulation-flocculation, 21.9 %. BOD of feed water and permeate was 32 mg/L and 12 mg/L, respectively.

Total coliform and fecal coliform of feed water was $4.4*10^6$ MPN/100mL and $3.1*10^6$ MPN/100mL respectively. Both total coliform and fecal coliform of permeate were none-detected, so the removal rate of the hybrid system on these microbial pathogens was 100% .

4.4.3 Comparison of results

a. Filtration time, TMP, and TMP recovery

Figure 4.42 presents changes of TMP in different scenarios. Through the graph, the experiments with direct ceramic microfiltration had the shortest filtration filtration, only 4 days of a cycle. When combined with pre-treatment by PACl coagulation-flocculation, the hybrid CMF system had a longer filtration time, 18 days. The results pointed out the advantage of hybrid CMF systems in terms of prolonging filtration time compared with direct CMF system. The longer filtration cycle also increased treated water production and saved chemical utilization for the chemical cleaning.

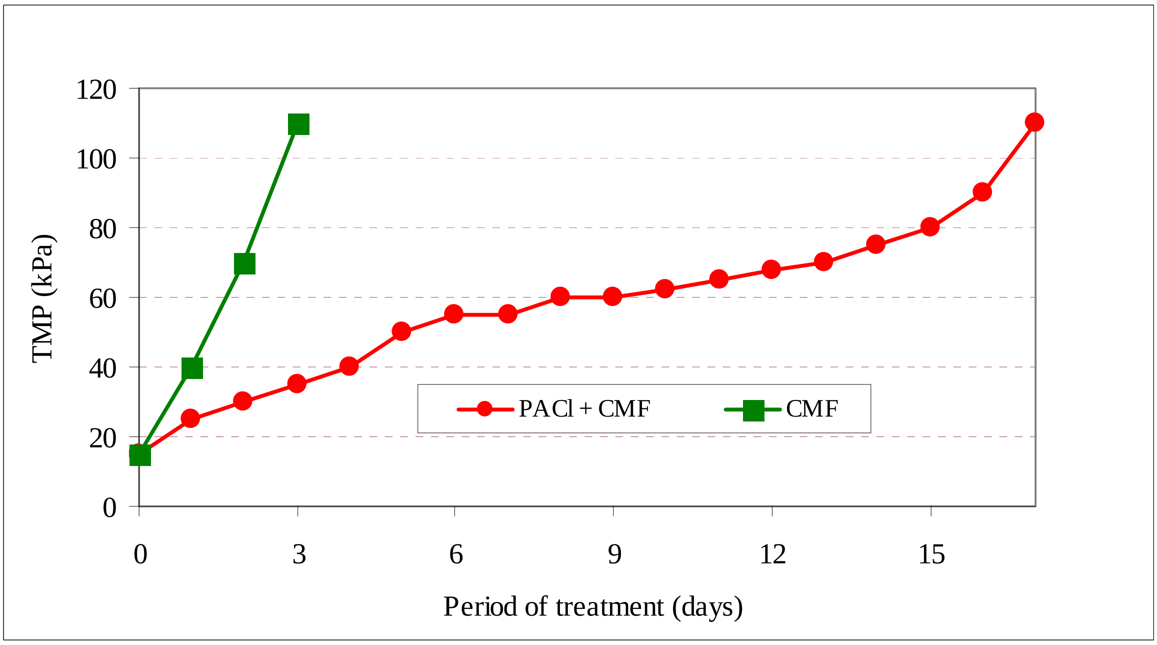


Figure 4.42 Changes of TMP with filtration time

The pre-treatment processes using coagulation-flocculation reduced effectively colloidal-organic matters. Therfore it helped the hybrid systems to reduce irreversible fouling caused by the colloidal materials inside the membrane pores. These results indicate lower TMP increase with time of the hybrid scenario compared with the direct CMF scenario.

In the direct CMF system, the TMP increased quickly. The average recovered TMP by each time of backwashing also was high. In contrast, TMP of hybrid system increased more slowly with time, and the average TMP recovery of backwashing was also smaller. The figures 4.42 and 4.43 tell that more hybridized system, lower TMP increase with time and smaller TMP recovery by backwashing as well.

TMP recovered by steps of chemical cleaning procedure is given in table 4.3. Based on the data, when enhanced by pre-treatment, the ceramic membrane was cleaned better by the first cleaning step using citric acid solution.

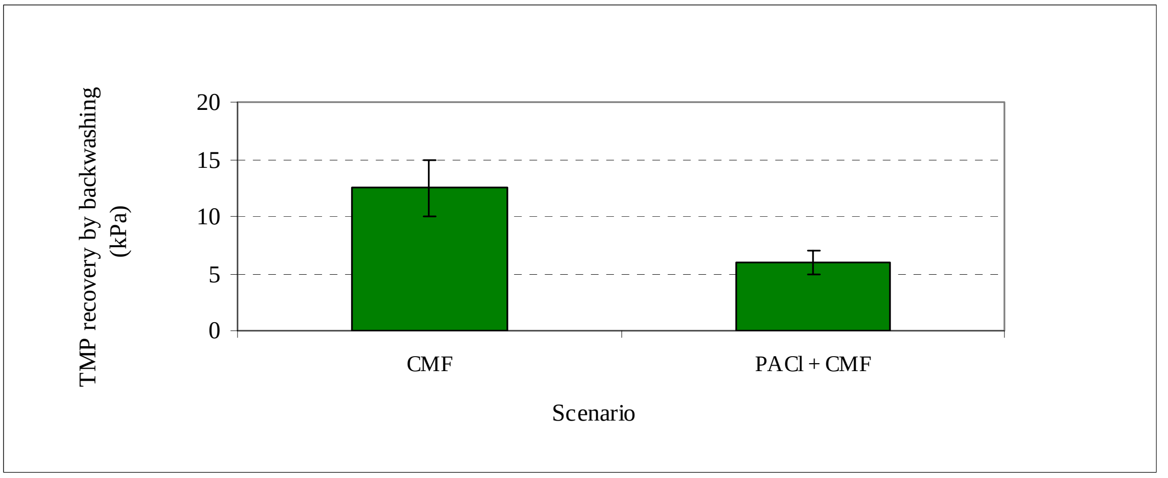


Figure 4.43 Recovery of TMP by each time of backwashing

Table 4.3 TMP recovery by chemical cleaning

Scenarios	TMP with tap water (kPa) at flux of 50 $L/m^2.h$			
	Before run	After run	After washed by citric acid 1 %	After washed by NaClO 0.3 %
Direct CMF	15	110	65	15
Hybrid PACl + CMF	15	110	40	15

b. Pollutant removal and quality of treated water

Figure 4.44 is summarized comparison on removing main pollutants of the two different scenarios. Table B.49, appendix B, presents detailed comparative results.

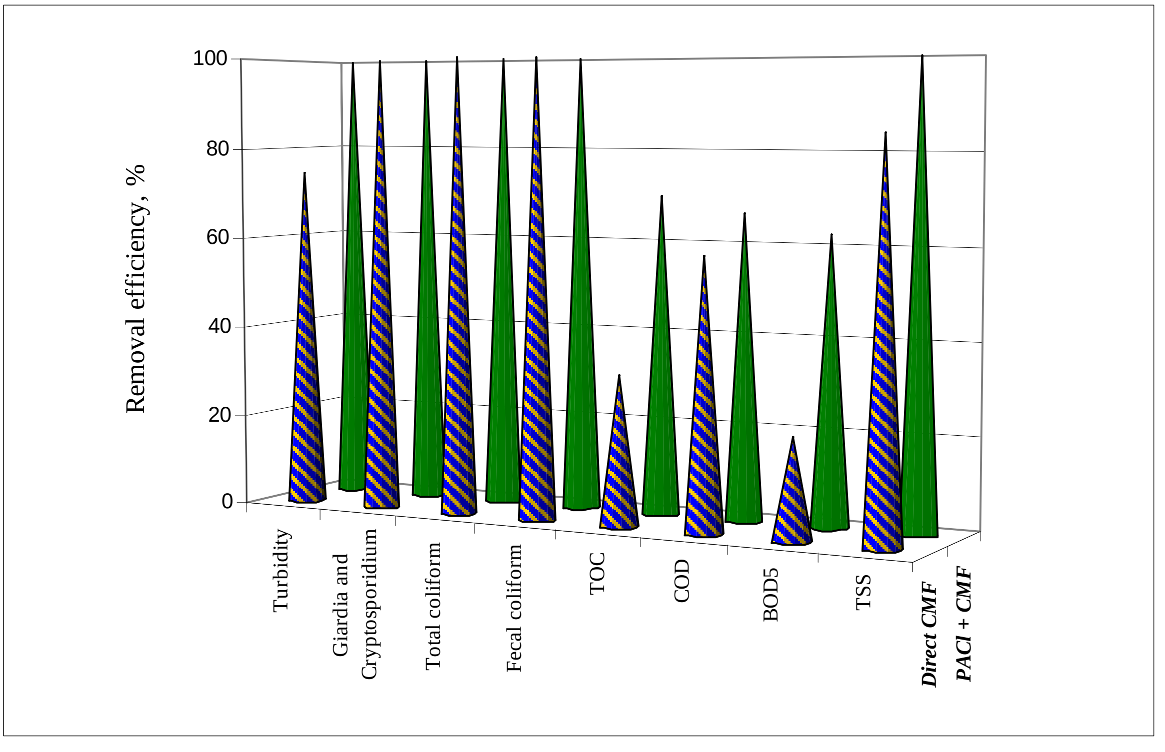


Figure 4.44 Comparison among scenarios on removals of major pollutants

In both the direct CMF and hybrid systems, total coliform, fecal coliform were removed completely. With the pore size of 0.1 μm, the ceramic membrane was very attractive to remove the bacteria. In addition, adding NaClO into the filtrate tank for enhancing backwashing also served as a disinfection factor for killing the bacteria.

The comparison also clarified important roles of the pre-treatment by the coagulation-flocculation. Without the pre-treatment, the direct CMF system had lower efficiency on removing pollutants. TOC, COD, and BOD_5 were removed better by the hybrid CMF system compared with the direct filtration. However, removals of both the two scenarios on these parameters were not high. This can be understood that the soluble form of organic carbon could not be treated by only the physico-chemical processes combined with the membrane.

Some currently available standards used for investigation of potentials of the treated wastewater for reuse activities are given in table 4.4.

With direct microfiltration, turbidity, BOD_5, and COD could not meet any the reuse standards except Vietnammese standards for irrigation. Other remaining parameters including pH, TSS, TDS, free Cl_2 residual, Fe, Mn , total coliform, and fecal coliform complied fully or partly requirements for reuse activities in the all given countries. These reuse activities are irrigation, toilet flushing, sprinkling, and landscape.

With the hybrid CMF system in which PACl coagulation-flocculation was combined with the CMF, the improved quality of treated wastewater become more suitable and compliable the reuse standards. The permeate completely met all Vietnamese, Taipei and Chinese national standards for irrigation, and reclaimed water standard in Florida, USA. Further more, this permeate also complied other standards for reuse activities of other countries including Japan, Italy, Korea, and etc.

In conclusion, there were great potentials for reusing treated municipal wastewater including irrigation, sprinkling, and etc. The hybrid ceramic microfiltration system presented attractive and important roles in treatment of the wastewater for reuse activities. Based on the achieved results in terms of standard compliance, technical and economical aspects, the research with municipal wastewater was stopped after the experiment on PACl + CMF hybrid systems.

Table 4.4 Quality of treated wastewater and standards for reusing activities

Parameters	Unit	Permeate of scenario		Standards											
		Direct CMF	PACl + CMF	Vietnam[a]	Italy[b]	Turkey[c]	China[d]			Korea [e]			Taiwan[f]	Japan[g]	EPA[h]
							d1	d2	d3	e1	e2	e3			
pH	-	6.8 – 7.8	6.3 – 7.2	5.5 – 8.5	6.0–9.5	6.5–8.5	-	-	-	-	-	-	5.5-9	5.8-9.	6-8.5
Turbidity	NTU	15	0.21	-	-	-	<5	<20	<5	<5	<5	<10	-	≤ 5	-
TSS	mg/L	4	0	-	10	30	-	-	-	-	-	-	250	≤ 5	5
TDS	mg/L	344	238	400	-	-	<1500	<1000	<1000		-	-	-		-
BOD_5	mg/L	25	12	-	20	25–50	<10	<20	<10	<10	<10	<10	-	≤ 10	20
COD	mg/L	44	36	-	100	-	-	-	-	-	-	-	-	≤ 40	-
Total Mn	mg/L	0.08	0.03	-	0.2	-	0.1	-	0.1	-	-	-	2	-	-
Total Fe	mg/L	0.03	ND	-	2.0	-	0.3	-	0.3	-	-	-	-	-	-
Chlorine residual	mg/L	0.05	2.05	-	0.2	-	> 1	-	-	-	-	-	-	-	> 1
Total coliform	MPN/100mL	ND	ND	200	-	-	-	-		-	-	-	-	-	ND
Fecal coliform	MPN/100mL	ND	ND	200	10 (CFU/100mL)	2–20 (CFU/100mL)	3	3	3	-	-	-	-	ND	-

[a] Vietnamese national standards TCVN 6773:2000 - Irrigation water − Quality requirements (Vietnam Environmental Protection Agency, 2008)
[b] Italian standards (D.M 185/03, 2003) for reclaimed wastewater (Cirelli et al, 2008)
[c] National irrigation water quality standards of Turkey, class: satisfactory (Alaton et al, 2007).
[d] Chinese national water quality standards for reclamation (GB/T18920,T18921-2002): d1) Toilet flushing, d2) Irrigation of green, d3) Washing purpose. (Ernst et al, 2007).
[e] Korean national standard for water reuse: e1) For toilet flushing, e2) For sprinkling, e3) For landscape. (Ahn & Song, 1999).
[f] Water quality requirements for agricultural irrigation in Taiwan, Long-term usage: continuously used for all types of soil. (Lin & Cheng, 2001).
[g] Japanese standard for toilet flushing purpose (Asian Science and Technology Seminar by Japan Science and Technology Agency. 10th March,2008, Bangkok, Thailand)
[h] Guidelines for Water Reuse-EPA/625/R-04/108 September 2004. Unrestricted urban reuse in Florida including use of reclaimed water for irrigation of residential lawns, golf courses, cemeteries, parks, playgrounds, schoolyards, highway medians, and other public access areas (EPA, 2004).

4.5 Operational problems generated from the dead-end CMF system and solutions

Operational problems during treatment of the surface water and municipal wastewater were investigated in the study with the dead-end filtration. The problems were generated in direct CMF or hybrid ceramic microfiltration systems in the tropical condition. Preventative solutions for avoiding the operational problems were found out based on experience during the study. However, in some urgent cases that problems still were occurred, successful solutions were investigated and adopted to overcome them. Table 4.5 presents briefly operational problems, preventative solutions, and usefully applied solutions for the dead-end CMF system.

Table 4.5 Operational problems and solutions of the dead-end CMF system

Problems	Sign	Preventative solutions	Overcoming solutions
During power failure	The system was stopped and could not automatically re-started	Need to frequently check the system	Re-start system manually on PLC
Too low level of water in the storage tank	The system was stopped and "low level" lamp on PLC is on	Need to frequently check the system	Feed raw water to the storage tank, increase capacity of the first raw water pump before storage tank until appearing overflow in drainage pipe.
Clogging of feed pump (piston pump)	The system was stopped and "overload" lamp on PLC is on	Considering quality of feed water and checking frequently the system	Stopping operation, plugging out electricity, and cleaning the piston pump using tap water and washing liquid.
Piston pump has sound	Big sound generated form the piston pump	Checking carefully the pump whether it was heated up.	Taking out and filling machine oil into the suitable part of the pump.
Damage of PG due to TMP was increased too rapidly more than maximum level.	PG was damaged or not indicating exactly TMP	Considering quality of feed water and status of pre-treatment such as mesh screen and pre-sedimentation tank	Cleaning and setting up pre-treatment system to reduce TSS of feed water as high as possible. Changing PG.
Membrane was fouled too rapidly	TMP was increased quickly before BW	Considering quality of feed water and status of pre-treatment such as mesh screen and pre-sedimentation tank	Shortening BW interval and increase NaClO dosage for EBW

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

In this study, the influences of pre-treatment processes on treatment of SW and MWW of ceramic membrane filtration were investigated on a series of scenarios in pilot scale. The membrane was operated at constant flux of 50 $L/m^2.h$ in all the experimental runs. It was found out that pollutants removal efficiency and performance of a hybrid CMF system would differ depending on the pre-treatment process and operational conditions.

The research on treatment of surface water was conducted with the highly organic surface water source. Coagulation-flocculation with poly aluminum chloride (PACl) was optimized for the hybrid system at a coagulant dose of 2.0 mg Al/L. With the coagulation-flocculation, the hybrid CMF system removed completely TSS, total coliform, and fecal coliform. In addition, 99.8% of Crytoporidium and Giadia, 99 % of turbidity, 70.8 % of TOC and 63.5 % of influent DOC were also pollutants removal efficiencies of the hybrid CMF system.

Furthermore, optimum conditions in combination between adsorption and coagulation-flocculation were found out to enhance the ceramic microfiltration. With optimized doses of 20 mg/L powder activated carbon (PAC) and 2 mg Al/L PACl, the hybrid PAC + PACl + CMF system removed completely TSS, total coliform, and fecal coliform. On the other hand, the highest efficiencies on removing other pollutants also were achieved in this scenario. More than 99 %, 83 %, and 81 % are the removal efficiencies of Crytoporidium and Giadia, TOC, and DOC of the influent, respectively.

Reduction of fouling, higher filtration time and more effectively chemical cleaning are also investigated in the hybrid CMF systems. With direct CMF system, the time duration of a filtration cycle that was needed to conduct chemical cleaning was only 7 - 11 days. The filtration time was prolonged in hybrid CMF systems, 13 – 19 days for PAC + CMF and 21 days for PAC + PACl + CMF. The highest quality of permeate was found out in the PAC + PACl + CMF hybrid system and it complies all requirements of the EPA's drinking water standard, especially on Giardia and Cryptoporidium removal.

In reclamation of wastewater aspect, the research focused on investigation of reuse potentials of municipal wastewater. Pre-treatments also influenced strongly to the operation of ceramic filtration and quality of treated wastewater. Performance of the ceramic membrane was improved notably when the CMF was combined with PACl coagulation-flocculation. In the hybrid system, all total coliform, fecal coliform and TSS of the influent were removed completely, 100 %. COD and BOD_5 removal efficiencies were 70 % and 63 %, respectively.

In comparisons with national reclaimed wastewater standards, reuse applications were investigated for the treated MWW in the direct and hybrid CMF systems. The treated MWW could be reused for toilet flushing, sprinkling, and irrigation purposes. Irrigations activities are the most suitable applications due to the rich nutrient budget of the permeates.

The direct CMF for the MWWT had a filtration cycle of 4 days only. But in the hybrid CMF system, the time duration of a filtration cycle would be increased up to 18 days. The prolonged filtration cycle helped to increase amount of treated WW production, reduce chemical utilization for chemical cleaning and increase life time of the membrane.

In the both SWT and MWWT, lower TMP recovery by each time of backwashing and lower TMP increase were found out in the hybrid systems. Chemical cleaning by citric acid solution also was more effective with the hybrid CMF systems.

In conclusion, ceramic membrane has been investigated many its unique advantages in water and wastewater treatment in this research. Moreover, the study evaluated and investigated performances of different CMF systems. Technical advantages such as highly automatic operation and higher period of treatment are also observed during the experiments. It was investigated that the more enhanced hybrid systems, the higher qualities and more satisfied use activities of the permeates.

5.2 Recommendations for future works

Due to limitations of time budget and currently analytical equipment, some interesting works could not be conducted in the thesis study. Therefore, the followings are proposed on-going researches for the CMF system:

1. Researches on hybrid Ozonation + PACl coagulation + CMF system in which the CMF will be enhanced by pre-ozonation process prior to the coagulation process:

Ozonation will serve as both pre-disinfection and physical processes for enhancement of coagulation. As a pre-disinfection, the ozonation helps to reduce bio-fouling by killing bacteria. In addition, the process also helps to disinfect protozoan parasites, Cryptoporidium and Giadia, especially their oocyst and cyst, that are very resistant to other conventional disinfectants.

In the other hand, the pre-ozonation process should also be considered in terms of enhancement for the PACl coagulation process. Ozonation will reduce Zeta potential of raw water leading to a reduction of optimum coagulant dosage needed for the coagulation. However, DOC concentration will be increased with the increase of ozone dosage due to the breaking down of organic materials caused by ozone. Once DOC concentration is too high, it will not be removed completely by coagulation and flocculation. The remained DOC then will go though membrane pores and cause high DOC content in permeate. Therefore, an optimum ozone dosage has to be considered carefully to enhance coagulation and also limit DOC produced.

In short, an optimum ozone dosage should be found by doing ozonation test and jar-test. Analytical parameters for the tests should be pH, zeta potential, and DOC.

2. A practical research with a real river water source in Thailand.

In the thesis, AIT pond water was used as a surface water source. Actually, this water was created by the combination of rain water and secondary effluent (effluent of oxidation ponds) of AIT WWT plant. Therefore, compositions of the AIT pond water can be different from those of real river water. A case study in Thailand is a very interesting research direction. Certainly a case study will contribute attractively to transferring the CMF technology for SWT in Thailand and other adjacent countries in the Mekong river delta.

To conduct the research, the CMF pilot should be moved to a SWT plant nearly from an obtain river. Moreover, it should sure that the laboratory conditions where placing the pilot are good enough for sampling, preservation, and quick measurements of some parameters.

3. Researches on potentials of reusing the secondary effluent of the AIT WWT plant.

The effluent of AIT oxidation pond has a better quality compared with this of AIT sewer. Therefore, treatment of the effluent promises many other reusing activities even portabilities of treated water.

The research can be conducted in the same scenarios which were implemented with the AIT Pond water: direct microfiltration and hybrid CMF systems including PAC adsorption and PACl coagulation-flocculation.

4. Researches on functions of the PAC or ozonation in removing organic toxic substances in surface water.

Although the PAC adsorption was used in the thesis study, toxic organic pollutants such as herbicides and fertilizers were not subjected and researched. Actually, the PAC can remove effectively the toxic substances existing in many surface water sources affected by agricultural activities. Therefore, researches on effects of the PAC can be clarified in terms of toxic chemicals affecting to health safety aspects of drinking water.

Furthermore, ozonation also is an attractive solution for removing the toxic substances, especially aromatic organics. Ozone is a strong oxidant, it breaks well persistent organics. When combing the pre-ozonation with the CMF system, it is very interesting to point out important roles of the hybrid system for treatment of surface water sources contaminated by POPs from agricultural activities.

Based on results of the PAC or ozonation combined with CMF, a most suitable solution will be selected for a case study with specific characteristics of raw water (in the Mekong delta, for example).

5. A comparative study between the hybrid CMF and conventional treatment systems in pilot scale.

Although the CMF is an advanced technology, it almost has been being researched in pilot scales. In the world, only some developed countries such as Japan and Turkey transferred it to practical cases. In the Southeast region, there is no water treatment plant built by the technology. Therefore, a comparative study in terms of technical and economic aspects should be conducted.

A pilot modeling a conventional surface water treatment plant can be set-up including bar screen, coagulation, flocculation, sedimentation, sand filtration, and post disinfection by chlorine. The treatment of same raw water will be conducted in parallel with that of the hybrid CMF system.

Comparisons among the conventional pilot and differently operational scenarios of the hybrid CMF system will be pointed out in terms of economy (capital and operational cost) and technique aspects (complication, problems and solutions for design and operation of the systems, and etc.).

In conclusion, on-going researches can be conducted with the fives proposed directions, but the followings should be considered for the operation and analysis of the hybrid CMF systems:

- Depending on specific feed water and scenario, backwashing interval should be checked and adjusted if necessary. The adjustments are to get good TMP recovery, low energy consumption, and high treated water production a day.
- NaClO dosage for enhancement of backwashing should be adjusted depending on the characteristics and levels of pollutants in raw water. The used NaClO should be selected carefully to get both high reduction of fouling and compliance of standards (on free chlorine residual for detailed using/reusing activities of treated water).
- Cryptosporidium and Giaidia should be measured exactly by a microbial-analysis such as polymerase chain reaction (PCR) method to get more exact results on the micro pathogens removal.
- In the treatment of such highly organic surface water for drinking purposes, once the chloride solution (NaClO) is injected continuously to the filtrate, THMs should be measured. This is to ensure health safety aspects of the treated water.

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APPENDIX A

Operation procedure of the pilot system

Photos of the experiments

Operation procedure for the CMF pilot

a. Manual operation

- Turn the switches located on the middle to lower control panel on to operate the equipment manually.
- Turn the switch OFF to stop the operation
- Turn the switch to open the valve. Turn the switch SHUT to close the valve. Either operation is full open or full close.
- The membrane feed after valve (AV1) needs to be opened when the feed pump is operated
- Compressed air (0.2 – 0.5 MPa) will flow into the equipment when backwash air valve and blow valve

b. Automatic operation

The system can be operated automatically by a program that was set in the controller PLC. The equipment will repeat the automatic operation process following the software program. The cycle including feeding water, filtration and backwashing is repeated. This automatic operation is shown on the upper side of the control panel.

"Raw water feed" means filling up the raw water side of the ceramic membrane with the coagulated water. "Filtration" means filtrating the coagulated water through the ceramic membrane. "Backwash" means the ceramic membrane with the filtrate pushed by the compressed air through the raw water side of the ceramic membrane. Automatic operation procedure is as expressed as the following step:

- Turn all the switches located on the middle to lower part of the control panel to "AUTO"
- Press the "operation START button"
- The equipment operating" and the "feed water" sign that are located on the upper part of the control panel are on and connecting, this indicates that the equipment began operating.

In cases that need to stop automatic operation such as for taking membrane out to clean by chemical, the following steps should be implemented:

- Press the "equipment STOP button"
- "Run" pilot lamp located on the upper part of the control panel will be off after the equipment stops
- For emergency situation, press the "Emergency stop: (red color) located on the bottom part of the control panel. Also, turn the emergency switch to the right to clear all.

Backwash is automatically operated after 2-3 hours of filtration (depending on setting up interval). However, we can use manual backwash during automatic operation. While the "Filtration" pilot lamp is light, press "manual backwash button". Backwash process is operated automatically, after completed the process enters into the "feed water" process automatically and continues automatic operation.

Figure A.1 The hybrid ceramic micro-filtration systems

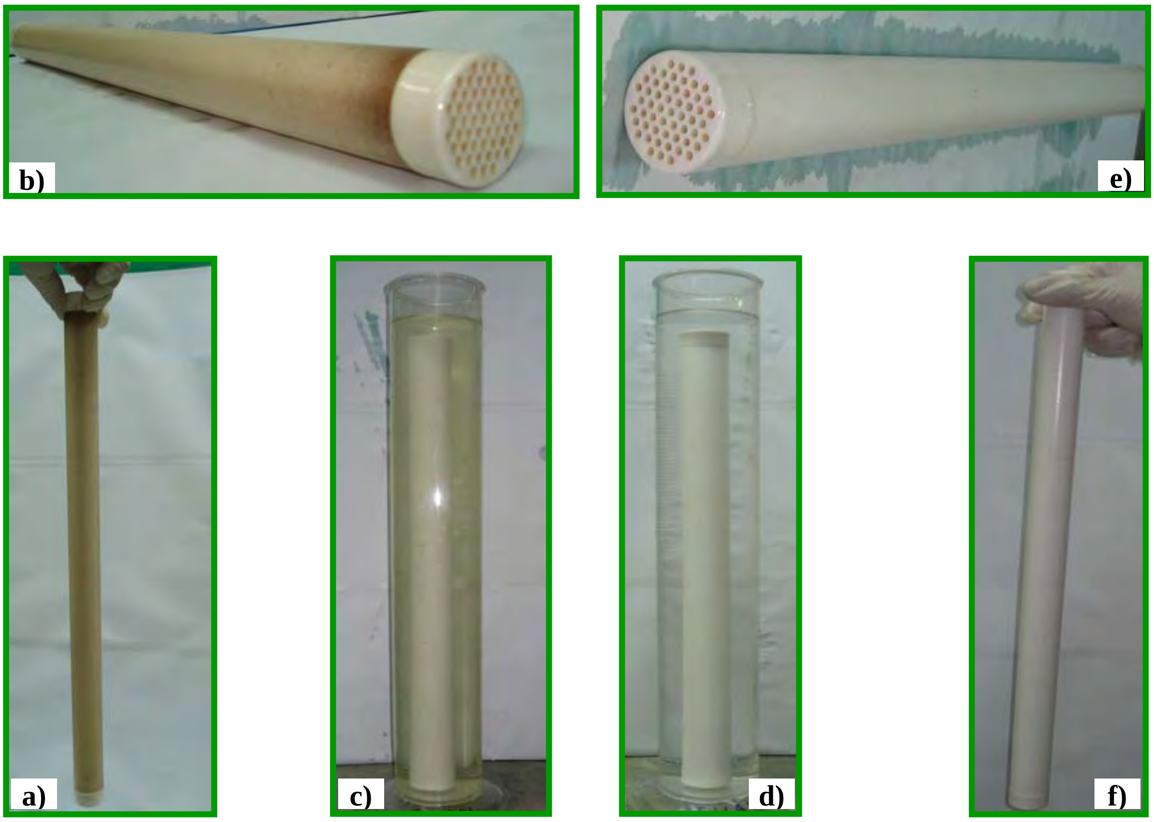


Figure A.2 Chemical cleaning after the experiment with synthetic water: a) & b): After the experimental run; c) Cleaning by citric acid solution 1%; d) Cleaning by NaClO solution 0.3 %; e) & f): Cleaned ceramic membrane

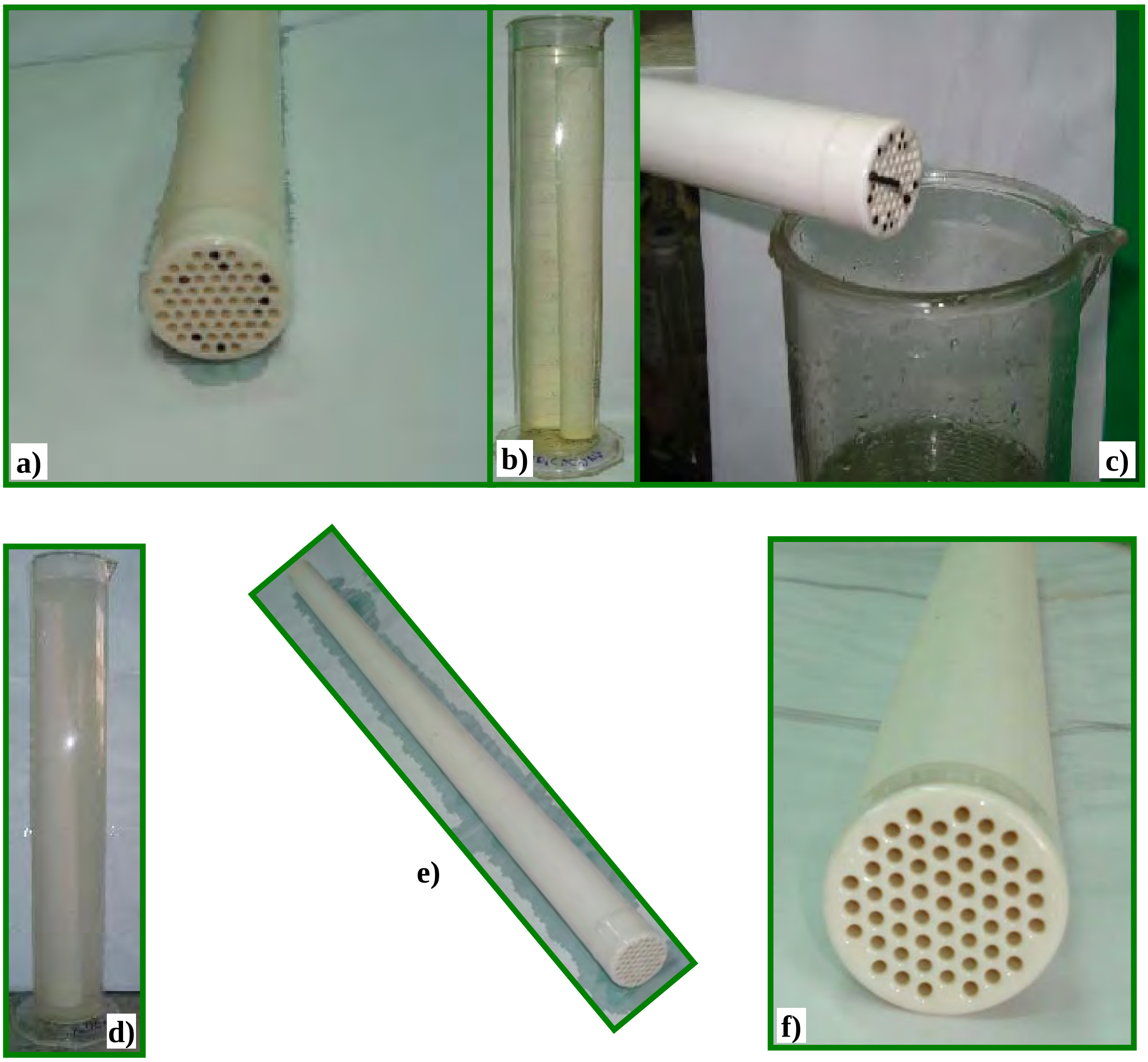


Figure A.3 a) Fouled ceramic membrane after the PAC + PCl + CMF hybrid system used for the SWT, b) Cleaning by citric acid solution 1%; c) PAC cake foulant; d) Cleaning by NaClO solution 0.3%; e) & f) Cleaned membrane

Figure A.4 a) Fouled ceramic membrane after the MWWT by the PCl + CMF hybrid system; b) During chemical cleaning; c) Cleaned membrane

APPENDIX B

Standard curves used for the analysis

Monitoring and analyzing results

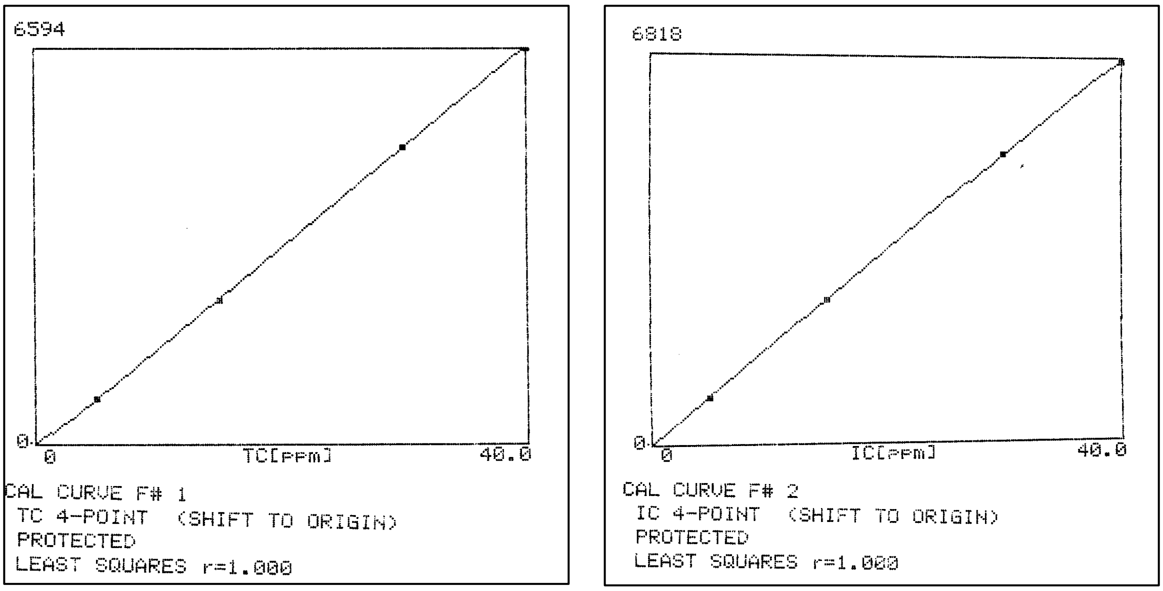


Figure B.1 TC and IC standard curves which were used for TOC measurement

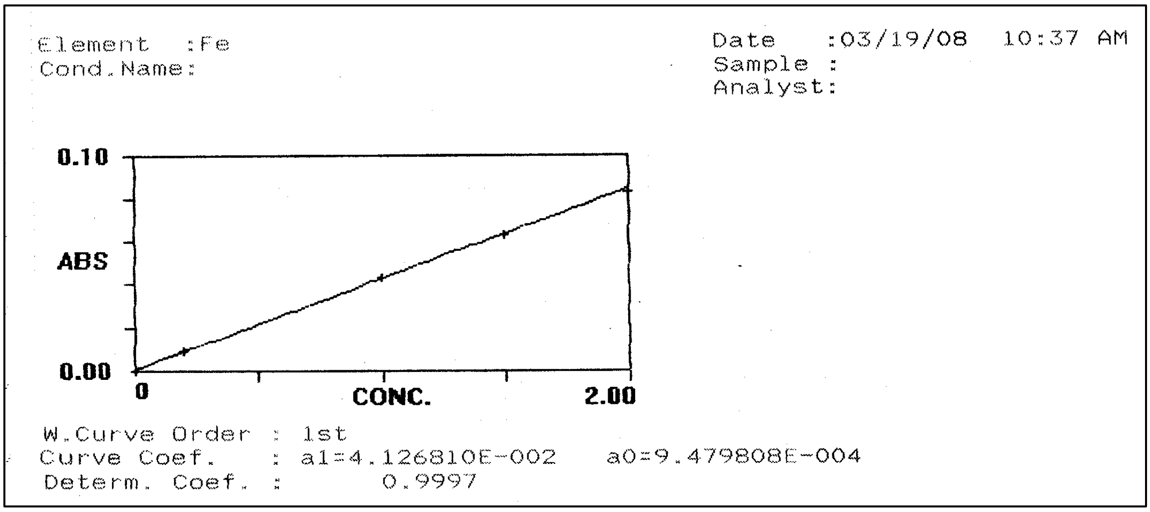


Figure B.2 Fe standard curve which was used for iron measurement by AAS machine

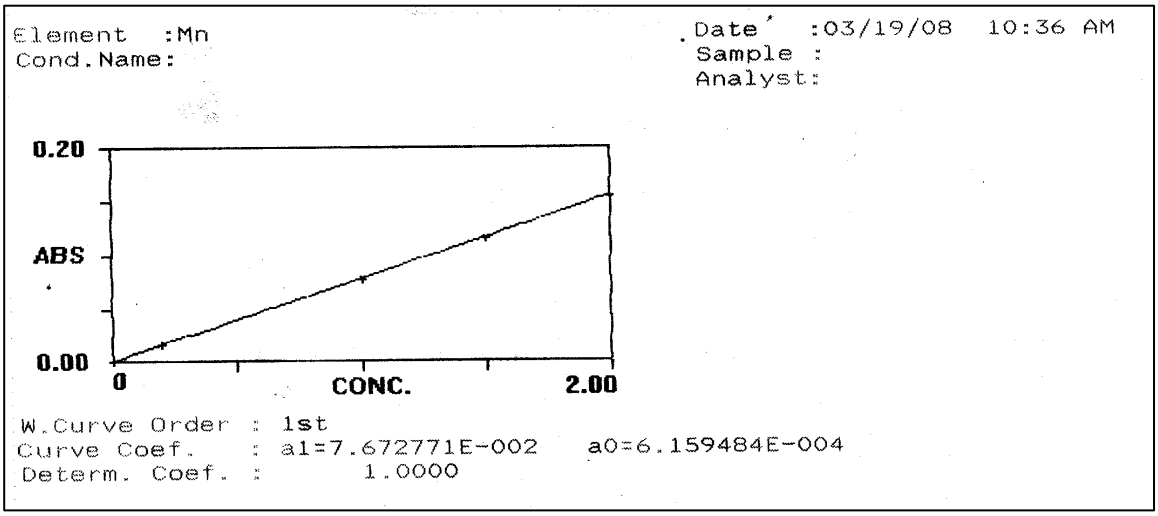


Figure B.3 Mn standard curve used for manganese measurement by AAS machine

Table B.1 Characteristics of tap water in the AIT's ambient lab

Parameter	Unit	Value
Temperature	^{o}C	27.5
pH	-	6.8
Conductivity	µs/c	198
Turbidity	NTU	1.32
TS	mg/L	118
TSS	mg/L	4.5
Fe	mg/L	0.95
Mn	mg/L	0.02
Micro particles	count/mL	
1 – 25 µm		1678
1 – 5 µm		1537
5 – 15 µm		191
15 – 25 µm		5

Table B.2 Relationship between Kaolin clay dosage and turbidity of synthetic water

Kaolin clay dosage (mg/L)	Turbidity (NTU)
0	0.651
20	14.5
40	28.2
60	42
80	58.5
100	73.2
120	115
140	131
160	145
180	171
200	199
250	238

Table B.3 Jar test with coagulation-flocculation for AIT pond water

PACl Dosage (mg/L)	pH	Turbidity (NTU)	TOC (mg/L)
0	7.2	26.5	8.68
5	6.9	0.724	3.07
10	6.7	0.464	2.65
15	6.5	0.39	2.55
20	6.3	1.67	2.29
25	6.1	1.71	4.02
30	5.9	26.1	5.92
35	5.5	27.9	6.88
40	5.1	27.2	7.23
45	4.5	26.35	7.85

Table B.4 Jar test with adsorption for AIT pond water

PAC (mg/L)	pH	Color (ADMI)	TOC (mg/L)
0	7.1	8	10.83
5	7.12	8	9.83
10	7.15	4	9.55
15	7.16	4	9.49
20	7.18	4	9.31
25	7.2	4	9.23
30	7.24	4	9.04
35	7.26	4	8.95
40	7.29	4	8.25
45	7.3	4	7.97
50	7.33	3	7.49
100	7.4	2	6.59
150	7.5	2	6.2
200	7.75	2	6.1
250	7.9	2	6

Table B.5 Jar test with the combination of adsorption and coagulation-flocculation for AIT pond water (with PAC dosage of 20 mg/L)

PACl (mg/L)	pH	Turbidity (NTU)	TOC (mg/L)
0	8.06	9.36	9.72
5	7.61	1.48	7.96
10	7.35	0.634	6.25
15	7.16	0.381	4.99
20	6.97	0.37	4.27
25	6.5	0.339	3.92
30	6.42	0.435	3.73
35	6.27	0.481	3.81
40	6.14	0.497	3.69
45	5.96	0.62	3.75

Table B.6 Jar test with coagulation-flocculation for AIT wastewater

PACl Dosage (mg/L)	pH	Turbidity (NTU)	TOC (mg/L)
0	7.31	59.7	23.1
5	7.16	22.6	12.64
10	7.02	4.33	7.44
15	6.88	2.86	6.89
20	6.8	1.84	5.29
25	6.63	3.03	8.95
30	6.57	3.04	9.81
35	6.51	2.87	9.89
40	6.47	2.03	10.25
45	6.37	1.69	12.12

Table B.7 Jar test with adsorption for AIT wastewater

PAC (mg/L)	pH	Color (ADMI)	TOC (mg/L)
0	6.98	19	11.75
10	6.99	18	10.77
20	7.01	18	9.2
30	7.04	18	8.7
40	7.05	18	8.22
50	7.14	17	8.13
60	7.21	17	6.2
80	7.32	14	5.75
100	7.58	13	5.34
150	7.72	10	3.15

Table B.8 Jar test with the combination of adsorption and coagulation-flocculation for AIT wastewater (with PAC dosage of 30 mg/L)

PACl (mg/L)	Turbidity (NTU)	pH	TOC (mg/L)
0	15.8	7.15	9.5
5	3.07	6.96	7.2
10	0.938	6.81	6.03
15	0.583	6.72	3.5
20	0.554	6.63	3.42
25	0.426	6.4	3.55
30	0.436	6.31	4.23
35	0.477	6.18	5.43
40	0.559	6.14	6.04
45	0.498	6.06	6.75

Table B.9 Conductivity, pH and temperature of the experiment with synthetic water

Date	Days	Conductivity (μs/cm)		pH		Temperature (^oC)	
		Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
6-Sep	0	50.2	49.7	7.2	7.3	27.3	26.9
7-Sep	1	50.7	48.3	7.1	7	27.6	27.2
8-Sep	2	50.5	50.2	6.8	6.7	30.6	29.1
9-Sep	3	49.5	47.9	7.1	7.1	27.5	27.1
10-Sep	4	49.8	47.9	6.9	7.2	27.1	26.9
11-Sep	5	47.5	47.6	7.1	7	27.6	28.5
12-Sep	6	48.9	48.2	7.3	7.2	29.1	29.3
9/13/2007	7	49.1	48.9	7.1	7.1	28.5	28.7
9/14/2007	8	48.6	48.5	7.4	7.4	27.2	27.6
9/15/2007	9	49.5	49.1	7.3	7.1	27.6	28.1
9/16/2007	10	50.1	48.9	7.5	7.4	28.4	29.2
9/17/2007	11	47.9	49.3	6.9	6.8	26.8	27.5
9/18/2007	12	48.9	50.5	6.7	6.8	27.8	28.2
9/19/2007	13	49.5	51.4	7.3	7.2	27.6	28.3
9/20/2007	14	51.2	53.6	7.4	7.5	27.9	28.5
9/21/2007	15	50.3	52.7	7.1	7.2	28.5	29.1
9/22/2007	16	48.9	50.5	7.3	7.1	27.2	27.6
9/23/2007	17	50.2	53.5	7.2	7.3	27.9	28.3
9/24/2007	18	48.8	52.7	7.4	7.6	26.8	27.5
9/25/2007	19	223	227	7.3	7.5	28.8	29.3
9/26/2007	20	218	221	7.1	7.4	28.1	28.8
9/27/2007	21	209	218	7.5	7.9	27.9	28.7
9/28/2007	22	218	225	7.2	7.6	27.3	27.9
9/29/2007	23	209	219	6.7	7.1	27.5	28.1
9/30/2007	24	216	223	6.5	7.1	27.7	28.5
10/1/2007	25	221	225	7.4	7.7	27.9	28.9
10/2/2007	26	216	222	7.3	7.6	28.1	29.4
10/3/2007	27	217	221	7.2	7.4	26.5	27.3
10/4/2007	28	218	227	7	7.5	27.6	28.5
10/5/2007	29	219	230	6.9	7.3	27.1	27.7
10/6/2007	30	220	231	6.7	7.3	27.4	28.1
10/7/2007	31	218	225	7.3	7.8	28.3	29.3
10/8/2007	32	215	214	7.1	7.7	28.6	29.2
10/9/2007	33	218	259	7.2	7.5	27.9	28.8
10/10/2007	34	219	247	7.3	7.8	27.1	27.9
10/11/2007	35	223	246	6.9	7.3	27.3	28.1
10/12/2007	36	218	221	7.1	7.6	28.4	29.2
10/13/2007	37	216	218	7.4	7.7	28.1	28.8
10/14/2007	38	222	220	7.2	7.8	29	29.8
10/15/2007	39	212	252	7.3	7.5	28.8	29.6
10/16/2007	40	174	247	7.4	7.6	27.6	28.1
10/17/2007	41	172	243	7.4	7.9	26.9	27.6
10/18/2007	42	195	240	6.6	7.1	26.5	27.7
10/19/2007	43	194	242	6.8	7.2	26.2	27.5
10/20/2007	44	215	236	7.6	7.9	28.3	29.2
10/21/2007	45	199	242	7.5	7.8	28.2	29.9
10/22/2007	46	203	243	6.6	7.4	28.8	30.6
10/23/2007	47	206	247	7.6	7.9	28.7	30.2
10/24/2007	48	200	243	6.7	6.8	29.5	31
10/25/2007	49	203	241	6.9	7.6	29.1	30

Table B.10 Turbidity and TMP of the experimental run with synthetic water

Date	Days	Turbidity (NTU)		Turbidity removal efficiency, %	TMP (kPa)
		Feed water	Permeate		
6-Sep	0	37.5	0.087	99.77	30
7-Sep	1	39.3	0.074	99.81	30
8-Sep	2	39.4	0.059	99.85	30
9-Sep	3	41.8	0.079	99.81	35
10-Sep	4	40.5	0.069	99.83	40
11-Sep	5	39.2	0.066	99.83	43
12-Sep	6	38.7	0.058	99.85	45
9/13/2007	7	35.9	0.098	99.73	48
9/14/2007	8	38.2	0.082	99.78	50
9/15/2007	9	41.7	0.077	99.81	55
9/16/2007	10	38.9	0.069	99.82	58
9/17/2007	11	39.5	0.072	99.82	53
9/18/2007	12	40.1	0.057	99.86	48
9/19/2007	13	39.5	0.061	99.85	45
9/20/2007	14	38.7	0.076	99.80	50
9/21/2007	15	39.2	0.068	99.83	50
9/22/2007	16	39.8	0.077	99.81	43
9/23/2007	17	39.5	0.063	99.84	38
9/24/2007	18	41.7	0.085	99.80	38
9/25/2007	19	80.6	0.092	99.89	40
9/26/2007	20	77.3	0.079	99.90	37
9/27/2007	21	79.8	0.082	99.90	32
9/28/2007	22	80.5	0.065	99.92	30
9/29/2007	23	81.5	0.073	99.91	32
9/30/2007	24	82.5	0.085	99.90	31
10/1/2007	25	85.7	0.094	99.89	30
10/2/2007	26	81.6	0.078	99.90	31
10/3/2007	27	82.6	0.08	99.90	30
10/4/2007	28	81.7	0.086	99.89	30
10/5/2007	29	84.5	0.084	99.90	30
10/6/2007	30	80.7	0.069	99.91	30
10/7/2007	31	80.2	0.077	99.90	30
10/8/2007	32	79.5	0.067	99.92	30
10/9/2007	33	84.5	0.087	99.90	30
10/10/2007	34	80.2	0.076	99.90	30
10/11/2007	35	122.5	0.115	99.91	30
10/12/2007	36	127	0.09	99.93	32
10/13/2007	37	121	0.062	99.95	32
10/14/2007	38	124	0.067	99.95	35
10/15/2007	39	117	0.072	99.94	38
10/16/2007	40	125	0.075	99.94	40
10/17/2007	41	121	0.074	99.94	40
10/18/2007	42	124	0.058	99.95	38
10/19/2007	43	125	0.065	99.95	38
10/20/2007	44	114	0.089	99.92	38
10/21/2007	45	127	0.071	99.94	38
10/22/2007	46	117	0.065	99.94	38
10/23/2007	47	118	0.085	99.93	40
10/24/2007	48	119	0.076	99.94	38
10/25/2007	49	121	0.073	99.94	38

Table B.11 Total Fe and Mn of the experimental run with synthetic water

Period of treatment (days)	Total Fe (mg/L)		Total Mn (μg/L)	
	Feed water	Permeate	Feed water	Permeate
0	1.25	0.03	10	ND
5	1.22	0.04	20	10
12	1.53	0.03	30	10
19	1.02	0.03	20	10
26	1.52	0.07	185	ND
36	2.05	0.07	40	ND
42	1.47	0.05	50	ND
48	1.57	0.03	40	ND

Table B.12 DOC, TOC, TSS, and TS of the experimental run with synthetic water

Period of treatment (days)	DOC (mg/L)		TOC(mg/L)		TSS (mg/L)		TS (mg/L)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0	1.859	1.062	2.89	1.23	150	0.5	226	126
5	1.706	0.998	2.91	1.79	148	0.5	221	131
12	1.587	1.011	2.87	1.63	153	0.5	219	129
19	1.557	1.005	2.57	1.12	304	0.5	454	142
26	1.58	1.08	3.79	1.73	302.5	0.5	460	135
36	1.48	1.18	2.59	2.08	149	0.5	442	201
42	1.13	0.86	1.93	1.13	153	0.5	304	154
48	1.07	0.78	2.14	1.22	178	ND	314	135

Table B.13 Micro-particles measurement of the experiment with synthetic water

Period of treatment (days)	Micro-particles, 1 – 25 μm (count/mL)		Micro-particles, 1 – 5 μm (count/mL)		Micro-particles , 5 – 15 μm (count/mL)		Micro-particles, 15 – 25 μm (count/mL)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0 (7/9/07)	398,060	249	364,340	232	33,100	16	620	1
5 (10/9/07)	412,320	238	376310	223	35,300	14	710	1
10 (15/9/07)	378,770	265	338,630	248	39,500	16	640	1
12 (17/9/07)	369,100	259	329,610	243	38,800	15	690	1
17 (22/9/07)	372,120	266	334,150	249	37,220	16	750	1
22 (27/9/07)	356,700	356	313,100	340	42,300	15	1300	1
27 (2/10/07)	681,420	253	583280	235	95,940	16	2200	2
29 (4/10/07)	823,400	127	728,500	117	93,100	9	1800	1
31 (6/10/07)	442,900	125	338,800	116	102,200	8	1900	1
34 (9/10/07)	724,150	274	644,850	245	77,800	17	1500	2
36 (11/10/07)	677,540	83	592,980	71	82,760	11	1800	1
38 (13/10/07)	3,336,100	140	3,129,860	125	203,840	14	2400	1
40 (15/10/07)	3,452,200	134	3,244,242	118	205,658	15	2300	1
47 (22/10/07)	3.049,840	116	2,705,040	100	339.040	15	5760	1
49 (24/10/07)	2,529,520	132	2,285,600	119	237,360	12	6560	1

Table B.14 pH, conductivity, and temperature of the experimental run 1 on direct CMF with surface water

Parameters	Unit	Value	
		Feed water	Permeate
Conductivity	µs/cm	430 ± 10	465 ± 10
pH	-	7.4 ± 0.5	7.7 ± 0.5
Temperature	^{o}C	27± 0.5	29± 0.5

Table B.15 Turbidity and TMP of the experimental run 1 on direct CMF with surface water

Date	Days	Turbidity (NTU)		Turbidity removal rate, %	TMP (kPa)
		Feed water	Permeate		
12-Jan-08	0	7.87	0.266	96.62	15
13-Jan-08	1	7.84	0.098	98.75	29
14-Jan-08	2	7.94	0.071	99.11	35
15-Jan-08	3	7.52	0.069	99.08	45
16-Jan-08	4	7.67	0.068	99.11	60
17-Jan-08	5	7.38	0.072	99.02	70
18-Jan-08	6	7.42	0.069	99.07	120

Table B.16 DOC, TOC, TSS, and TS of the experimental run 1 on direct CMF with surface water

Period of treatment (days)	DOC (mg/L)		TOC(mg/L)		TSS (mg/L)		TS (mg/L)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0	10.51	7.23	11.23	8.30	11	0.5	210	188
3	9.15	7.01	10.05	7.46	8	ND	198	195
6	9.21	7.81	12.01	9.75	11	ND	220	204

Table B.17 Fe and Mn of the experimental run 1 on direct CMF with surface water

Period of treatment (days)	Total Fe (mg/L)		Dissolved Fe (mg/L)		Total Mn (µg/L)		Dissolved Mn (µg/L)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0	0.723	0.059	0.299	ND	110	5	5	ND
3	0.740	0.032	0.193	ND	90	10	5	ND
6	0.752	0.041	0.241	ND	114	5	3	ND

Table B.18 Micro-particles measurement of the experimental run 1 on direct CMF with surface water

Period of treatment (days)	Micro-particles, 1 – 25 µm (count/mL)		Micro-particles, 1 – 5 µm (count/mL)		Micro-particles , 5 – 15 µm (count/mL)		Micro-particles, 15 – 25 µm (count/mL)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0	74,120	176	66,808	145	6872	28	440	2
3	68,440	166	63,520	141	4592	24	328	1
6	70,590	167	64,740	143	5488	23	364	1

Table B.19 pH, conductivity, and temperature of the experimental run 2 on direct CMF with surface water

Parameters	Unit	Value	
		Feed water	Permeate
Conductivity	μs/cm	460 ± 10	490 ± 10
pH	-	7.8 ± 0.5	8.1 ± 0.5
Temperature	^oC	27± 0.5	29± 0.5

Table B.20 Turbidity and TMP of the experimental run 2 on direct CMF with surface water

Date	Days	Turbidity (NTU)		Turbidity removal rate, %	TMP (kPa)
		Feed water	Permeate		
18-Feb	0	14.2	0.33	97.68	15
19-Feb	1	10.6	0.108	98.98	22
20-Feb	2	8.14	0.068	99.16	25
21-Feb	3	7.22	0.067	99.07	30
22-Feb	4	7.62	0.066	99.13	35
23-Feb	5	7.14	0.064	99.10	35
24-Feb	6	7.29	0.065	99.11	38
25/2/2008	7	7.33	0.064	99.13	45
26/2/2008	8	7.47	0.064	99.14	55
27/2/2008	9	7.07	0.064	99.09	80
28/2/2008	10	7.39	0.064	99.13	120

Table B.21 DOC, TOC, TSS, and TS of the experimental run 2 on direct CMF with surface water

Period of treatment (days)	DOC (mg/L)		TOC(mg/L)		TSS (mg/L)		TS (mg/L)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0	10.37	7.68	12.34	8.85	21	0.5	315	312
3	8.42	7.05	11.67	9.42	9	0.5	321	311
6	8.55	7.15	10.97	8.50	12	ND	311	308
9	9.32	7.53	10.88	7.83	10	ND	327	309

Table B.22 Fe and Mn of the experimental run 2 on direct CMF with surface water

Period of treatment (days)	Total Fe (mg/L)		Dissolved Fe (mg/L)		Total Mn (μg/L)		Dissolved Mn (μg/L)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0	0.632	0.08	0.157	0.008	90	15	ND	ND
3	0.392	0.07	0.195	0.007	30	5	5	ND
6	0.396	0.06	0.168	0.005	40	5	ND	ND
9	0.472	0.03	0.151	0.007	70	5	ND	ND

Table B.23 Micro-particles measurement of the experimental run 2 on direct CMF with surface water

Period of treatment (days)	Micro-particles, 1 – 25 μm (count/mL)		Micro-particles, 1 – 5 μm (count/mL)		Micro-particles , 5 – 15 μm (count/mL)		Micro-particles, 15 – 25 μm (count/mL)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0	111,712	335	99,472	303	11448	30	792	2
3	81,600	330	70,800	306	10240	22	560	2
6	55,612	243	50,124	221	5200	21	288	1
9	50,104	188	45,168	168	4680	19	256	1

Table B.24 Conductivity, pH and temperature of the experiment 1 with surface water on CMF combined with pretreatment by coagulation-flocculation

Parameters	Unit	Value	
		Feed water	Permeate
Conductivity	μs/cm	350 ± 10	415 ± 10
pH	-	7.0 ± 0.5	6.5 ± 0.5
Temperature	^{o}C	27± 0.5	29± 0.5

Table B.25 Turbidity and TMP of the experiment 1 with surface water on CMF combined with pretreatment by coagulation-flocculation

Date	Days	Turbidity (NTU)		Turbidity removal rate, %	TMP (kPa)
		Feed water	Permeate		
6-Nov	0	16.4	0.071	99.57	15
7-Nov	1	17.2	0.061	99.64	20
8-Nov	2	15.4	0.065	99.58	30
9-Nov	3	18.1	0.064	99.65	32
10-Nov	4	16.2	0.067	99.59	37
11-Nov	5	17.1	0.063	99.63	38
12-Nov	6	16.3	0.061	99.63	40
13/11/2007	7	15.2	0.065	99.57	45
14/11/2007	8	15.1	0.063	99.58	52
15/11/2007	9	14.2	0.064	99.55	64
16/11/2007	10	15.1	0.061	99.60	75
17/11/2007	11	14.7	0.065	99.56	87
18/11/2007	12	15.6	0.069	99.56	105

Table B.26 DOC, TOC, TSS, and TS of the experiment 1 with surface water on CMF combined with pretreatment by coagulation-flocculation

Period of treatment (days)	DOC (mg/L)		TOC(mg/L)		TSS (mg/L)		TS (mg/L)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0	6.86	2.52	11.45	2.97	15	ND	240	192
3	7.87	2.84	11.02	3.02	10	ND	232	188
6	6.93	2.36	10.97	2.74	16	ND	232	178
9	7.47	2.28	11.04	2.69	12	ND	227	182
12	7.31	2.29	11.22	2.86	18	ND	243	178

Table B.27 Fe and Mn of the experiment 1 with surface water on CMF combined with pretreatment by coagulation-flocculation

Period of treatment (days)	Total Fe (mg/L)		Dissolved Fe (mg/L)		Total Mn (μg/L)		Dissolved Mn (μg/L)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0	1.623	0.105	1.068	ND	30	ND	10	ND
3	1.531	0.101	0.985	ND	50	ND	10	ND
6	1.498	0.098	0.866	ND	30	ND	10	ND
9	1.377	0.092	0.981	ND	30	ND	0	ND
12	1.333	0.097	1.014	ND	40	ND	0	ND

Table B.28 Micro-particles measurement of the experiment 1 with surface water on CMF combined with pretreatment by coagulation-flocculation

Period of treatment (days)	Micro-particles, 1 – 25 μm (count/mL)		Micro-particles, 1 – 5 μm (count/mL)		Micro-particles , 5 – 15 μm (count/mL)		Micro-particles, 15 – 25 μm (count/mL)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0	67,968	236	60,941	214	6825	21	202	1
3	55,110	186	49,092	170	5918	14	100	1
6	66,510	198	59,864	181	6412	16	234	1
9	68,430	213	60,893	197	7266	15	271	1
12	61,270	237	54,432	223	6521	13	317	1

Table B.29 Conductivity, pH and temperature of the experiment 2 with surface water on CMF combined with pretreatment by coagulation-flocculation

Parameters	Unit	Value	
		Feed water	Permeate
Conductivity	μs/cm	370 ± 10	420 ± 10
pH	-	7.0 ± 0.5	6.5 ± 0.5
Temperature	^{o}C	27± 0.5	29± 0.5

Table B.30 Turbidity and TMP of the experiment 2 with surface water on CMF combined with pretreatment by coagulation-flocculation

Date	Days	Turbidity (NTU)		Turbidity removal efficiency (%)	TMP (kPa)
		Feed water	Permeate		
9-Dec	0	9.02	0.075	99.17	15
10-Dec	1	8.56	0.072	99.16	20
11-Dec	2	8.17	0.068	99.17	24
12-Dec	3	8.03	0.062	99.23	30
13-Dec	4	6.97	0.057	99.18	35
14-Dec	5	5.76	0.054	99.06	35
15-Dec	6	6.13	0.053	99.13	37
16/12/2007	7	7.18	0.061	99.15	37
17/12/2007	8	6.29	0.054	99.14	40
18/12/2007	9	5.92	0.058	99.02	45
19/12/2007	10	6.62	0.062	99.06	45

20/12/2007	11	7.37	0.057	99.23	50
21/12/2007	12	6.78	0.061	99.10	55
22/12/2007	14	6.45	0.063	99.02	60
23/12/2007	15	6.39	0.062	99.03	65
24/12/2007	16	7.29	0.063	99.14	70
25/12/2007	17	7.03	0.062	99.12	85
26/12/2007	18	6.81	0.059	99.13	95
27/12/2007	19	6.96	0.058	99.17	110

Table B.31 DOC, TOC, TSS, and TS of the experiment 2 with surface water on CMF combined with pretreatment by coagulation-flocculation

Period of treatment (days)	DOC (mg/L)		TOC(mg/L)		TSS (mg/L)		TS (mg/L)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0	8.11	3.38	10.88	3.62	20	ND	239	214
3	9.74	3.8	10.93	3.98	18	ND	233	203
6	9.6	3.6	11.92	3.65	18	ND	237	198
9	8.55	3.62	12.5	3.78	15	ND	249	197
12	9.12	3.55	11.88	3.69	16	ND	228	188
15	8.87	3.37	10.39	3.54	18	ND	232	182
18	8.92	3.28	10.18	3.41	18	ND	235	179

Table B.32 Fe and Mn of the experiment 2 with surface water on CMF combined with pretreatment by coagulation-flocculation

Period of treatment (days)	Total Fe (mg/L)		Dissolved Fe (mg/L)		Total Mn (μg/L)		Dissolved Mn (μg/L)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0	0.49	0.02	0.19	ND	40	10	10	ND
3	0.69	0.01	0.32	ND	30	ND	10	ND
6	1.02	0.03	0.45	ND	30	ND	5	ND
9	0.67	0.02	0.33	ND	30	ND	5	ND
12	0.87	0.02	0.37	ND	40	ND	10	ND
15	0.89	0.02	0.36	ND	30	ND	10	ND
18	0.92	0.03	0.41	ND	55	ND	20	ND

Table B.33 Micro-particles measurement of the experiment 2 with surface water on CMF combined with pretreatment by coagulation-flocculation

Period of treatmen t (days)	Micro-particles, 1 – 25 μm (count/mL)		Micro-particles, 1 – 5 μm (count/mL)		Micro-particles , 5 – 15 μm (count/mL)		Micro-particles, 15 – 25 μm (count/mL)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeat e
0	65,812	270	59,316	248	6240	20	256	2
3	68,964	230	61,276	211	7418	18	270	1
6	65,836	222	59,426	205	6169	16	241	1
9	67,648	214	60,179	198	7232	17	237	1
12	63,476	215	56,969	202	6188	12	319	1
15	60,966	217	54,824	204	5890	12	252	1
18	69,260	223	61,475	210	7511	12	274	1

Table B.34 Conductivity, pH and temperature of the experiment with surface water on CMF combined with pretreatments by adsorption and coagulation-flocculation

Parameters	Unit	Value	
		Feed water	Permeate
Conductivity	µs/cm	470 ± 10	520 ± 10
pH	-	7.5 ± 0.5	6.8 ± 0.5
Temperature	^{o}C	28± 0.5	29± 0.5

Table B.35 Turbidity and TMP of the experiment with surface water on CMF combined with pretreatments by adsorption and coagulation-flocculation

Date	Days	Turbidity (NTU)		Turbidity removal rate (%)	TMP (kPa)
		Feed water	Permeate		
3-Mar	0	7.37	0.181	97.54	15
4-Mar	1	7.55	0.066	99.13	22
5-Mar	2	9.91	0.058	99.41	25
6-Mar	3	9.55	0.053	99.44	28
7-Mar	4	9.47	0.053	99.44	30
8-Mar	5	9.91	0.055	99.44	35
9-Mar	6	9.46	0.056	99.41	40
10/3/2008	7	8.97	0.055	99.39	40
11/3/2008	8	9.32	0.055	99.41	45
12/3/2008	9	8.47	0.056	99.34	50
13/3/2008	10	8.29	0.056	99.32	48
14/3/2008	11	8.67	0.056	99.35	55
15/3/2008	12	8.43	0.056	99.34	63
16/3/2008	13	7.68	0.056	99.27	60
17/3/2008	14	10.9	0.055	99.49	65
18/3/2008	15	9.03	0.056	99.38	75
19/3/2008	16	11.1	0.056	99.50	82
20/3/2008	17	10.9	0.055	99.49	85
21/3/2008	18	11.6	0.055	99.53	85
22/3/2008	19	10.5	0.055	99.48	95
23/3/2008	20	11.07	0.055	99.50	105

Table B.36 DOC, TOC, TSS, and TS of the experiment with surface water on CMF combined with pretreatments by adsorption and coagulation-flocculation

Period of treatment (days)	DOC (mg/L)		TOC(mg/L)		TSS (mg/L)		TS (mg/L)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0	7.31	1.47	8.85	2.2	8	ND	264	202
3	7.8	1.83	10.54	1.99	18	ND	240	206
6	6.68	1.23	8.54	1.35	12	ND	252	201
9	6.26	1.11	8.72	1.32	21	ND	247	204
12	7.01	1.2	8.92	1.29	10	ND	258	198
15	6.37	1.27	7.47	1.37	16	ND	261	198
18	7.21	1.28	9.56	1.31	18	ND	219	204

Table B.37 Fe and Mn of the experiment with surface water on CMF combined with pretreatments by adsorption and coagulation-flocculation

Period of treatment (days)	Total Fe (mg/L)		Dissolved Fe (mg/L)		Total Mn (μg/L)		Dissolved Mn (μg/L)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0	0.55	0.09	0.25	ND	30	ND	5	ND
3	0.34	0.07	0.19	ND	10	ND	5	ND
6	0.71	0.08	0.1	ND	20	ND	3	ND
9	0.63	0.02	0.08	ND	30	ND	0	ND
12	0.67	0.03	0.17	ND	40	ND	5	ND
15	0.59	0.02	0.21	ND	10	ND	5	ND
18	0.87	0.05	0.18	ND	10	ND	5	ND

Table B.38 Micro-particles measurement of the experiment with surface water on CMF combined with pretreatments by adsorption and coagulation-flocculation

Period of treatment (days)	Micro-particles, 1 – 25 μm (count/mL)		Micro-particles, 1 – 5 μm (count/mL)		Micro-particles , 5 – 15 μm (count/mL)		Micro-particles, 15 – 25 μm (count/mL)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0	49,088	97	42,216	87	5672	9	200	1
3	52,648	54	46,088	47	5392	6	168	1
6	82,120	92	72,929	88	8429	7	762	0
9	84,520	91	74,998	85	8736	6	768	0
12	74,360	46	66,470	42	7218	4	458	0
15	75,680	41	68,385	37	6607	4	688	0
18	73,640	40	67,636	36	6928	4	676	0

Table B.39 Comparison among different scenarios for surface water treatment

Parameters	Average removal rate, %		
	Direct CMF	PACl + CMF	PAC + PACl + CMF
Turbidity	99.32	99.36	99.32
Giardia and Cryptosporidium	99.61	99.77	99.92
Total coliform	100	100	100
Fecal coliform	100	100	100
TOC	24.05	70.81	82.69
DOC	21.36	63.54	80.78
TSS	100	100	100

Table B.40 Conductivity, pH and temperature of the experiment with municipal wastewater on direct CMF

Parameters	Unit	Value	
		Feed water	Permeate
Conductivity	μs/cm	610 ± 10	650 ± 10
pH	-	7.1 ± 0.5	7.3 ± 0.5
Temperature	^oC	29± 0.5	31± 0.5

Table B.41 Turbidity and TMP of the experiment with municipal wastewater on direct CMF

Date	Day	Turbidity (NTU)		Turbidity removal rate (%)	TMP (kPa)
		Feed water	Permeate		
7-Apr	0	56.9	23.3	59.05	15
8-Apr	1	58.9	19.2	67.40	40
9-Apr	2	61.5	15.1	75.44	70
10-Apr-08	3	57.7	15.1	73.83	110

Table B.42 Micro-particles measurement of the experiment with municipal wastewater on direct CMF

Period of treatment (days)	Micro-particles, 1 – 25 µm (count/mL)		Micro-particles, 1 – 5 µm (count/mL)		Micro-particles , 5 – 15 µm (count/mL)		Micro-particles, 15 – 25 µm (count/mL)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0	421,200	5121	383,160	4807	36780	303	1260	11
1	422,420	4529	384,220	4374	36840	151	1360	4
2	427,120	4518	387,904	4368	37800	146	1416	4
3	425,600	4494	387,288	4347	37080	144	1232	3

Table B.43 Performance of direct CMF on removing pollutants of municipal wastewater

Parameters	Unit	Value		Removal rate (%)
		Feed water	Permeate	
TOC	mg/L	16.9	11.4	32.54
COD	mg/L	106	44	58.49
BOD_5	mg/L	32	25	21.88
TSS	mg/L	25	4	84
Free Cl_2 residual	mg/L	ND	0.05	-
Total Coliform	MPN/100mL	$4.4*10^6$	ND	100
Fecal coliform	MPN/100mL	$3.1*10^6$	ND	100

Table B.44 Conductivity, pH and temperature of the experiment with municipal wastewater on CMF combined with pre-treatment by coagulation-flocculation

Parameters	Unit	Value	
		Feed water	Permeate
Conductivity	µs/cm	620 ± 10	700 ± 10
pH	-	7.3 ± 0.5	6.8 ± 0.5
Temperature	^oC	29± 0.5	31± 0.5

Table B.45 Turbidity and TMP of the experiment with municipal wastewater by the PACl + CMF hybrid system

Date	Day	Turbidity (NTU)		Turbidity removal rate (%)	TMP (kPa)
		Feed water	Permeate		
14-Apr	0	61.2	3.68	93.99	15
15-Apr	1	62.5	1.12	98.21	25
16-Apr	2	62.9	0.43	99.32	30
17-Apr	3	61.1	0.22	99.64	35
18-Apr	4	62.8	0.22	99.65	40
19-Apr	5	63.2	0.23	99.64	50
20-Apr	6	64.1	0.22	99.66	55
21/4/2008	7	62.8	0.24	99.62	55
22/4/2008	8	63.3	0.23	99.64	60
23/4/2008	9	61.3	0.19	99.69	60
24/4/2008	10	62.7	0.23	99.63	62
25/4/2008	11	63.1	0.23	99.64	65
26/4/2008	12	64.2	0.23	99.64	68
27/4/2008	13	61.8	0.22	99.64	70
28/4/2008	14	62.1	0.21	99.66	75
29/4/2008	15	63.1	0.21	99.67	80
30/4/2008	16	63.8	0.21	99.67	90
01/5/2008	17	63.7	0.21	99.67	110

Table B.46 Micro-particles measurement of the experiment with municipal wastewater by the PACl + CMF hybrid system

Period of treatment (days)	Micro-particles, 1 – 25 μm (count/mL)		Micro-particles, 1 – 5 μm (count/mL)		Micro-particles , 5 – 15 μm (count/mL)		Micro-particles, 15 – 25 μm (count/mL)	
	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate	Feed water	Permeate
0	430,100	602	391,324	546	37380	51	1396	5
3	428,160	294	389,432	271	37400	21	1328	2
6	429,600	227	390,864	207	37420	19	1316	1
9	428,400	231	389,676	212	37440	18	1284	1
12	422520	241	383,824	222	37420	18	1276	1
15	428626	233	389,866	214	37480	18	1280	1

Table B.47 Performance of removals of pollutants by the PACl + CMF hybrid system

Parameters	Unit	Value		Removal rate (%)
		Feed water	Permeate	
TOC	mg/L	17.3	5.22	69.83
COD	mg/L	108	36	66.67
BOD_5	mg/L	32	12	62.5
TSS	mg/L	26	ND	100
Free Cl_2 residual	mg/L	ND	2.05	-
Total Coliform	MPN/100mL	$4.4*10^6$	ND	100
Fecal coliform	MPN/100mL	$3.1*10^6$	ND	100

Table B.48 Comparison between different scenarios for municipal wastewater treatment

Parameters	Average removal rate, %	
	Direct CMF	PACl + CMF
Turbidity	74.5	99.65
Giardia and Cryptosporidium	99.61	99.95
Total coliform	100	100
Fecal coliform	100	100
TOC	32.5	69.83
COD	58.5	66.67
BOD_5	21.9	62.5
TSS	84	100

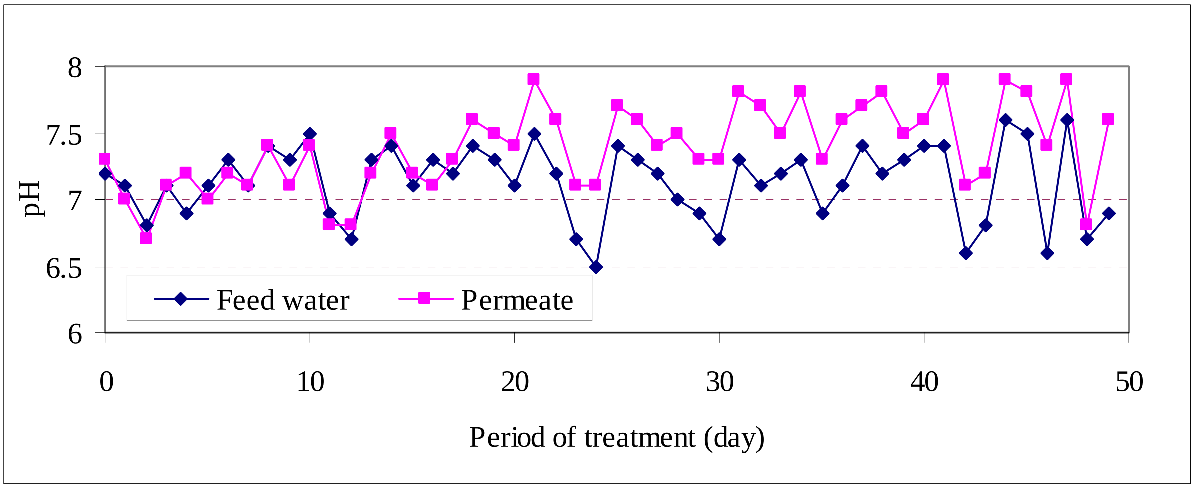


Figure B.1 pH of feed water and permeate of the experiment with synthetic water

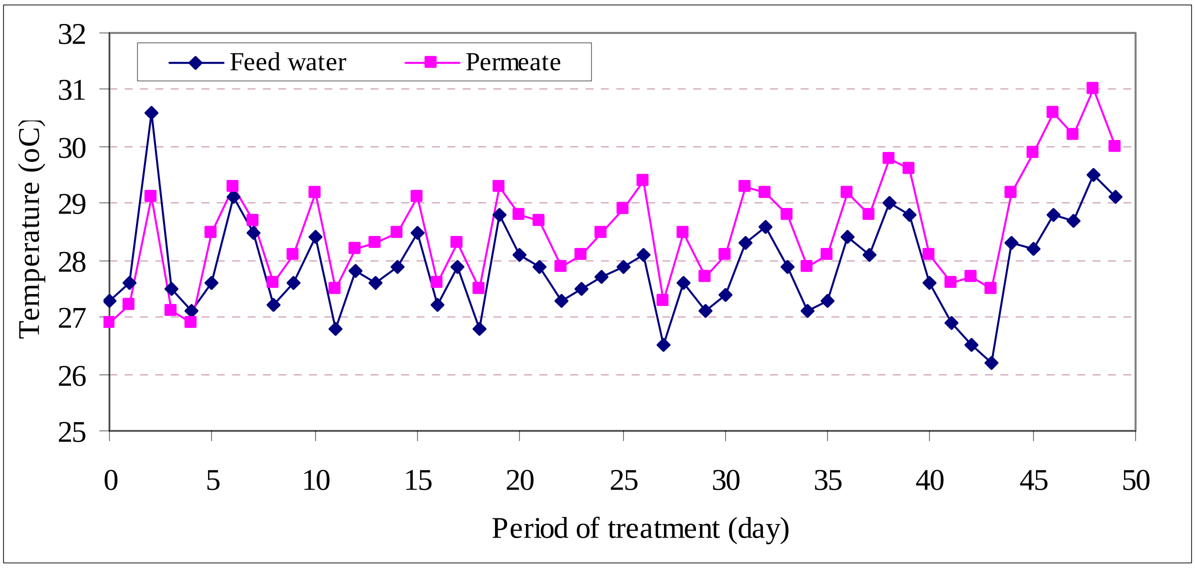


Figure B.2 Variations of temperature of the experiment with synthetic water

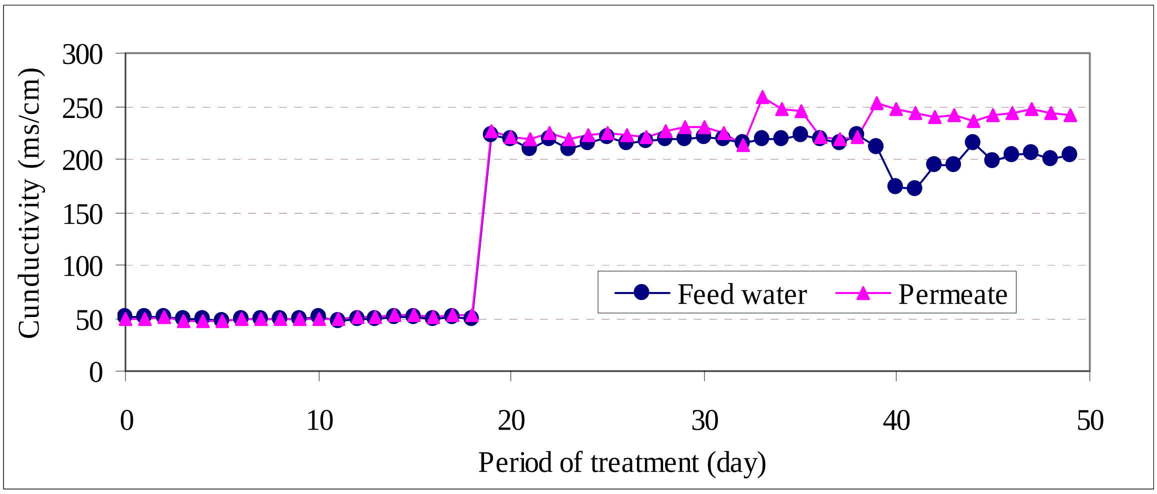


Figure B.3 Changes of conductivity of the experiment with synthetic water

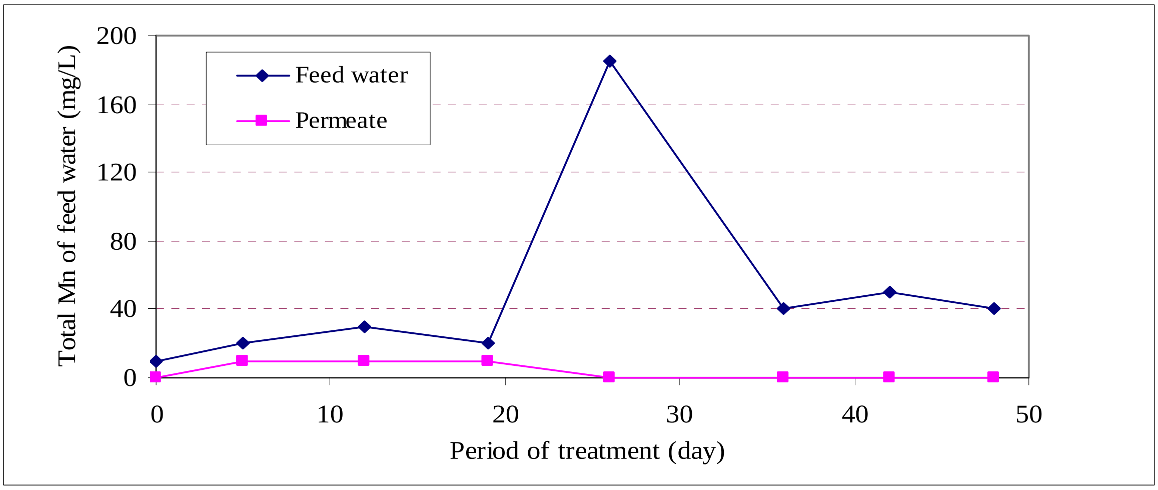


Figure B.4 Variation of Mn with filtration time of the experiment with synthetic water

ASIAN INSTITUTE OF TECHNOLOGY

Treatment of Surface Water and Municipal Wastewater by Hybrid Ceramic Microfiltration Systems

by

Le Anh Tuan

Examination Committee: Prof. C.Visvanathan (Chairperson)

Dr. Preeda Parkian

Dr. Thammarat Koottatep

Content

1. Introduction
2. Literature review
3. Methodology
4. Results and discussions
5. Conclusions and recommendations

Introduction

Need of the surface water treatment and reclamation of wastewater

Conventional treatment systems: disadvantages

Alternatives

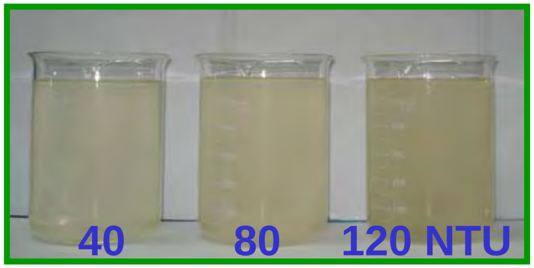
Membrane technology: ceramic microfiltration (CMF)

Objectives

1. Evaluate the efficiency of the CMF on surface water treatment
2. Investigate potentials and evaluate the efficiency of the CMF on municipal wastewater treatment for reuse activities
3. Investigate operational problems related to dead-end filtration for the treatment of surface water and municipal wastewater

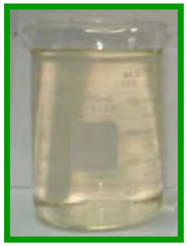
Scope of The Study

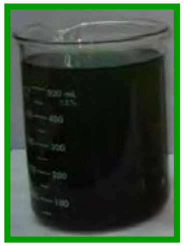
✎ First Stage: Experiment on synthetic water



☞ Second Stage: Research on

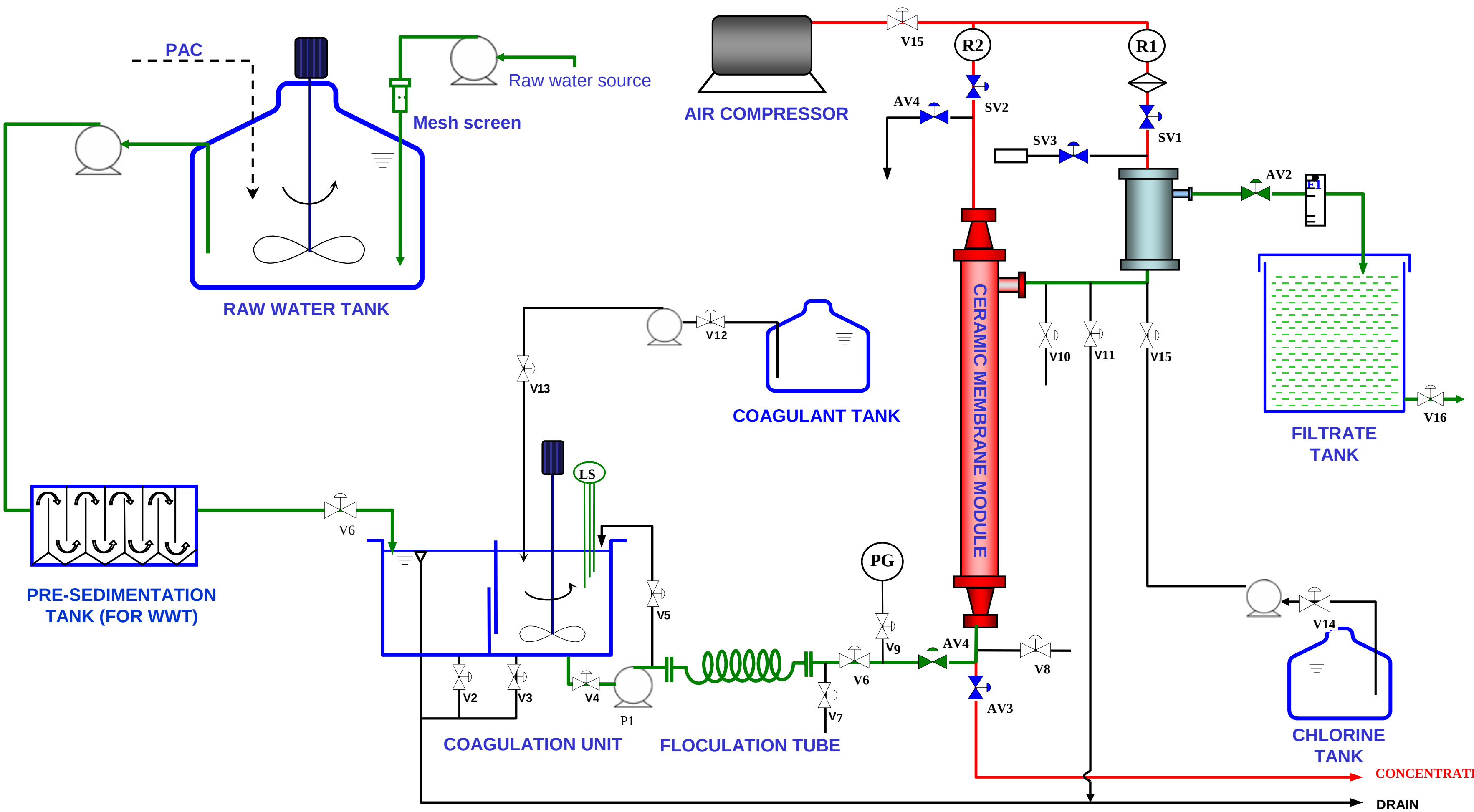
surface water and municipal wastewater





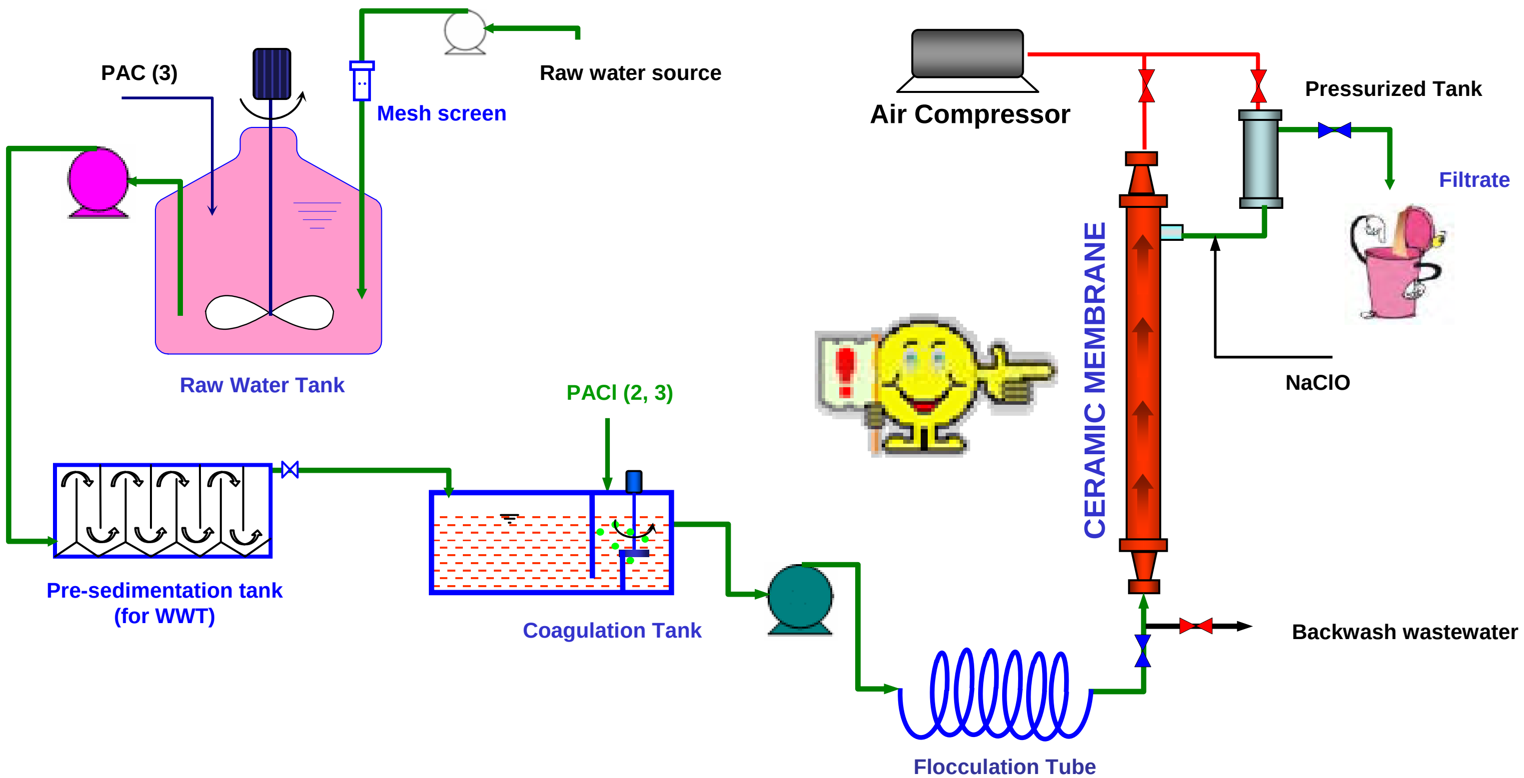
System Set-up

System Set-up



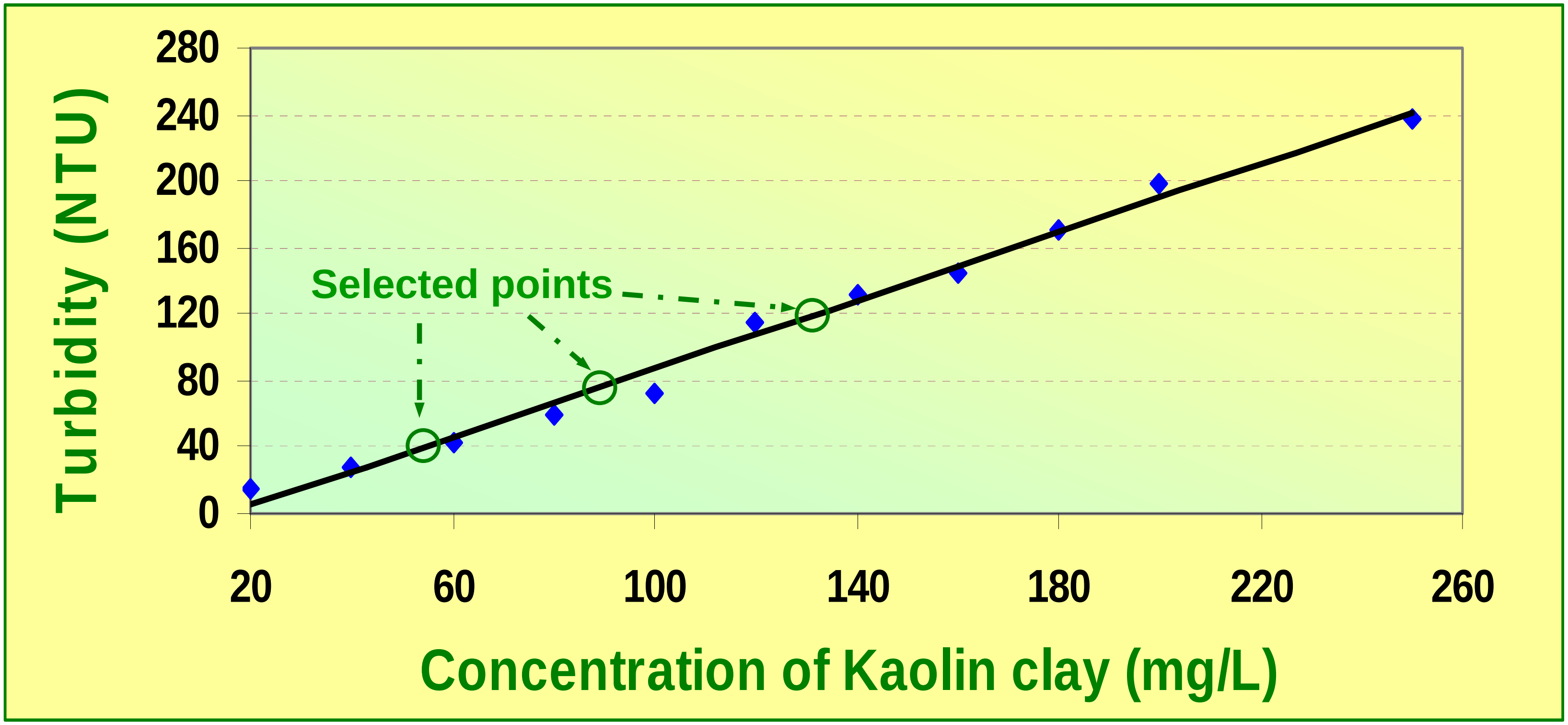
Technical diagram for the operational scenarios

System Set-up



Simplified flow diagram of the hybrid CMF systems

Pre-experiments

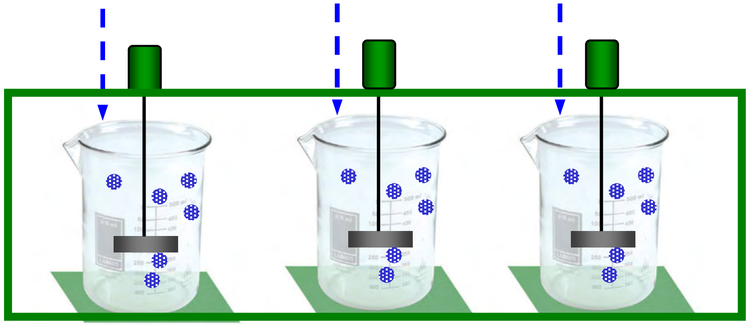


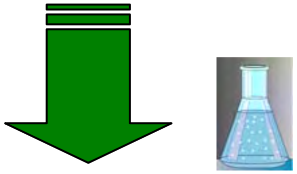
☞ **Synthetic water was prepared at three different types:**

1. Synthetic water 1: 40 NTU, Kaolin clay of 55 mg/L
2. Synthetic water 2: 80 NTU, Kaolin clay of 95 mg/L
3. Synthetic water 3: 120 NTU, Kaolin clay of 137 mg/L

Pre-experiments

Coagulant (PACl)/Adsorbent (PAC)/Combination

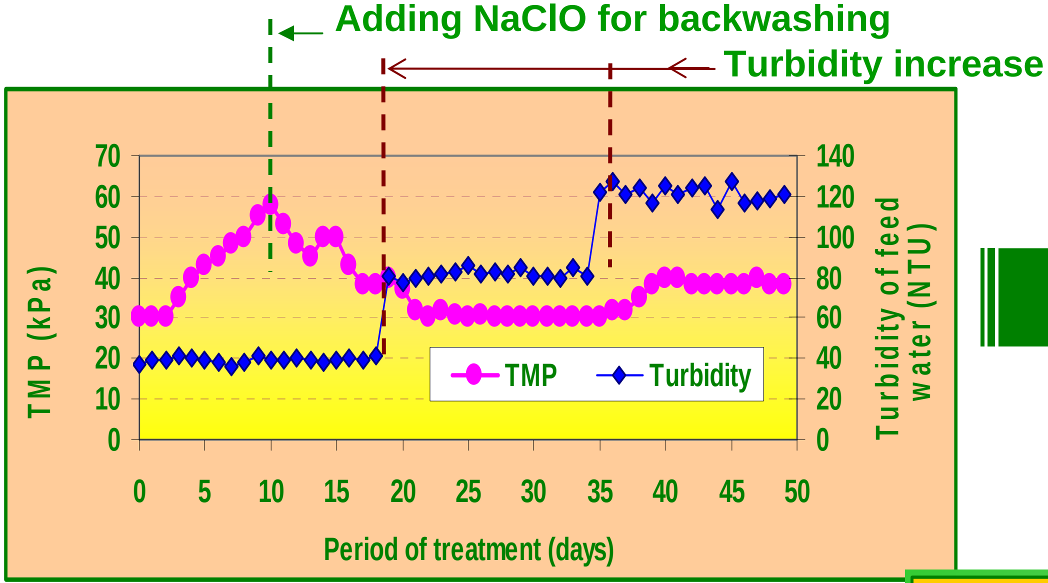




Optimum dosage, mg/L

Jar test	Surface water	Wastewater
PACl	20	20
PAC	20	30
PAC& PACl	20, 20	30, 20

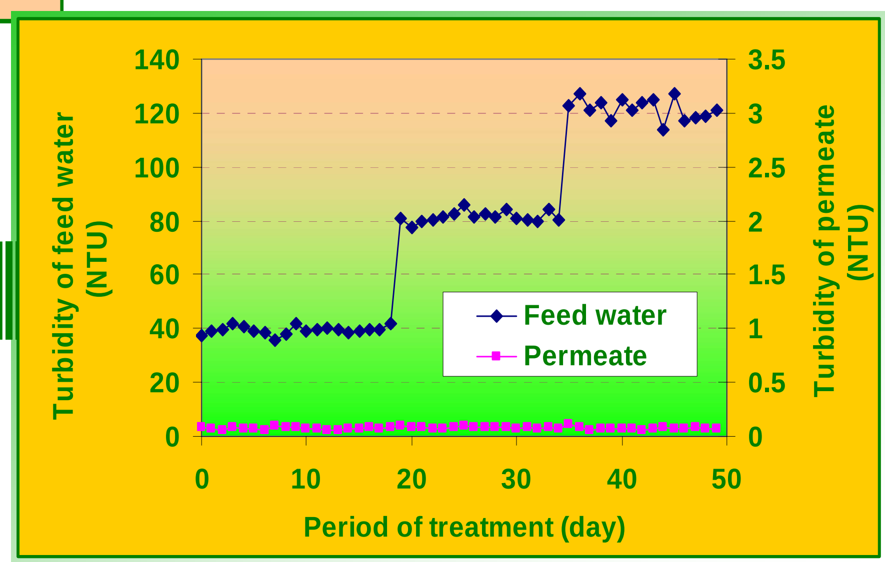
Experiments with Synthetic Water



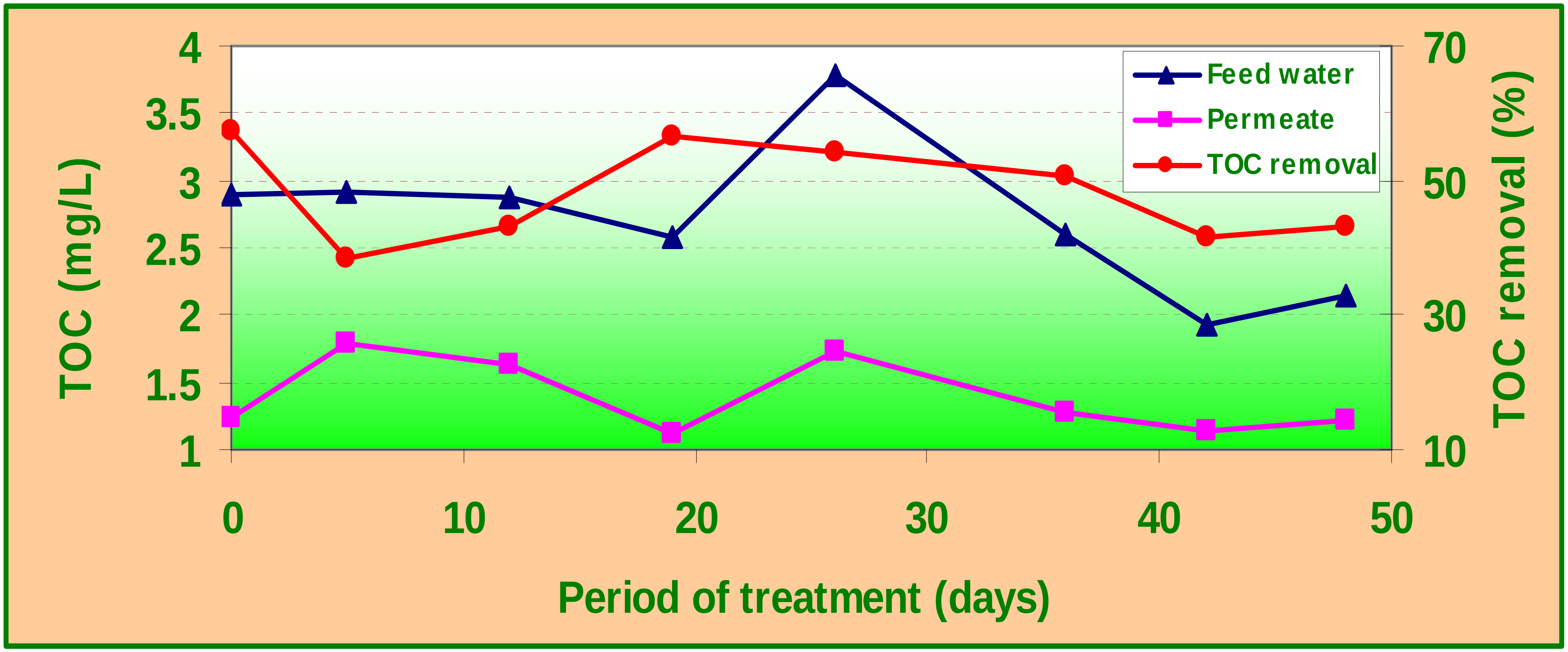
☞ Effectively cleaned by backwash

✸Turbidity of permeate was very low and stable

✸ TSS was removed completely



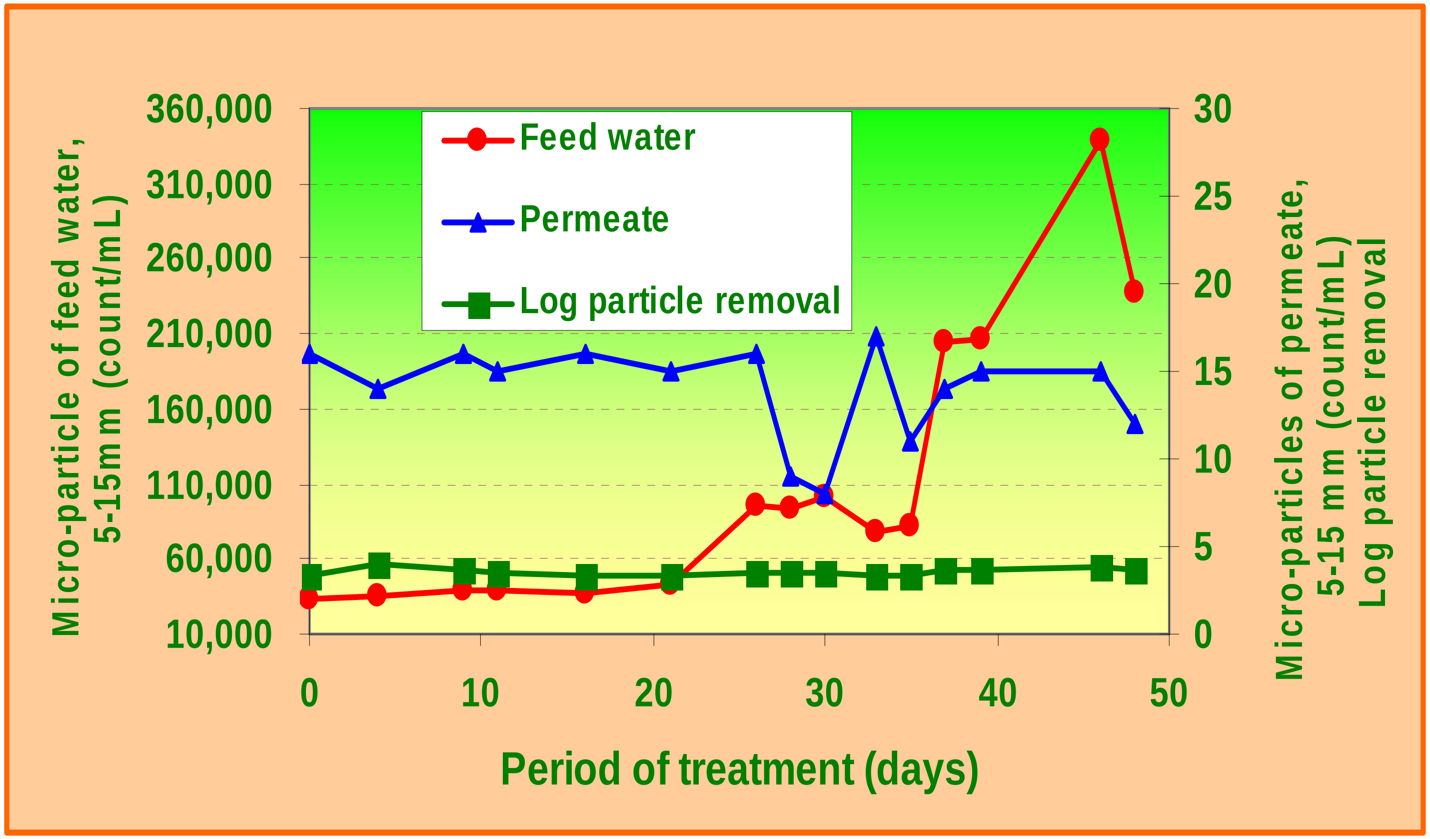
Experiments with Synthetic Water



TOC removal: 38 - 57 %

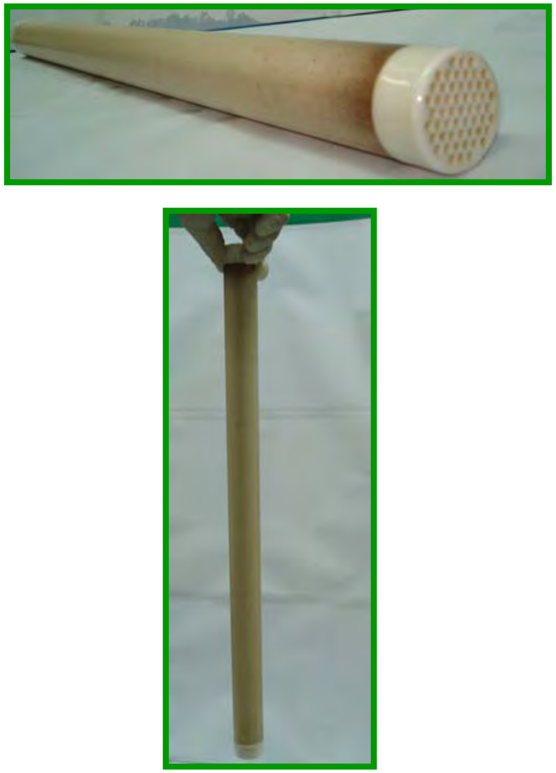
Why low ? → **No coagulation-flocculation/adsorption**

Experiments with Synthetic Water



☞ **Micro-particles (5 – 15 μm) removal: 99.95 - 99.99%. Log removal: 3.28 – 4.21**

Chemical Cleaning



After experimental run

Chemical cleaning

After chemical cleaning

Intermediate Conclusion

The characteristics of synthetic water

↓

Foulants are inorganic and particular matters

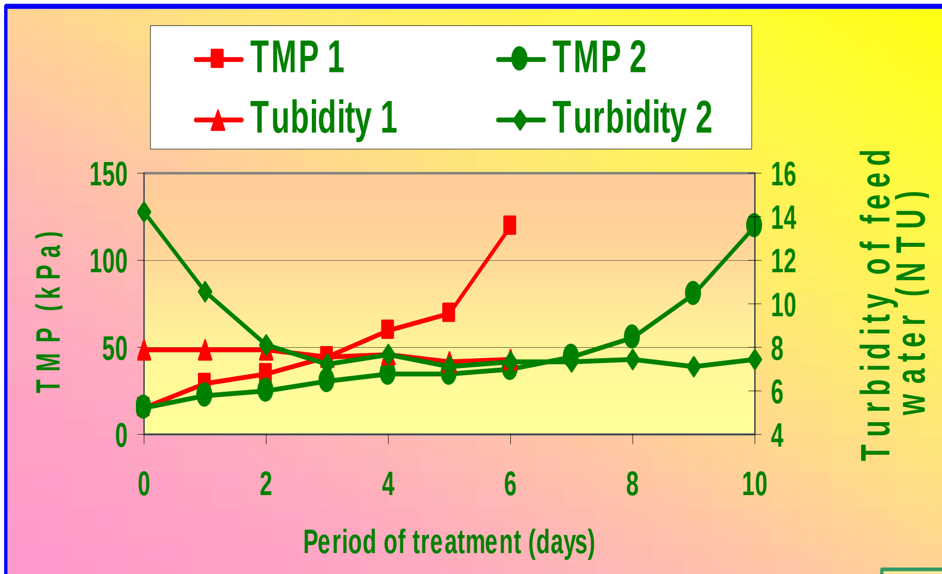
↓

Easily removed by backwash (BW)

↓

Surface water and municipal wastewater: NaClO enhanced BW

Experiments with Surface Water

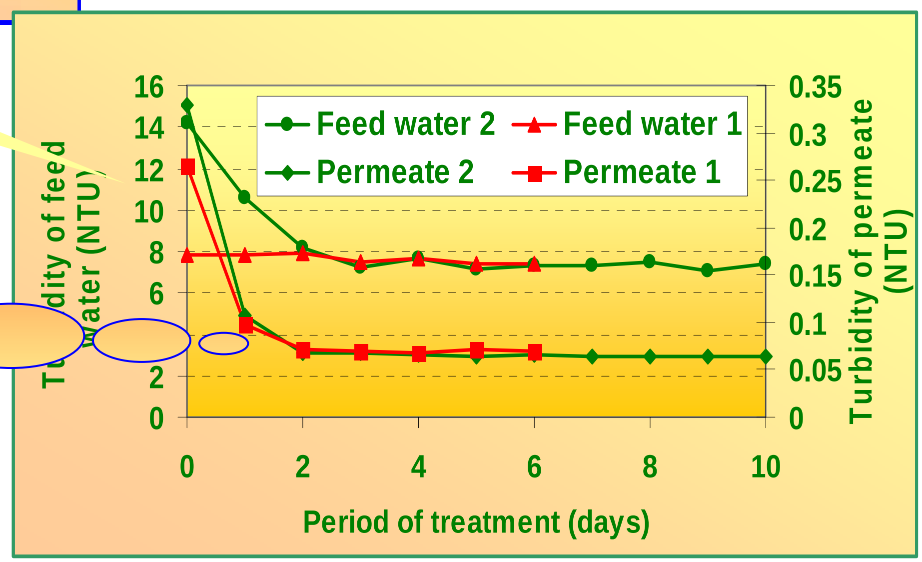


Scenario1: Direct CMF

- ☞The higher turbidity, the lower filtration time
- ☞ Fouled after 7 & 11 days of operation
- ☞ Role of foulants accumulation

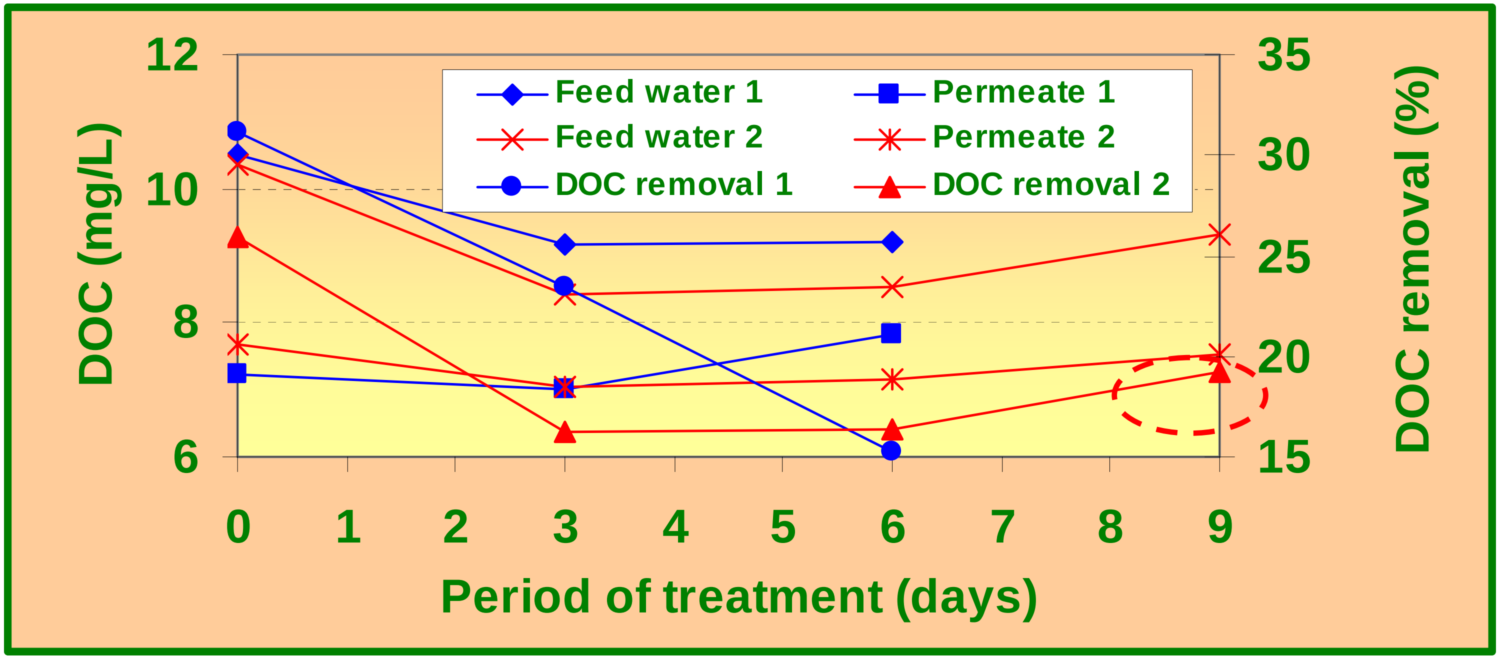
No foulants

- Role of foulants accumulation started on the 3rd day



Experiments with Surface Water

Scenario1: Direct CMF



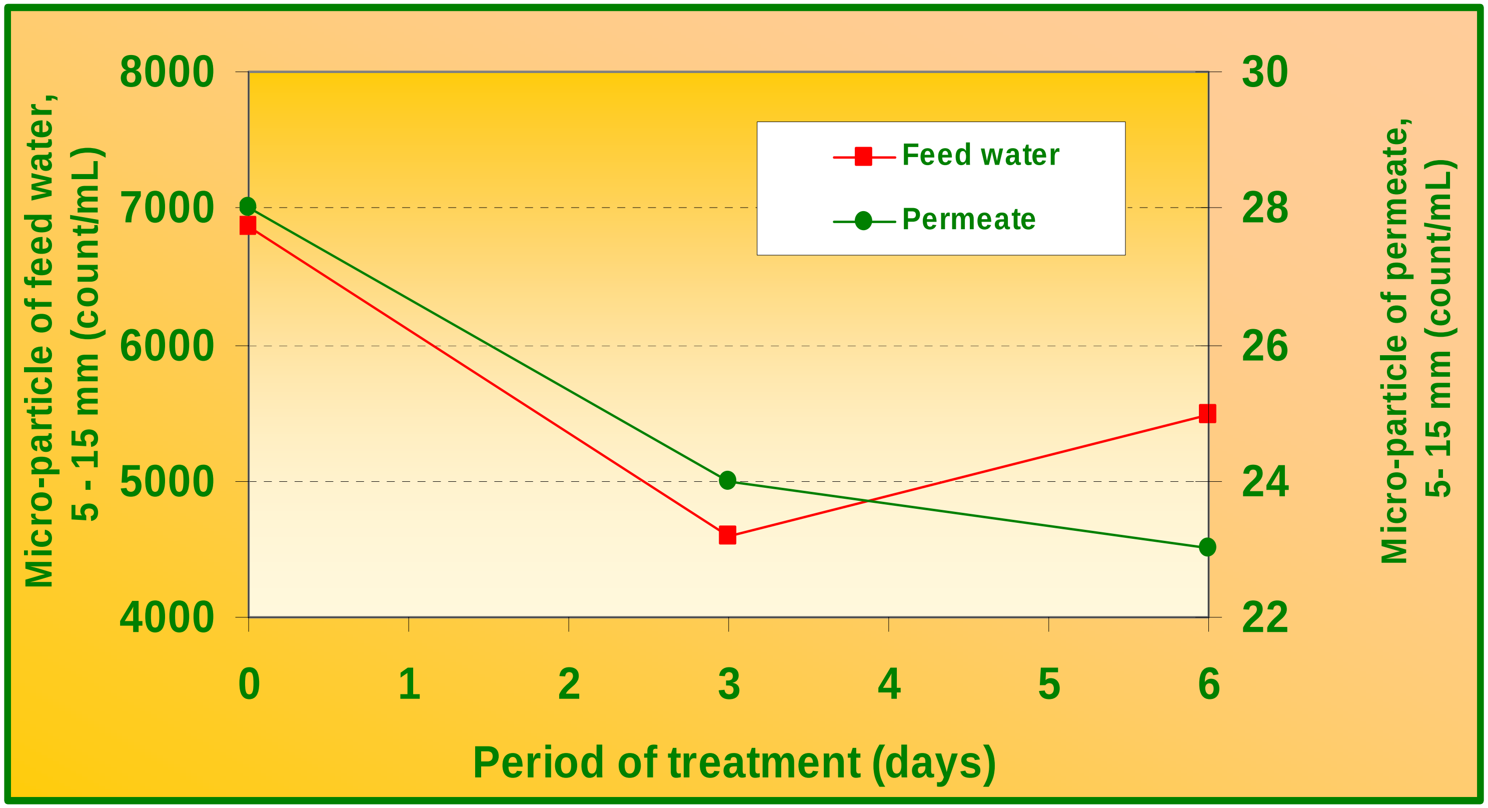
✍ TOC and DOC removals were low

☞ Need to have pre-treatments:

- Coagulation-flocculation
- Adsorption

Experiments with Surface Water

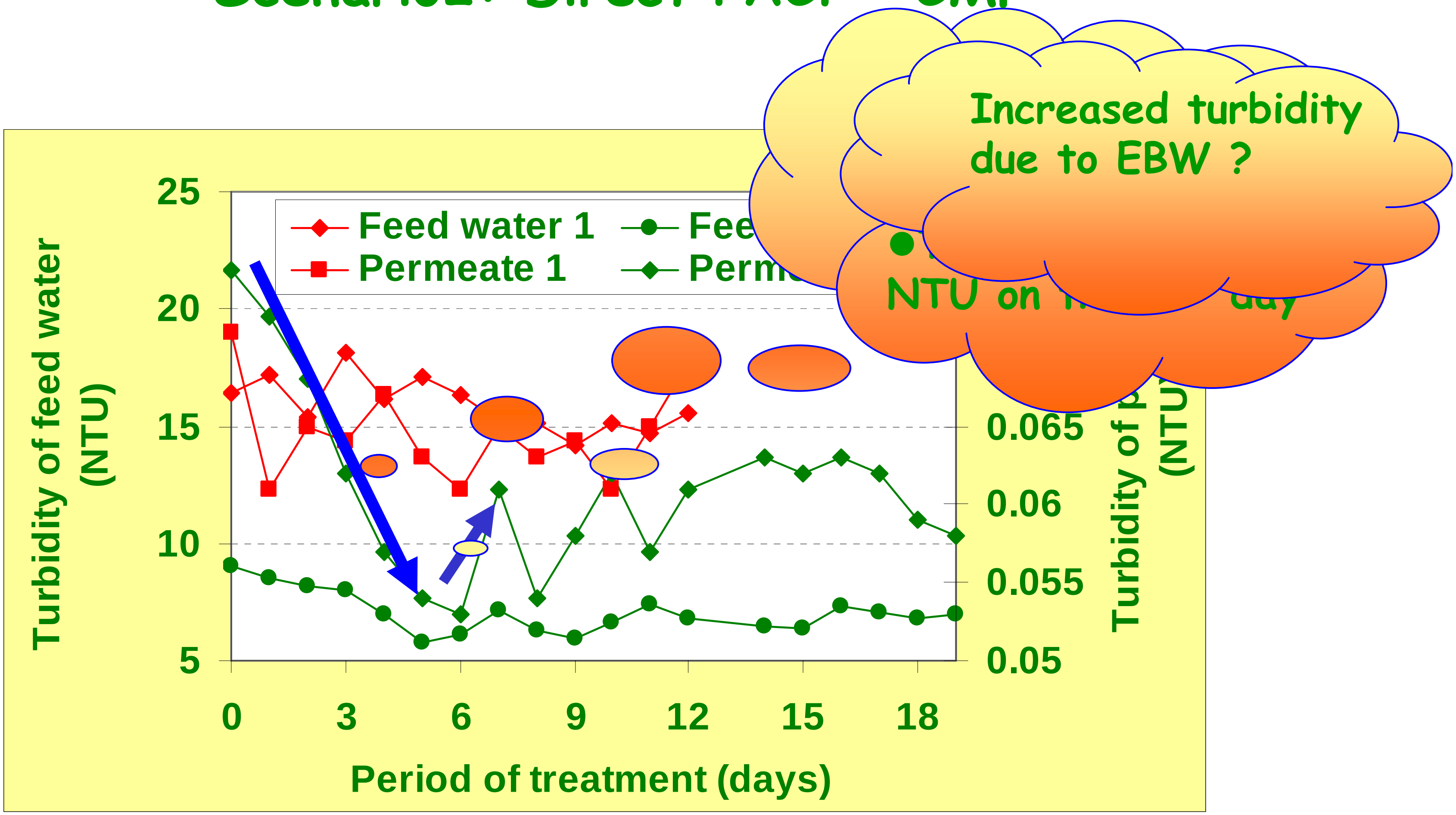
Scenario1: Direct CMF



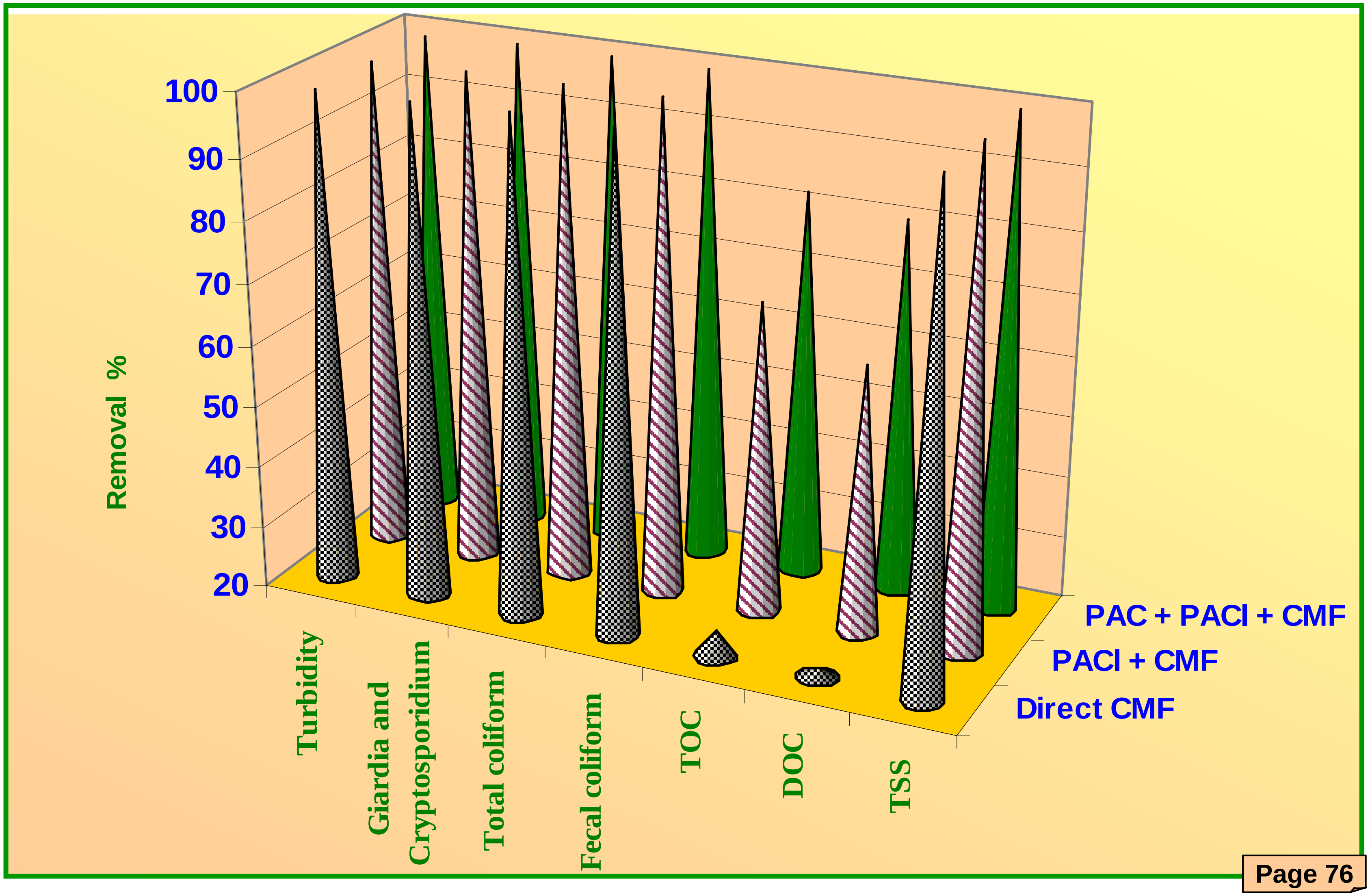
☞Removal efficiency in terms of micro-particles (5 - 15 μm) or Giadia and Crypto was 99.48 - 99.78 %.

Experiments with Surface Water

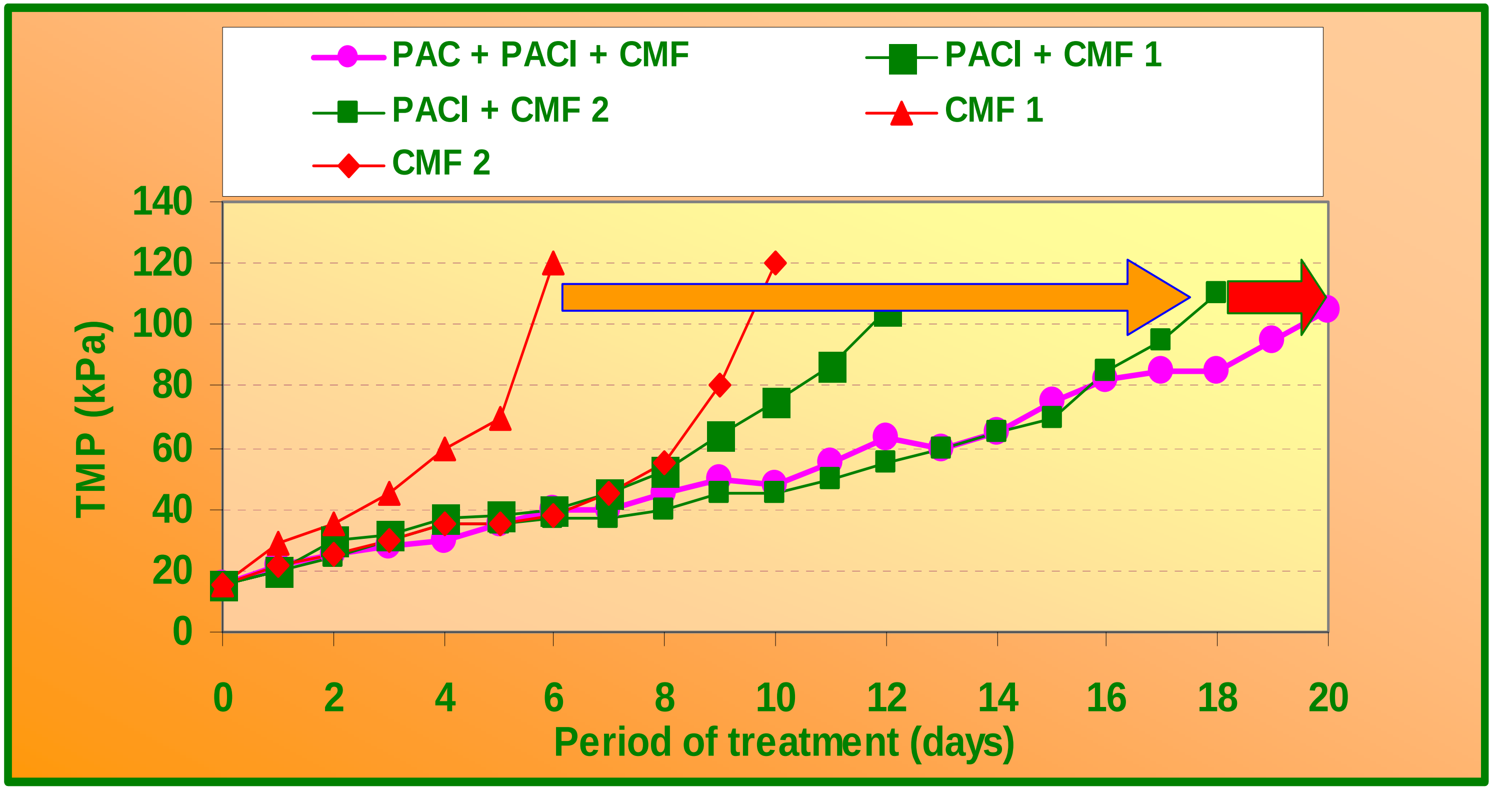
Scenario2: Direct PACl + CMF



Comparisons of Results

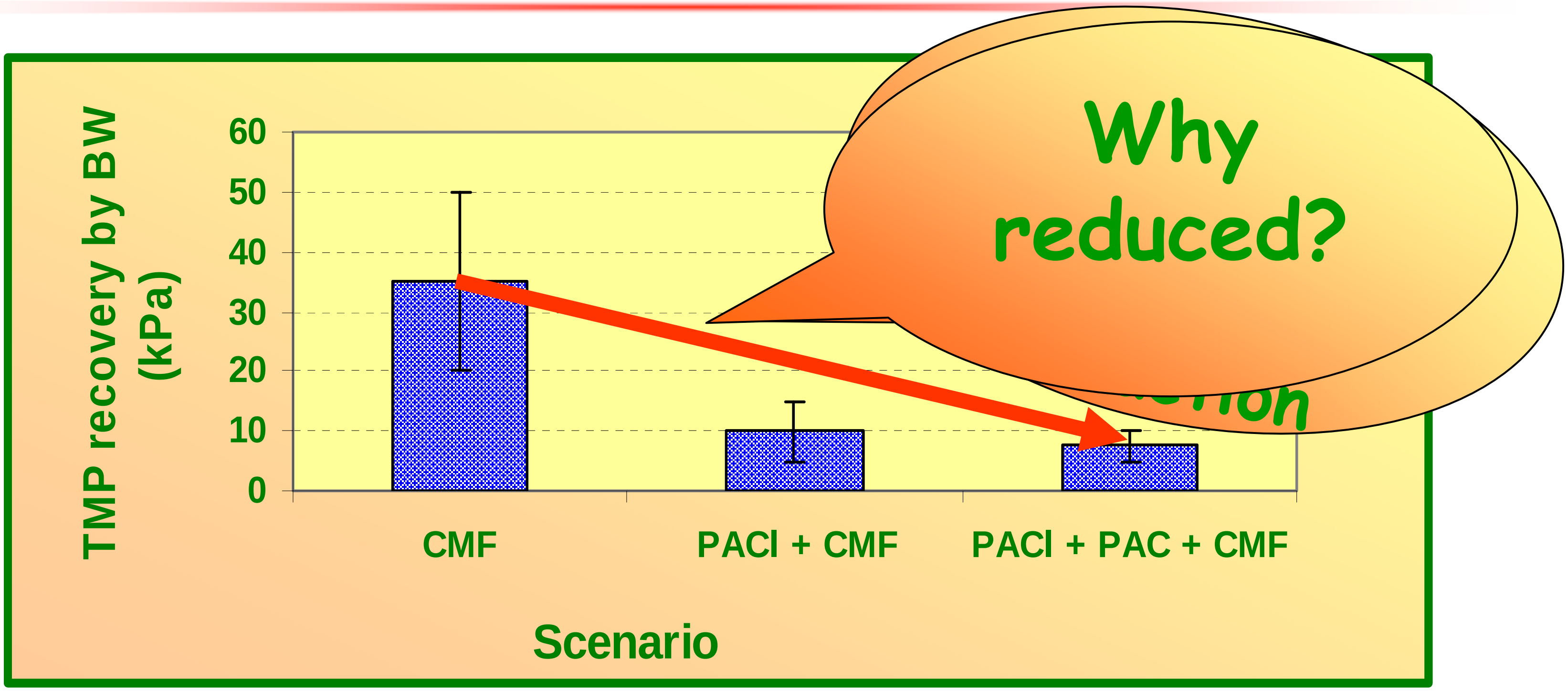


Comparisons of Results



The more hybridized systems, the slower TMP increase and longer filtration time

Comparisons of Results



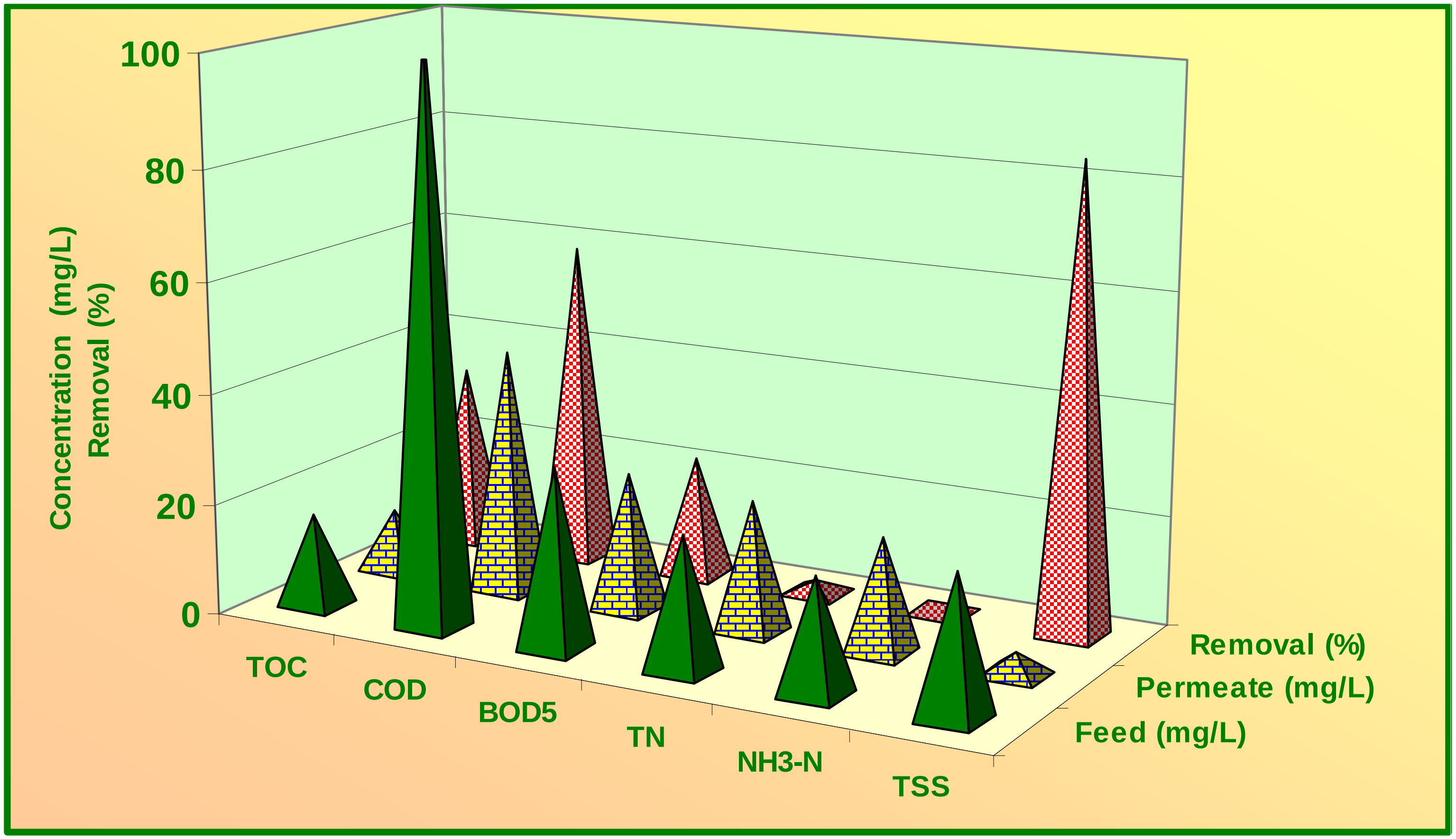
☞ **Very interesting, attractive and important roles of the pre-treatment processes**

Experiments with Surface Water

1. TSS, Total coliform and fecal coliform were removed completely
2. Others were removed more effectively by hybrid systems
3. Permeate meets domestic supply/drinking water standards (Vietnam & US.).
4. Fouling of the experimental runs could be overcome well by enhanced backwashing (EBW) and chemical cleaning.
5. Considerations of clogging of feed pump: should have a spare one in practical situation.

Experiments with Municipal Wastewater (MW)

Scenario1: Direct CMF

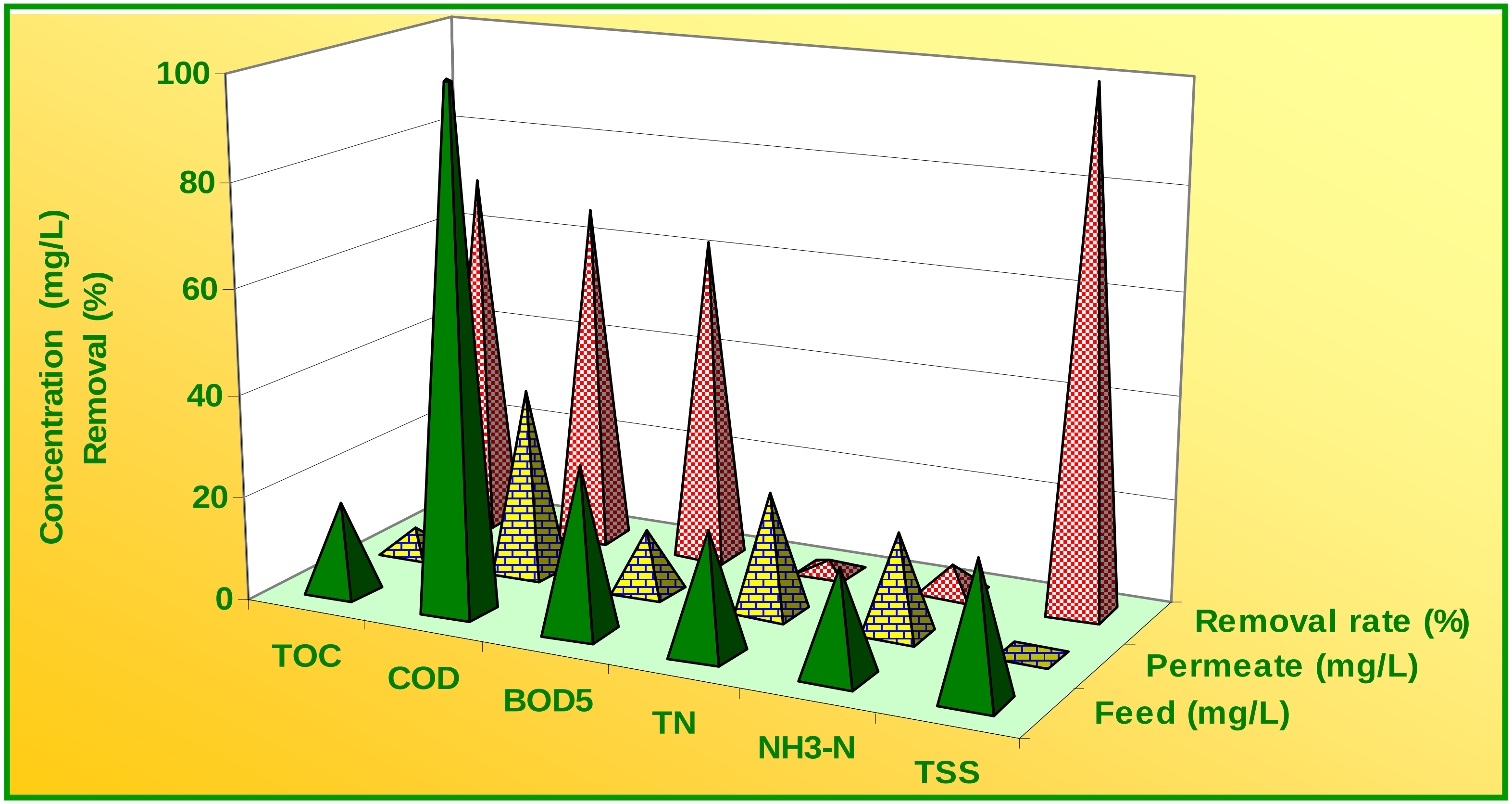


☞ 4 days for 1 cycle

Permeate turbidity of 15 NTU

Experiments with MW

Scenario2: PACl + CMF

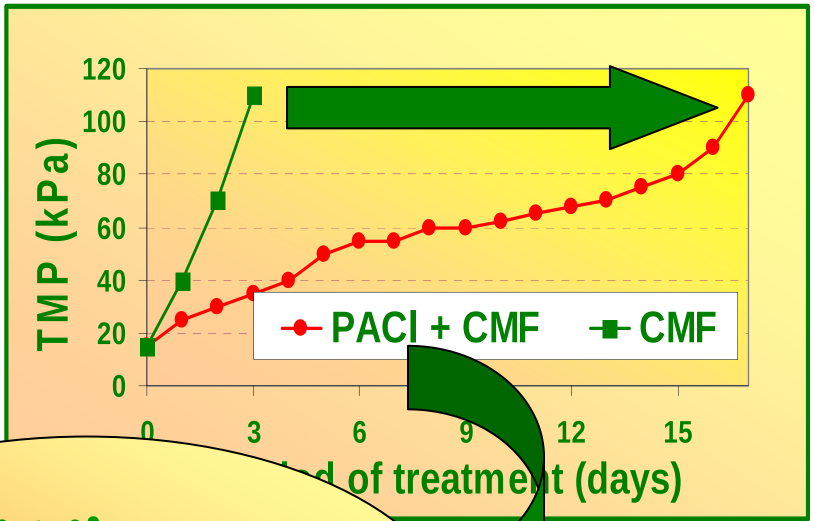


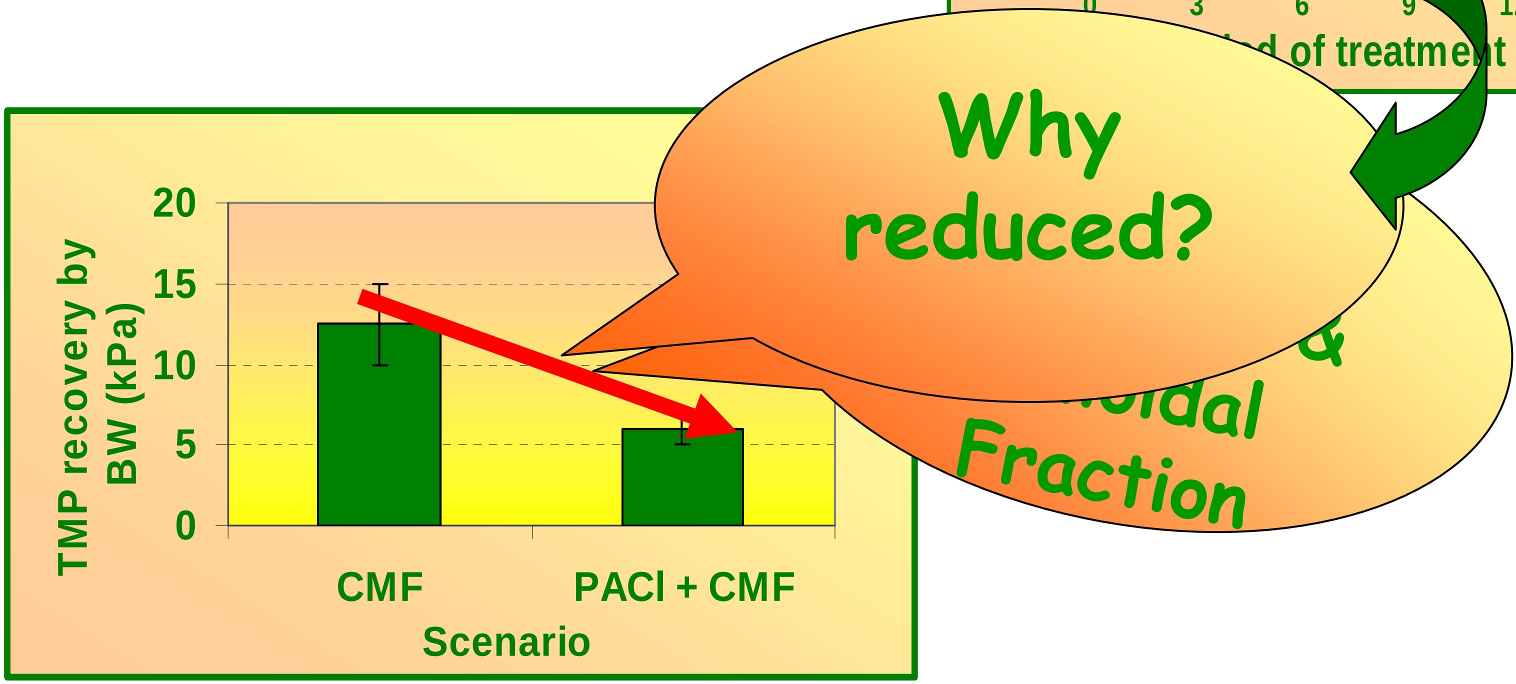
☞ 18 days for 1 cycle

Permeate turbidity of 0.21 NTU

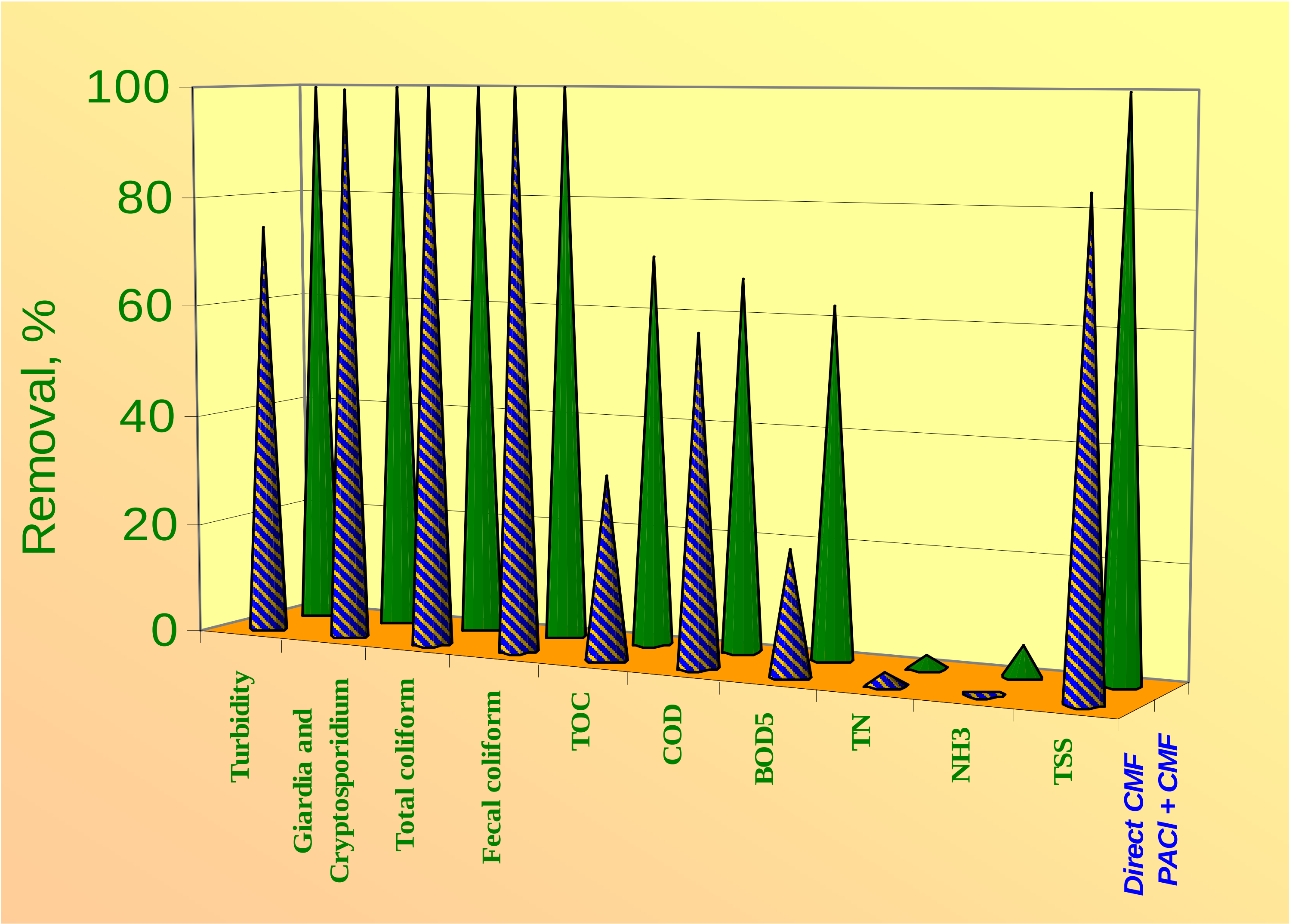
Comparisons of Results

☞ Once again… confirming the very interesting, attractive and important roles of the pre-treatment





Comparisons of Results



Conclusions

1. Performance of a hybrid CMF system would differ depending on pre-treatment process and operational conditions.

2. Better permeate, reduction of fouling, higher filtration time and more effectively chemical cleaning in the hybrid CMF systems.

3. The highest performance for SWT was in the PAC + PACl + CMF hybrid system.

4. The treated MWW by direct CMF and hybrid CMF systems can be reused for irrigation and other agricultural activities.

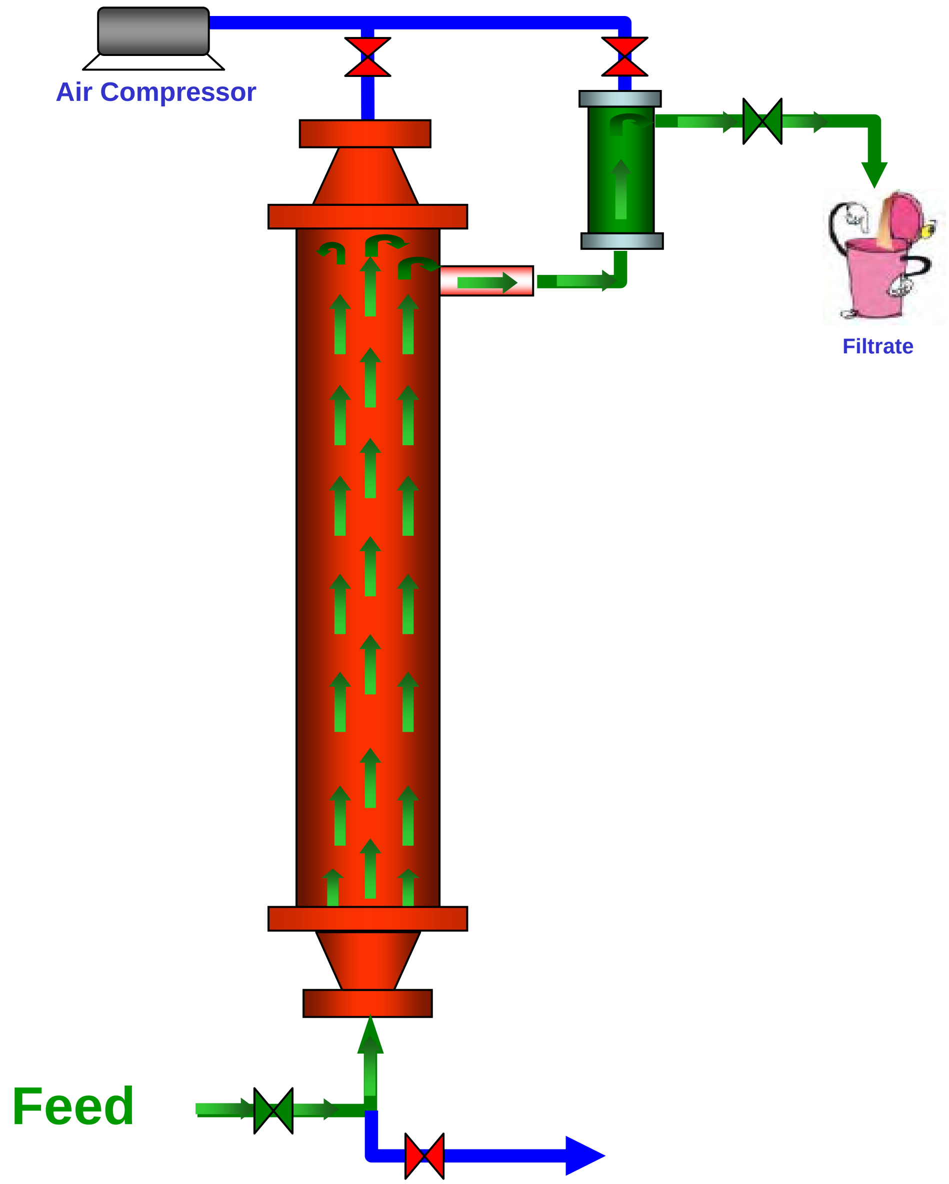
5. The highest performance for MWWT was in the PACl + CMF hybrid system

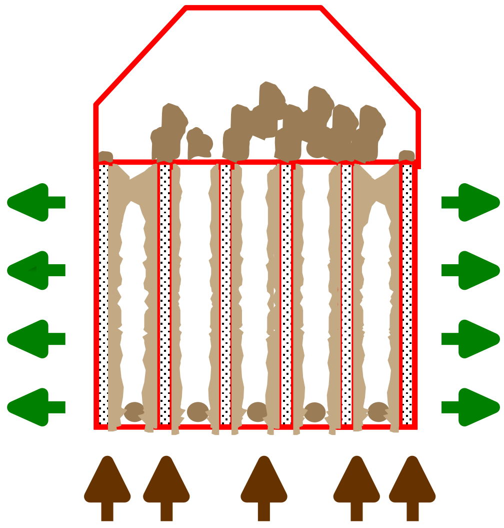
Recommendations

1. The hybrid CMF system can be enhanced by pre-ozonation process prior to coagulation process.
2. Practical researches with real river water sources in Thailand.
3. Research on potentials of reusing the secondary effluent of AIT wastewater treatment plant.
4. Research on function of PAC or ozonation in removing organic toxic substances in surface water.
5. Comparative study between the hybrid CMF system and conventional treatment in pilot scale.

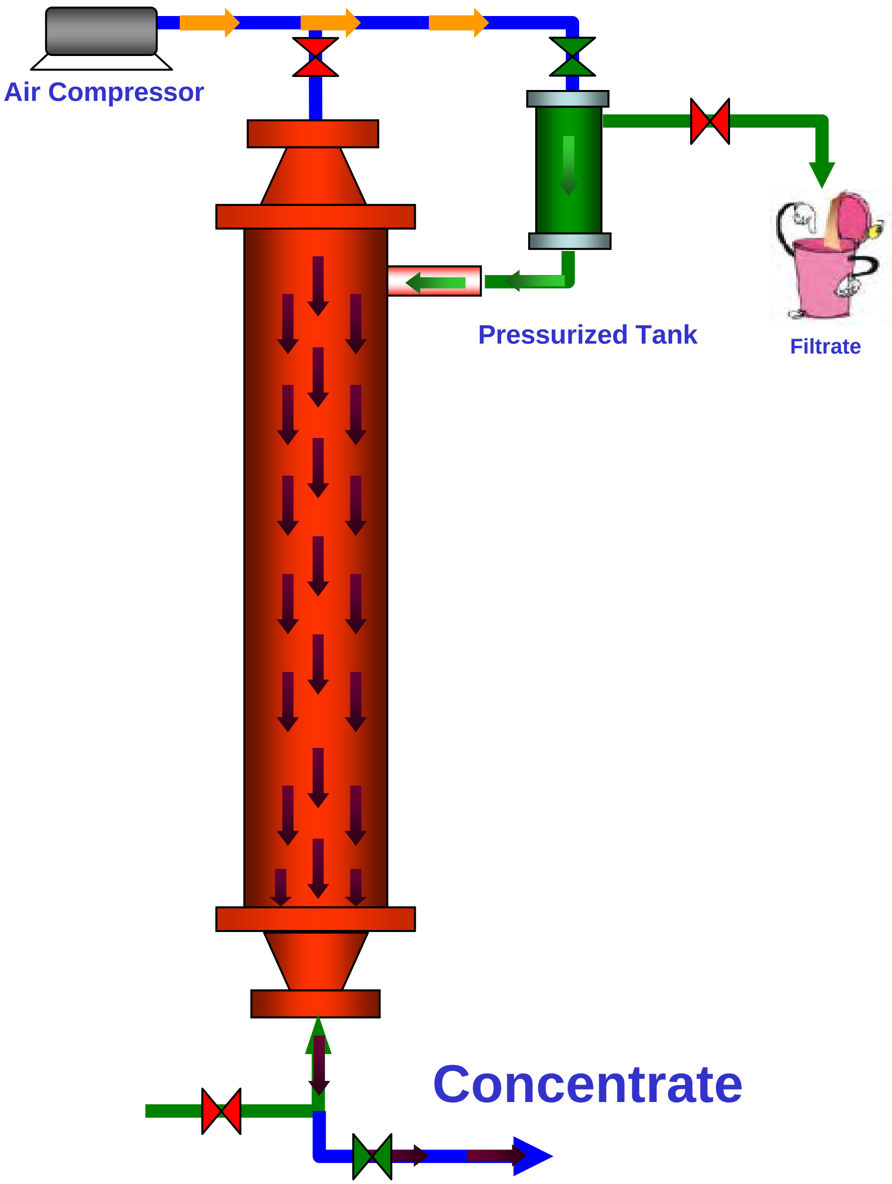
THANK YOU FOR YOUR ATTENTION!

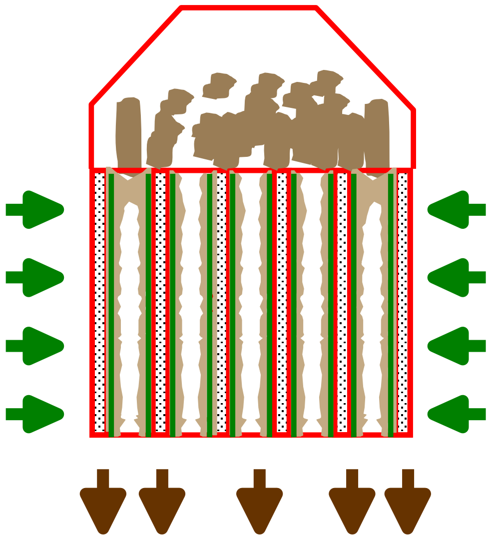
Filtration



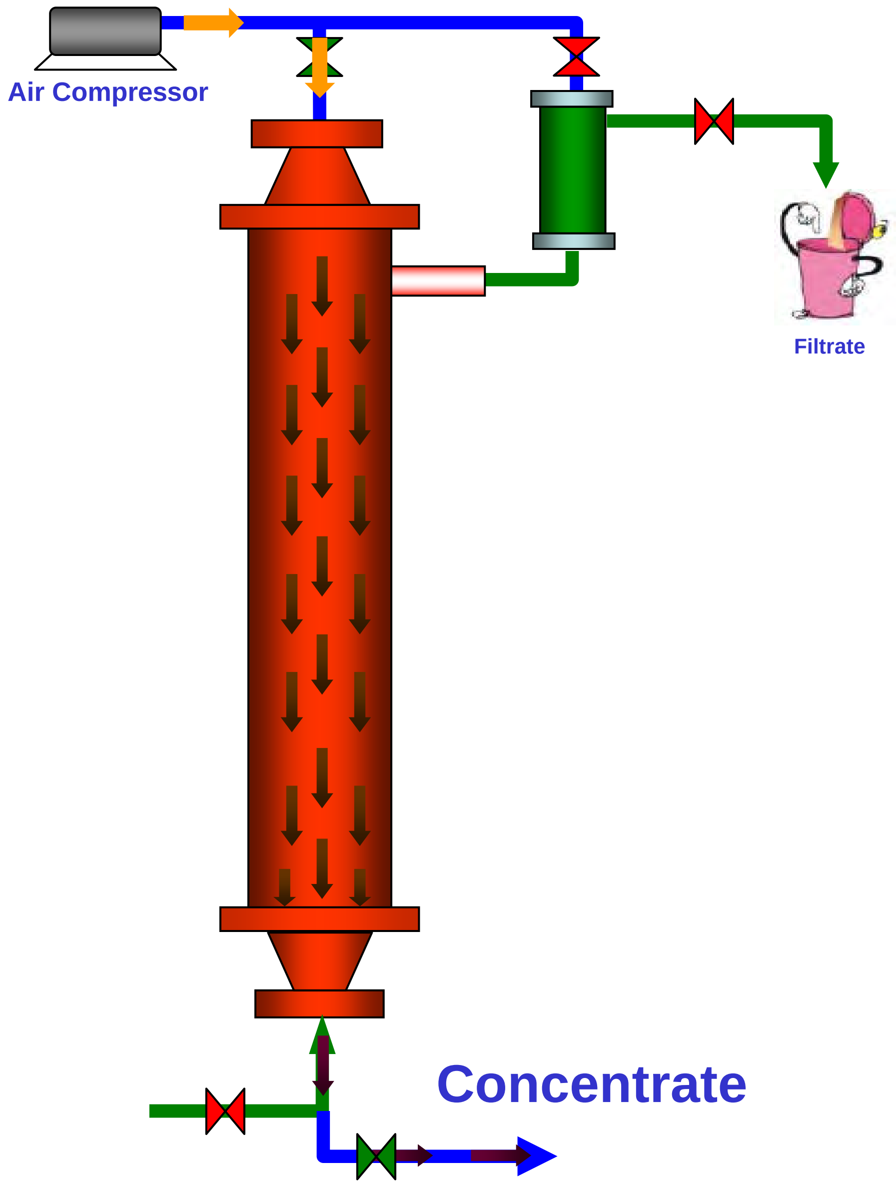


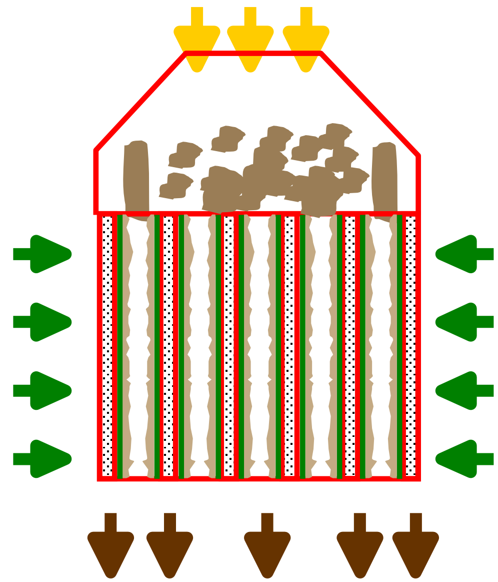
Backwashing





Air-flush





Chemical Cleaning after SWT

Cleaned membrane

Chemical Cleaning after MWWT

Feed pump problems and solutions

Parasite Protozoa

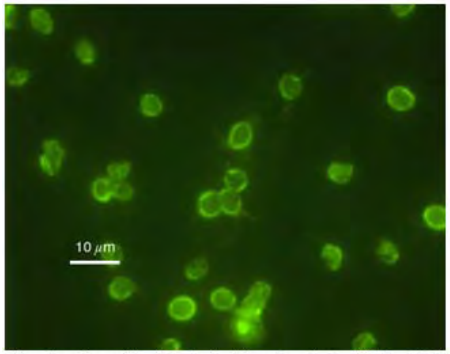


Photo Credit: H.D.A Lindquist, U.S. EPA

Cryptosporidium

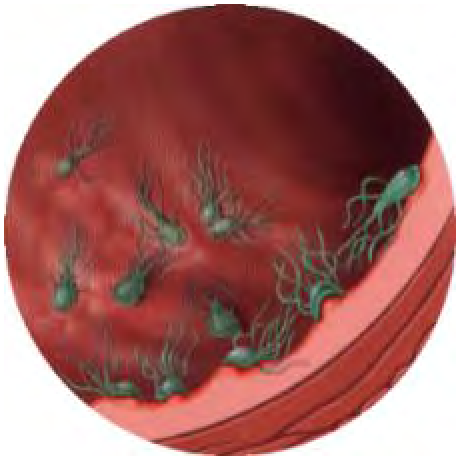
O-cyst
(4.5～5.4×4.2～5.0 µm)

Trophozoite
(10～15×6～10 µm)

Giardia

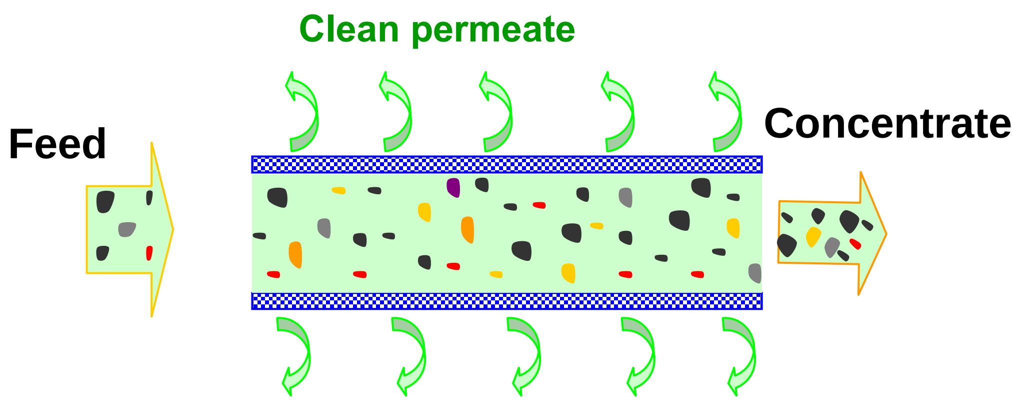
Cyst
(8～12×5～8 µm)

Effects on Human Health



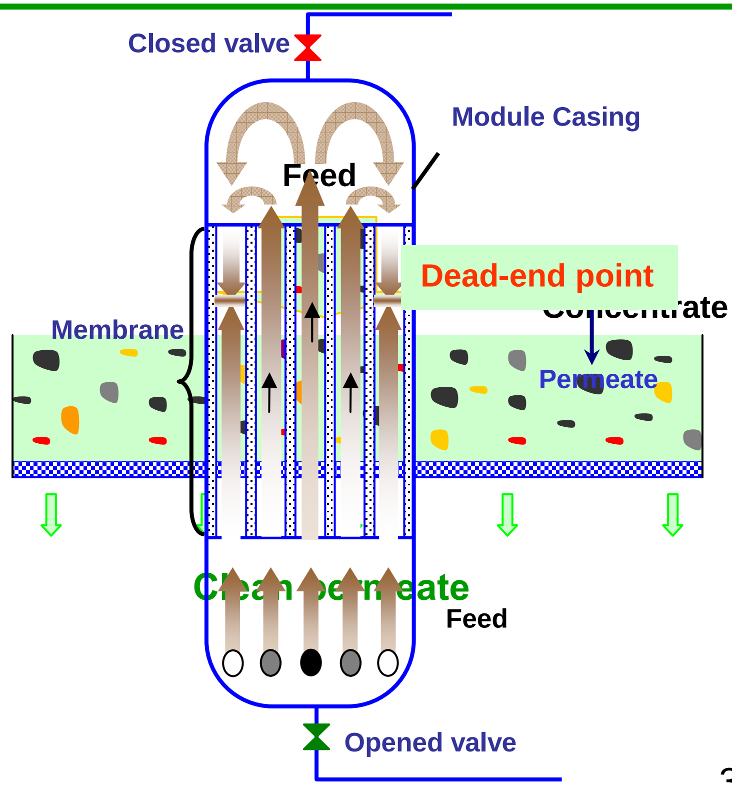
- Giardiasis, an intestinal illness.
- Chronic diarrhea, weight loss.
- Watery diarrhea/Stomach cramps
- Fever/General malaise
- Vomiting/Weight loss

Why Dead-end Selected?



Why not cross-flow ?

High pressure applied
High energy consumption
High operation cost



Dead-end

- Low flux
- Low pressure applied
- Low energy consumption
- Low operation cost
- Low fouling due to BW
- High filtration time

TMP Recovery by Chemical Cleaning

Surface water treatment

Scenarios	TMP with tap water (kPa) at flux of 50 $L/m^2.h$			
	Before run	After run	After washed by citric acid 1 %	After washed by NaClO 0.3 %
Direct CMF	15	120	60	15
PACl + CMF	15	105	25	15
PAC + PACl + CMF	15	105	20	15

TMP Recovery by Chemical Cleaning

Municipal wastewater treatment

Scenarios	TMP with tap water (kPa) at flux of 50 L/m2.h			
	Before run	After run	After washed by citric acid 1 %	After washed by NaClO 0.3 %
Direct CMF	15	110	65	15
Hybrid PACl + CMF	15	110	40	15

Experiments with Surface Water

Quality of treated water and standards

Parameters	Unit	Permeate of scenario			Standard	
		Direct CMF	PACl + CMF	PAC + PACl + CMF	Vietnam[a]	USA[b]
pH	-	7.5 – 8.1	6.5 - 7	6.8 – 7.2	6.5 – 8.5	6.5 – 8.5
Turbidity	NTU	0.066	0.064	0.055	5	1
Giardia and Cryptosporidium	% removed	99.61	99.77	99.92	-	99.9
Total coliform	MPN/100mL	0	0	0	2.2	0
Fecal coliform	MPN/100mL	0	0	0	0	0
TDS	mg/L	312	214	204	1000	500
Total Fe	mg/L	0.06	0.01	ND	0.5	0.3
Total Mn	mg/L	0.01	ND	ND	0.5	0.05
NH_3 - N	mg/L	0.49	0.03	ND	3	-

[a] Vietnamese national standards TCVN 5502:2003 - Domestic supply water

[b] National secondary drinking water standards, EPA, USA- The maximum permissible level of a contaminant in water which is delivered to any user of a public water system

Experiments with MWW

Quality of treated wastewater and standards for reusing activities

Parameters	Unit	Permeate of scenario		Reuse Standards											
		Direct CMF	PACl + CMF	Vietnam[a]	Italy[b]	Turkey[c]	China[d]			Korea[e]			Taiwan[f]	Japan[g]	EPA[h]
							d1	d2	d3	e1	e2	e3			
pH	-	6.8 – 7.8	6.3 – 7.2	5.5 – 8.5	6.0–9.5	6.5–8.5	-	-	-	-	-	-	5.5-9	5.8-9.	6-8.5
Turbidity	NTU	15	0.21	-	-	-	<5	<20	<5	<5	<5	<10	-	≤ 5	-
TSS	mg/L	4	0	-	10	30	-	-	-	-	-	-	250	≤ 5	5
TDS	mg/L	344	238	400	-	-	<1500	<1000	<1000		-	-	-		-
BOD_5	mg/L	25	12	-	20	25–50	<10	<20	<10	<10	<10	<10	-	≤ 10	20
COD	mg/L	44	36	-	100	-	-	-	-	-	-	-	-	≤ 40	-
Total Mn	mg/L	0.08	0.03	-	0.2	-	0.1	-	0.1	-	-	-	2	-	-
Total Fe	mg/L	0.03	ND	-	2.0	-	0.3	-	0.3	-	-	-	-	-	-
TN	mg/L	23.25	23.01	-	15	-	-	-	-	-	-	-	10	-	-
NH_3 - N	mg/L	20.44	19.32	-	2.0	-	<10	<20	<10	-	-	-	-	≤ 5	-
Chlorine residual	mg/L	0.05	2.05	-	0.2	-	> 1	-	-	-	-	-	-	-	> 1
Total coliform	MPN/100mL	ND	ND	200	-	-	-	-		-	-	-	-	-	ND
Fecal coliform	MPN/100mL	ND	ND	200	10 (CFU/100mL)	2–20 (CFU/100mL)	3	3	3	-	-	-	-	ND	-