การศึกษาการเปรียบเทียบการใช้นาโนฟิวเตรชันและรีเวอร์สออสโมซิสสำหรับบำบัดน้ำโบล์วดาวน์ในโรงไฟฟ้า

นายบารเมธ พึ่งแสง

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาวิศวกรรมเคมี ภาควิชาวิศวกรรมเคมี
คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2559

COMPARISON OF NANOFILTRATION AND REVERSE OSMOSIS MEMBRANE WATER TREATMENT SYSTEMS FOR COOLING TOWER BLOWDOWN IN A CO-GENERATION POWER PLANT

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A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Chemical Engineering
Department of Chemical Engineering
Faculty of Engineering
Chulalongkorn University
Academic Year 2016

Thesis Title	COMPARISON OF NANOFILTRATION AND REVERSE OSMOSIS MEMBRANE WATER TREATMENT SYSTEMS FOR COOLING TOWER BLOWDOWN IN A CO-GENERATION POWER PLANT
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บารเมธ พึ่งแสง : การศึกษาการเปรียบเทียบการใช้นาโนฟิวเตรชันและรีเวอร์สออสโมซิสสำหรับบำบัดน้ำโบล์วดาวน์ในโรงไฟฟ้า (COMPARISON OF NANOFILTRATION AND REVERSE OSMOSIS MEMBRANE WATER TREATMENT SYSTEMS FOR COOLING TOWER BLOWDOWN IN A CO-GENERATION POWER PLANT) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: ดร.ชลิดา คล้ายโสม, 147 หน้า.

โรงไฟฟ้าหลายแห่งในประเทศไทยตั้งอยู่ห่างไกลจากแหล่งน้ำธรรมชาติและจำเป็นต้องซื้อน้ำประปาปริมาณมากที่มีราคาแพงเพื่อใช้เป็นน้ำหล่อเย็นในหอหล่อเย็น และปล่อยน้ำโบล์ดาวน์ทิ้งออกไปโดยไม่มีขั้นตอนการรีไซเคิลกลับมาใช้ใหม่ในกระบวนการระบายความร้อน ด้วยเหตุผลดังกล่าวทำให้เทคโนโลยีที่มีขนาดเล็ก ใช้พลังงานต่ำและมีประสิทธิภาพสำหรับการบำบัดน้ำโบล์ดาวน์ของโรงไฟฟ้าในชุมชน ดังเช่นเทคโนโลยีเมมเบรนมีความน่าสนใจที่จะศึกษา งานวิจัยนี้ได้ทำการศึกษาประสิทธิภาพการบำบัดน้ำโบล์วดาวน์จากหอหล่อเย็นของโรงไฟฟ้าด้วยเทคนิคเมมเบรนสองเทคนิค คือ นาโนฟิลเตรชัน (NF) และรีเวอร์สออสโมซิส (RO) นอกจากนี้ยังให้ความสนใจเกี่ยวกับวิธีการปรับสภาพน้ำก่อนการบำบัดด้วย NF และ RO เมมเบรนเพื่อลดปัญหาการอุดตันของเมมเบรนและเป็นการยืดอายุการใช้งานเมมเบรน โดยสนใจศึกษาวิธีในการปรับสภาพน้ำสองวิธี ได้แก่วิธีคอนเวนชันแนลและวิธีอัลตราฟิวเตรชัน (UF) โดยวิธีคอนเวนชันแนลนั้น ผลการทดลองแสดงให้เห็นว่าสำหรับน้ำตัวอย่างที่เติมสารโพลีอะลูมินัมคลอไรด์ (PACl) ความเข้มข้น 150 มิลลิกรัมต่อลิตร ร่วมกับการใช้สารโพลีอะครีลาไมด์ชนิดประจุบวกที่ความเข้มข้น 1 มิลลิกรัมต่อลิตร มีประสิทธิภาพในการปรับสภาพน้ำได้ดีที่สุดในแง่ของดัชนีความหนาแน่นของตะกอน (SDI) และความขุ่นที่ และเมื่อเปรียบเทียบผลลัพธ์ที่ได้จากการปรับสภาพน้ำด้วยวิธีอัลตราฟิวเตรชั่น ซึ่งมีค่า SDI และค่าความขุ่นที่ต่ำกว่า รวมถึงพื้นที่ในการก่อสร้างและของเสียจากสารเคมีที่น้อยกว่าวิธีคอนเวนชันแนล และถูกเลือกใช้เป็นวิธีการปรับสภาพน้ำที่เหมาะสมสำหรับการบำบัดน้ำด้วยเมมเบรน สำหรับการบำบัดน้ำด้วยเมมเบรน NF ผลการทดลองแสดงค่าการซึมผ่านของเมมเบรนที่สูง (14.03 ลิตร/ชั่วโมง.ตารางเมตร.บาร์) แต่ไม่เหมาะสมที่จะนำมาใช้บำบัดน้ำจากหอหล่อเย็นได้เนื่องจากสามารถกำจัดเกลือที่ละลายในน้ำได้ประมาณ 50% ขณะที่เมมเบรน RO แสดงค่าการซึมผ่านของเมมเบรนที่ต่ำกว่า (6.32 ลิตร/ชั่วโมง.ตารางเมตร.บาร์) แต่สามารถกำจัดเกลือที่ละลายในน้ำได้สูงประมาณ 98% ซึ่งถูกเลือกให้เป็นวิธีที่เหมาะสมในการบำบัดน้ำจากหอหล่อเย็นของโรงไฟฟ้าได้

ภาควิชา วิศวกรรมเคมี ลายมือชื่อนิสิต ....
สาขาวิชา วิศวกรรมเคมี ลายมือชื่อ อ.ที่ปรึกษาหลัก ....
ปีการศึกษา 2559

5671007021 : MAJOR CHEMICAL ENGINEERING

KEYWORDS: COOLING TOWER BLOWDOWN, NANOFILTRATION, REVERSE OSMOSIS

BARAMATE PUNGSANG: COMPARISON OF NANOFILTRATION AND REVERSE OSMOSIS MEMBRANE WATER TREATMENT SYSTEMS FOR COOLING TOWER BLOWDOWN IN A CO-GENERATION POWER PLANT. ADVISOR: CHALIDA KLAYSOM, Ph.D., 147 pp.

Several power plants in Thailand are located in community area far from the natural sources of water and need to buy expensive tap water from private suppliers for use as a cooling water. This water is normally discharged without recycling back to the cooling processes. For this reason, the small size, low power consumption and effectiveness treatment methods like membrane processes for recycle blowdown water in the district power plant are interested. In this work, the performances for treatment blowdown water via two membrane treatment technologies, nanofiltration (NF) and reverse osmosis (RO) were investigated. Furthermore, attention was paid to ensuring that the pretreatment method could enhance the lifespan of the NF and RO membranes and decrease the membranes' fouling characteristics. Two different pretreatment methods, conventional and ultrafiltration (UF) were compared. For the conventional pretreatment, the results showed that the concentration of 150 mg/L of Polyaluminium chloride (PACl) in the presence of 1.0 ppm of anionic polyacrylamide (APAM) showed the best pretreatment performance in terms of silt density index (SDI) and turbidity. However, UF membrane showed a better pretreatment performance with lower SDI, and turbidity values, lower construction area, less chemical waste, and was selected to be appropriate pretreatment method for membrane treatment. For membrane treatment, NF showed the higher membrane permeability values (14.03 L/hr.m^2.bar) but cannot be used as make up water because lower salts rejection (50%). Whereas RO showed the lower membrane permeability values (6.35 L/hr.m^2.bar) but higher salts rejection (98%) and available for treatment blowdown water.

Department:	Chemical Engineering	Student's Signature	....
Field of Study:	Chemical Engineering	Advisor's Signature	....
Academic Year:	2016		

ACKNOWLEDGEMENTS

I would like to express my sincere thanks to my thesis advisor, Dr. Chalida Klaysom, for her patience, motivation, invaluable help and constant encouragement throughout the course of this research. I am most grateful for her teaching and advice. Her guidance helped me in all the time of research and writing of this thesis. I would not have achieved this far and this thesis would not have been completed without all the support that I have always received from her.

Besides my advisor, I would like to thank the rest of my thesis committee: Dr. Varun Taepaisitphongse, Assoc. Prof. Tawatchai Charinpanitkul, and Asst. Prof. Jintawat Chaichanawong for their encouragement, insightful comments, hard questions, suggestions and all their help , not only the research methodologies but also many other methodologies in life.

Finally, I most gratefully acknowledge my parents and my friends for all their support throughout the period of this research.

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CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

Water is of crucial importance for all living beings and world economy. Every human activity, including agriculture, power production, industrial manufacturing and tourism, relies on water resources to grow and sustain their businesses. However, 97 percent of total global water is saline water that cannot be used directly for most human activities. The majority of the remaining three percent of freshwater is frozen or locked up in glaciers, and not available to the human. While only less than one percent of global water is surface water and ground water, which is appropriate and ready for use **(1)**. Figure 1.1 and Table 1.1 showed the distribution of water in the world and the information of quantity and its sources.

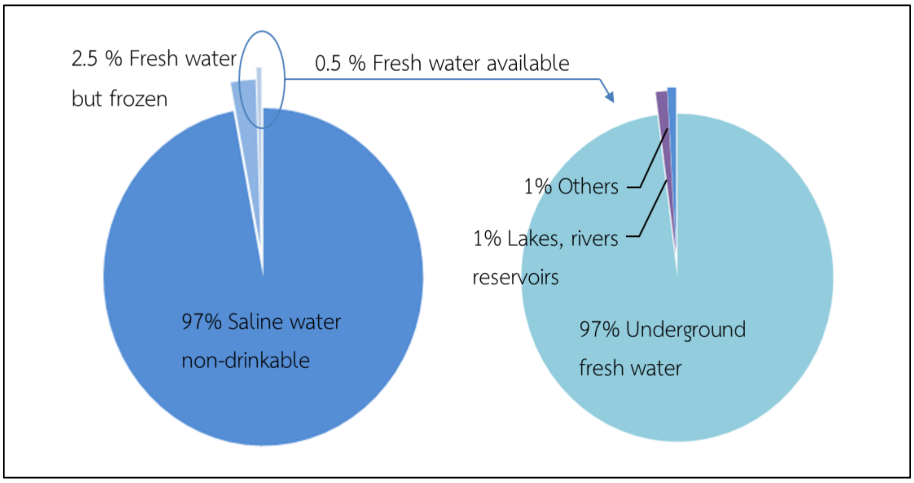

Figure 1.1 Percent distribution of water in the world **(2)**

Table 1.1 Sources, quantity and quality of water in the world **(1-3)**

Water sources	Volume*	Percent of total water	Percent of fresh water	Remarks
Salt water				
- Oceans, Seas, Bays	1,338,000	96.54	-	**- Can be indirectly used by humans** - Contains a high level of dissolved salt.
- Saline / brackish ground water	12,870	0.93	-	
- Salt water lakes	85	0.006	-	
Fresh water				
- Ice caps, Glaciers, Permanent Snow	24,064	1.74	68.70	**- Not accessible for human** - Stored in shallow (up to 2,000 meters) basins.
- Ground Ice & Permafrost	300	0.22	0.86	
- Fresh groundwater	10,530	0.76	30.06	**- Can be directly used by human**
- Fresh water lakes	91	0.007	0.26	
- Others	44	0.0033	0.12	
Total	**1,386,000**	**100**	**100**	

* Unit: 1,000 cubic kilometers

Available fresh water for people become lesser and two-thirds of the world population could be living under water-stressed situations in 2025 **(4)**. Accordingly, water scarcity will be a threat in the future; therefore, reclamation and reuse of wastewater from municipalities are a must-practice.

Recently, in Thailand the accelerated economic growth and the expansion of industries have caused a huge water demand and increasing water withdrawals, particularly in energy production sectors **(5)**. Water and energy are both important resources that are inextricably and reciprocally linked. Indeed, energy production requires a lot of water, for example cooling water at thermal power plants. Power production is considered to be an intensive - water - using process. Table 1.2 shows the various sources of water and their quantities used in some power plants in Thailand. Most water used in the power plant is for cooling purpose. Since a significant amount of water is lost due to evaporation, wind action, and drainage (blowdown), a large amount of make-up water is needed to maintain the water balance and keep cooling water operation at a steady state. In this regard, blowdown water which constitutes the biggest portion of feed water loss, was discharged directly to surface water bodies and was not reused as treated make-up water in many countries **(6)**.

Table 1.2 Water withdrawals from various resources by power plants (PP) in Thailand

Power Plant (Province)	**Plant Capacity (MWh)**	**Source of water**	**Water withdrawal (m^3/day)**	**Reference**
BLCP PP (Rayong)	1,435	Sea water (Gulf of Thailand)	5,340,000	**(7)**
Bangpakonk PP (Chachoengsao)	760	Bangpakong river	81,500	**(8)**
Krabi PP (Krabi)	340	Pakasai canal	51,700	**(9)**
North Bangkok PP (Bangkok)	705	Chaopraya river	40,000	**(10)**
Chana PP (Songklar)	730	Natub canal	39,000	**(11)**
Namphong PP (Khon Kaen)	710	Ubonrat Dam	29,200	**(12)**
Wang Noi PP (Ayutthaya)	800	Rapeepat canal	20,200	**(13)**
Maemoh PP (Lamphang)	2,400	Majam Dam	100,900	**(14)**
Rachaburi PP (Rachaburi)	3,645	Mae Klong River	91,700	**(15)**

For economic reasons, most of power plants are, therefore, sited close to the natural water resources like oceans or rivers. However several power plants in Thailand are located far from natural water supply, such the small power plant in community district or industrial estates. These power plants use large amount and high price of tap water supplied from a public sector that increases the plant production cost. Therefore, scarcity of water, large quantities of cooling tower blowdown water, and an increase in water prices were the primary motivations driving recent studies and researches on blowdown water treatment.

With the limited of useful space, membrane technologies such as nanofiltration (NF) and reverse osmosis (RO) were considered to be the most effective processes for removing soluble and insoluble organic and inorganic contaminants in wastewater **(16-27)**. However, passing the feed water directly through the NF and RO membranes could render an irreversible fouling that will affect operation costs, energy demand, membrane cleaning, and lifespan of the membrane elements **(28)**. Therefore, suitable pretreatment processes for feed water prior to membrane are required. Considering operation parameters and processes, combination of NF or RO with a pretreatment method such as conventional or UF can be effective for treatment blowdown water from power plant.

A 120 megawatt-hour co-generation power plant located near Suvarnabhumi International Airport was used as the case study of the design of blowdown water treatment unit for the power plant with space and water resource limits. This plant currently uses more than 6,000 m^3 per day of tap water supplied from a public sector for cooling water. This water is expensive, but it is discharged without recycle back to the process. Therefore, the main aim of this research is to design a water recycle/treatment membrane based unit for the plant that could improve the efficiency of water usage and reduce the plant production cost.

1.2 Outcomes

This research is advantageous for the power plants and other industry plants with constrains in space and water facility resource. The expected outcomes from this research are as follows.

1. The reduction of water consumption by recycling wastewater, which can reduce the production cost of the plant.
2. Design of efficient water management process.
3. A good reputation in the industry for social responsibility as an environmentally-friendly company.

1.3 Research Objectives

The main objective of this study is to design an efficient, economical membrane based system, nanofiltration (NF) and reverse osmosis (RO), for recycle discharged cooling water from a co-generation power plant located near Suvarnabhumi International Airport.

1.4 Scope of the Study

1. Survey of potential water treatment options.
2. Study the effect of coagulant and flocculant chemical dosage with multimedia filter for conventional pretreatment process before membrane desalting process.
3. Study the effect of UF for membrane pretreatment process before membrane desalting process.
4. Study the efficiency of NF and RO as a desalting process for treatment of discharged water from the power plant.
5. Design the treatment unit of discharged water from the power plant.
6. Study the feasibility analysis and sensitivity analysis of treatment unit.

CHAPTER 2

BACKGROUND & LITERATURE REVIEWS

2.1 Introduction

At present, about 20% of fresh water in the world is used by industries in the production process for various purposes, such as washing, cleaning, cooling, transportation of products, and sanitary needs of staff in company **(4)**. However, the industrial sector is not only the main water user, but also the major pollution producer. Electrical power production is one of the largest water users that consume more than 70 % of total water in industrial sector **(29)**. The power production uses approximately 1,700 L of water to produce a megawatt-hour of electric power and, of this volume, more than 90% is water for cooling system **(30)**. To meet the future constraints of limited freshwater resources and for long term water conservation, it is essential for power plants to develop and implement wastewater minimization technologies that can recover most water from the system.

In this chapter, water used for cooling tower in power production plants is explained. Parameters for determining water qualities suitable for the industrial use, especially for the cooling purpose, are provided. In addition, the technologies applied for water treatment in the power plants are reviewed.

2.2 Cooling Systems in Power Plants

Water is boiled to create high pressure steam, which then spins steam turbines to generate electricity in power plants. The heat used to boil water is from combustion of coal, natural gas, and oil, from nuclear reactions, or from geothermal heat sources underground. Once high pressure steam has passed through steam turbines, it is sent to the cooling systems to be condensed back into water phase before being re-circulated back to the system. There are three main types of cooling systems as shown in Figures 2.1-2.3.

(1) Once-through cooling systems

Once-through cooling systems in Figure 2.1 take water called cooling water from nearby sources and circulate it through pipes to absorb heat from the high pressure steam in condensers, and discharge the now warmer water to the local source, such as rivers, lakes and ocean. The pros of once-through systems are simplicity and low costs. However, few power plants use the once-through cooling system because it requires a lot of water withdrawals that interrupt local ecosystems and as well due to the limit in available abundant supplies of water sources.

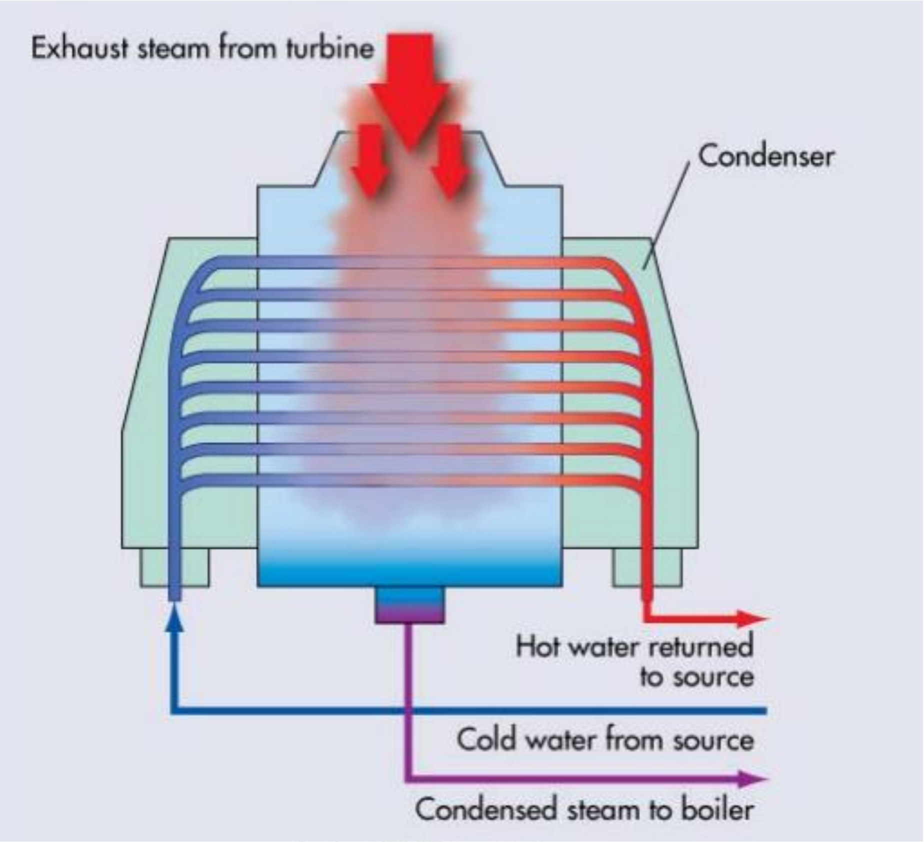

Figure 2.1 Once-through cooling systems **(31)**

(2) Wet-recirculating cooling systems or open-recirculating systems

Unlike once-through systems, wet recirculating systems (Figure 2.2) reuse cooling water by using an ambient air as a heat sink, rather than to immediately discharge it to the environment. There are some water losses from evaporation and the rest is sent back to the condensers. This system requires make-up water to replace the lost water through evaporation in the cooling towers. Wet-recirculating systems use much lower water withdrawals than the once-through systems.

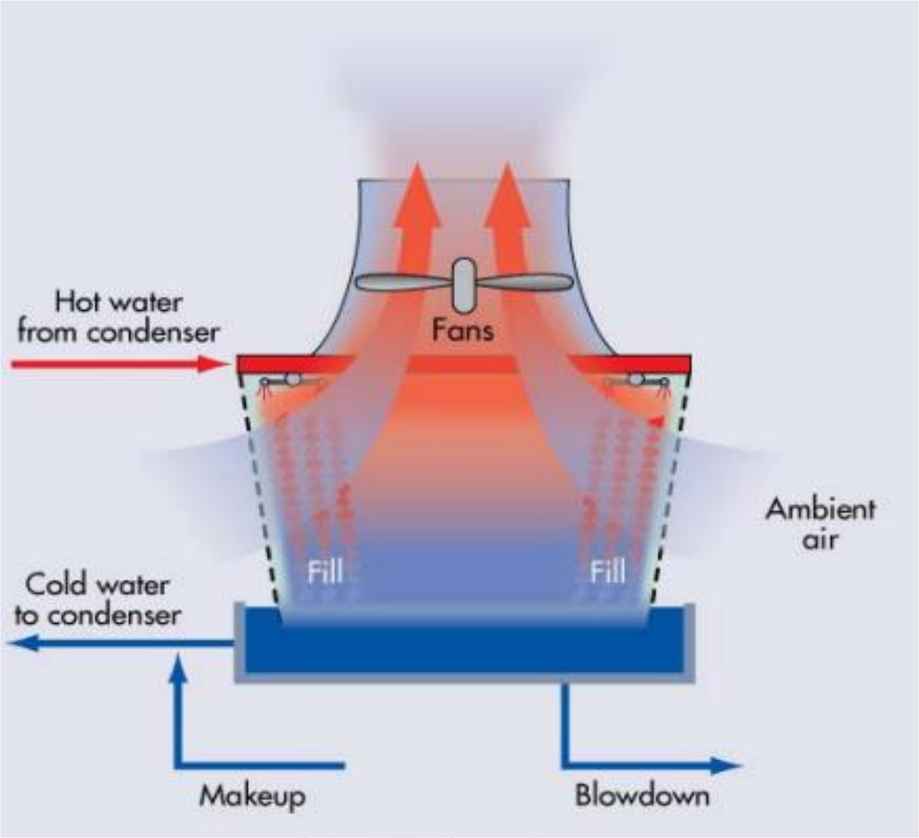

Figure 2.2 Wet-recirculating cooling systems or open-recirculating systems **(31)**

(3) Dry-cooling systems

Dry-cooling systems (Figure 2.3) use air instead of water to cool the high pressure steam. This system can decrease total water consumption of the power plant by more than 90 percent **(30)**. However, these water savings come with a high cost and high fuel consumption **(32)**. The installations of dry-cooling systems were mostly in small power plants. Table 2.1 shows the comparison of three main types of cooling systems.

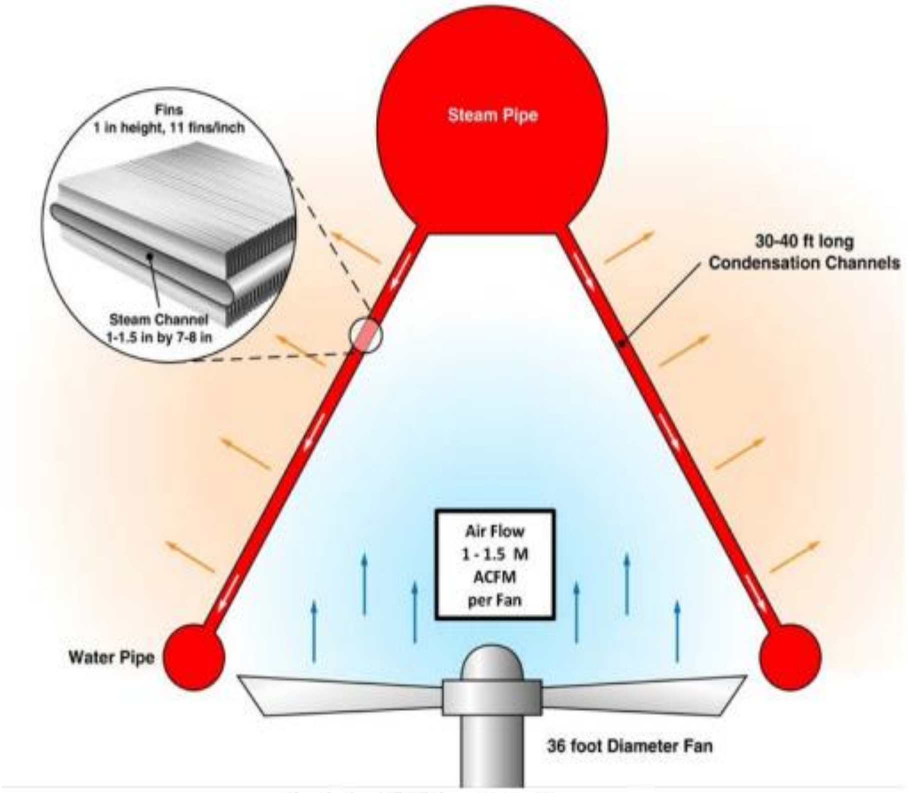

Figure 2.3 Dry-cooling systems **(31)**

Table 2.1 Comparison of each type of cooling system (31)

Cooling type	**Water Withdrawal**	**Water Quality**	**Capital Cost**	**Plant Efficiency**	**Ecological Impact**
Once-through	Intense	Moderate	Low	Good	Intense
Wet Cooling	Moderate	Intense	Moderate	Good	Moderate
Dry Cooling	None	None	High	Bad	Low

In Thailand, the once through cooling system and wet re-circulating cooling system are widely used **(33)**. The choice of cooling system depends on the quantity and quality of supplied water. According to water scarcity discussed earlier, the wet cooling system is predicted to be more popular in the near future.

2.3 Principle of Operation for Wet Cooling Tower

As earlier mentioned, after the heat exchanging process, this cooling water is heated up and in most cases it cannot be released directly to the environment, or circulated back to the system, unless it is cooled. One way to do this is by spraying the heated cooling water through a cooling tower to exchange the heat with air. The coolant water can thus now be re-circulated to the system for reuse (see Figure 2.2). Some water is lost in the process due to the evaporation and drift loss and thus, the remaining cooling water get more concentrated with dissolved ions and minerals. This recirculation will be repeated until the cooling water reaches critical concentration of ions that could accelerate scaling, and reduce efficiency and life time of the equipment **(34)**. To decrease ion concentration, a portion of cooling water is removed as blowdown water. To balance the volume of water in the system, make-up water is added to the cooling tower basin to compensate the loss of water from blowdown, evaporation, and drift loss. Figure 2.2 shows the diagram of water balance in a cooling tower.

The blowdown water contains high values of heavy metals and organic compounds, which typically needs to be subjected to some treatment processes in order to meet effluent standard for use as makeup water for cooling water or boiler in a plant **(35)**. However, in many situations the blowdown water is discharged directly to the environment without any recycle back to the process.

2.4 Quality of Water

Natural water generally found in environment is not pure water because it contains minerals, salts, dissolved gases, organic and inorganic compounds, and biological substances. The quality and quantity of these substances vary greatly from water resources and environment or activities that the water is circulated through. Knowing water quality is thus of necessary in order to determine whether the water is suitable for human use and consumption. In addition, monitoring water quality is also of crucial importance for industries, especially for power plants, to avoid corrosion and scaling of equipment. Table 2.2 summaries the information of some common parameters of water quality and their definition.

Table 2.2 Important parameters in water **(32)**

Parameter	Description	Associated Problems
pH	The measure of acidity in the water	Extreme pH value can lead to corrosion problem of materials.
Total dissolved solids (TDS) and Conductivity	The measure of the amount of particulate solids that are in the water and can be used as an indicator of ion concentration.	High TDS value can lead water to be corrosive, salty or brackish taste, result in scale formation, and interfere.
Total Suspended Solids (TSS) and Turbidity	The measure of the amount of sediment that is in the water, caused by the presence of colloidal and suspended matters.	High value can lead to erosion of equipment, and cause of plankton growth in water.
Biological Oxygen demand (BOD)	The amount of oxygen used by microorganism in the water to decompose organic matter.	High BOD indicates large amounts of organic matter.
Chemical Oxygen demand (COD)	An indicator of organics in the water, usually used in conjunction with BOD.	In areas of high COD there is frequently evidence of rapid sewage fungus colonization.
Hardness (Ca^{2+} or Mg^{2+})	The measure of calcium and magnesium in water.	Values below 250 ppm acceptable for drinking. Over 500 ppm, hazardous to health.
Chloride	Normal water treatment processes cannot remove chloride.	High chloride levels may render freshwater unsuitable for agricultural irrigation.

Table 2.2 Important parameters in water (continued) **(32)**

Parameter	Description	Associated Problems
Total Alkalinity	Related to the presence of bicarbonates, carbonates and hydroxides.	Low alkalinity value in water is very susceptible to changes in pH value.
Heavy Metals (Toxic)	The measurement of lead, arsenic, copper, cadmium cyanide, mercury, and other man-made compounds in water.	Miniscule amounts of these chemicals cause a variety of human problem ranging from liver and kidney disease.

2.5 Criteria of Water for Cooling Tower

As previously mentioned the concentration of ions in the cooling water increases after cycling through the cooling tower and becomes greater than the concentration in the original make up water. Cooling water quality can affect power plant performance. Water sources must be evaluated for their chemical constituents. Each constituent or constituent pair should be analyzed individually to determine the maximum allowable concentration. The concentration limit is typically defined by the solubility thresholds of one or more constituents. The standard criteria applicable to power plants are shown in Table 2.3.

Table 2.3 Water quality parameters for cooling towers **(35)**

Parameter	Units	Criteria	Associated problem
pH	pH unit	6.5 – 9.0	Lower values can galvanize steel surface. Higher values can increase scale formation.
TDS	mg/L	< 1,500	Organic, inorganic, salts mineral loading in the system can cause many problems.
TSS	mg/L	< 100	Cause of erosion on equipment.
Hardness	mg/L $CaCO_3$	< 500	Formation the calcium, magnesium scale.
Alkalinity	mg/L $CaCO_3$	< 500	Formation the carbonate scale.
Chloride	mg/L Cl^-	< 250	Corrode the stainless steel material.
Silica	mg/L	< 150	Hard scale of silica complex.
Sulfates	mg/L	< 250	Scale formation of calcium sulfate.

2.6 Water Treatment Process for Cooling Tower

To prevent the corrosion and scaling that could shorten the life time of heat exchanger equipment and lead to the inefficient process, the key water quality parameters must be monitored. In many cases, water treatment processes either via chemical or physical methods are applied to control the mineral constituents in water down to the level that is safe for the operation of equipment. For this purpose, three types of treatment options are used, pretreatment of the make-up water, side-stream treatment of the recirculation water and post-treatment of the discharged water. Figure 2.4 shows the descriptions of each treatment operation.

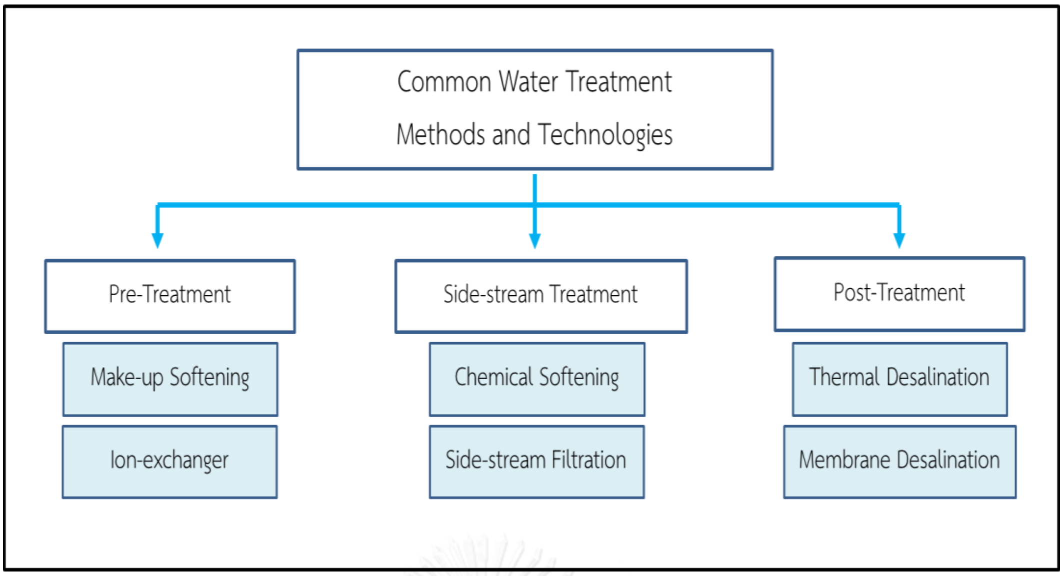

Figure 2.4 Diagram for common water treatments for cooling tower **(36)**

2.6.1 Water pretreatment technique

Precipitation softening and ion-exchange processes are used to reduce raw water hardness, alkalinity, silica, and other constituents. These processes prepare water for a direct use as a cooling tower makeup. The added cost of softening and ion-exchange processes is compensated by the decreased chemical and water usage **(36)**.

2.6.2 Side stream-treatment technologies

Chemical softening treats water by reacting lime or a combination of lime and soda ash with the hardness and natural alkalinity in the water to form insoluble compounds. These compounds are removed from the water by a side stream filtration, which continuously filters a portion of cooling water to remove suspended solids, organics, and silt particles. These processes can reduce the TSS and turbidity values, which directly decrease fouling and biological growth in systems and return filtered water to the cooling tower basin. This could reduce of the amount of water discharged from the cooling system.

2.6.3 Post-treatment cooling tower technologies

Post-treatment is a process that completely eliminates minerals and contaminants from discharge or blowdown water from cooling tower. Membrane desalination uses the principle of osmosis to remove salt and other impurities, by transferring water through a series of semi-permeable membranes. Thermal desalination uses heat to evaporate and condense water to purify it. When the dissolved solids in wastewater have been removed, the treated water is circulated back to the process.

2.7 Cooling Tower Blowdown Treatment Technologies

Presently, industries are reclaiming and reusing cooling tower blowdown by using different types of treatment processes to desalinate and remove the constituents. A typical flow diagram of the desalination process with inputs and outflows is shown in Figure 2.6. The process can be classified into two categories:

thermal and membrane processes. Some basic information on these processes is shown in Tables 2.4. The selection of suitable desalination technology depends on a number of site specific factors, including source water quality, the intended use of the water produced, plant size, capital costs, energy costs, and the potential for energy reuse **(37)**.

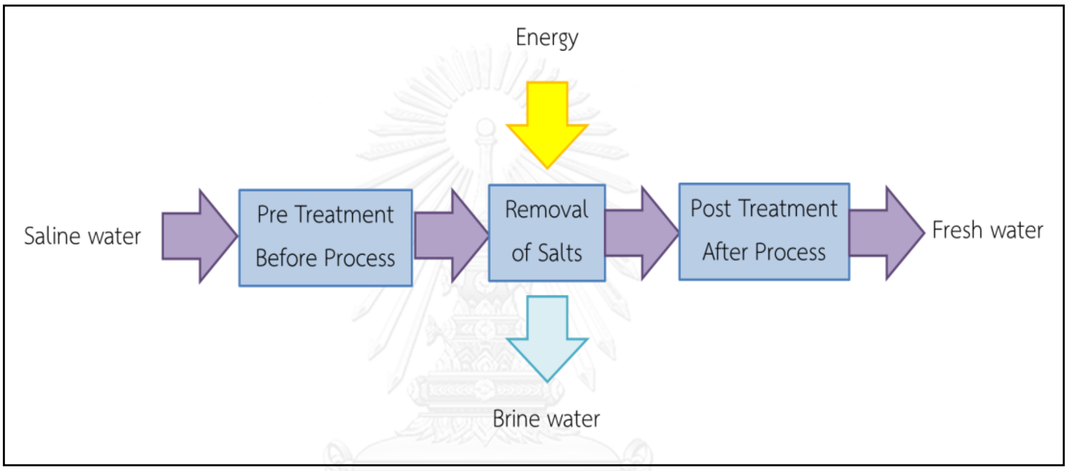

Figure 2.5 Typical flow diagram of the desalination process

(1) Thermal processes

Thermal process mimics the hydrological cycle in that saline water is heated to produce water vapor that in turn is condensed to form fresh water. Well-known thermal methods include the multi-stage flash process (MSF), multi effect distillation process (MED) and the vapor compression distillation process (VC). Thermal distillation technologies are mostly used in regions where cheap energy is available **(38)**.

(2) Membrane processes

Membranes have ability to transport one component of feed mixture more readily than others due to the differences in physical and/or chemical properties between the membrane and the permeating components. Three membrane desalination processes have been developed: electrodialysis (ED), reverse osmosis (RO) and nanofiltration (NF) **(38)**.

Compared to thermal processes, the membrane technologies generally require less energy and have lower capital and operating costs **(39)**. However, the quality of product water tends to be lower for membrane desalination (< 500 ppm TDS) than that produced by thermal technologies (< 25 ppm) **(39)** In this chapter, only membrane desalination process is reviewed because its low utilization of construction area as same as operation and maintenance cost, which suitable for the process in small power plant.

Table 2.4 Characteristics of thermal & membrane desalination technologies **(38, 40)**

Process Technologies	**Advantages**	**Disadvantages**
Thermal Process	- Can treat high saline waters. - High production capacity. - High product water quality.	- Large space and material required. - High energy consumption. - High operating cost. - Disposal of the output brine.
Membrane Process	- Can treat brackish and saline waters. - Low energy consumption. - Low space and material requirements. - Low operating and capital Costs.	- Requires high quality feed water. - Lower product water quality. - Lower production capacity.

2.8 Membrane Desalination Technologies

Membrane technologies are physical separation procedures, which can be operated without a heating source. Generally, membranes are semi-permeable to one substance; for instance in the case of membrane for water treatment, it will preferably let water pass through, while retaining suspended solids and other substances. Reverse Osmosis (RO) is one of the most widely studied membrane technologies for the treatment of cooling water **(6, 17-19, 21, 23-27)**. It has been reported that discharged water from cooling towers treated for re-make up cooling water or other proposes via the RO can achieve high treatment efficiency of more than 95% TDS rejection **(6, 16-19, 21-27)**. In addition, other membrane technologies such as NF and ED are also applied to treat discharged cooling water **(6, 20, 41)**. NF is a commonly known membrane technique that can treat water with high salinity. Though achieving lower TDS rejection, NF is usually preferred over RO for the removal of divalent ions because of lower operating pressure and higher flux of product water **(6, 38, 40)**. ED is a promising membrane process that utilizes electric potential as the driving force to remove charged ions. However, in ED, silica ions are inefficiently removed due to its low ionic strength **(42, 43)**.

2.8.1 RO/NF membranes principles

When a semi-permeable membrane is placed between two compartments with different salt concentrations, water will flow from a dilute saline solution through a membrane into a higher concentrated saline solution due to the osmotic pressure differences (Figure 2.6). Pressure-driven processes like in reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF) and microfiltration (MF) apply an external pressure at the high saline solution that overcomes the osmotic pressure difference to revert water flow from the high saline solution to the dilute one. The amount of water flux is proportional to the external pressure applied, which is the driving force of the process.

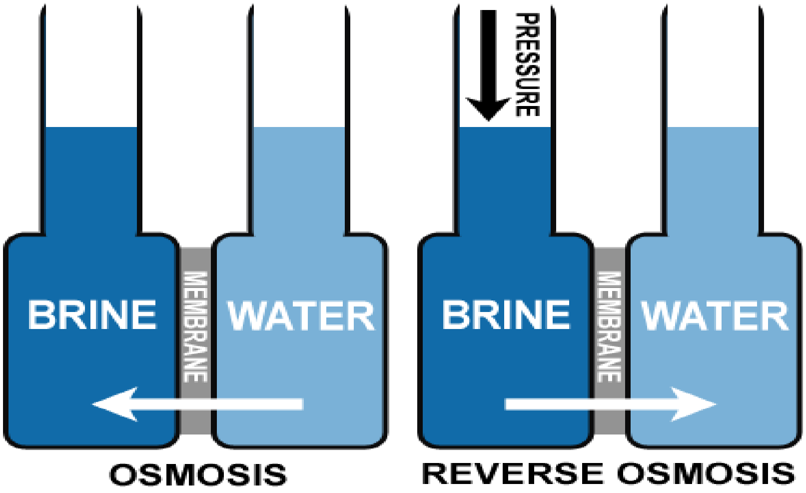

Figure 2.6 Osmosis and reverse osmosis diagram **(44)**

Unlike RO, The NF membrane is not a complete barrier to dissolved salts, depending on the type of salt and the type of membrane **(44)**. In practice, RO and NF are applied as a cross-flow filtration process, as shown in Figure 2.7

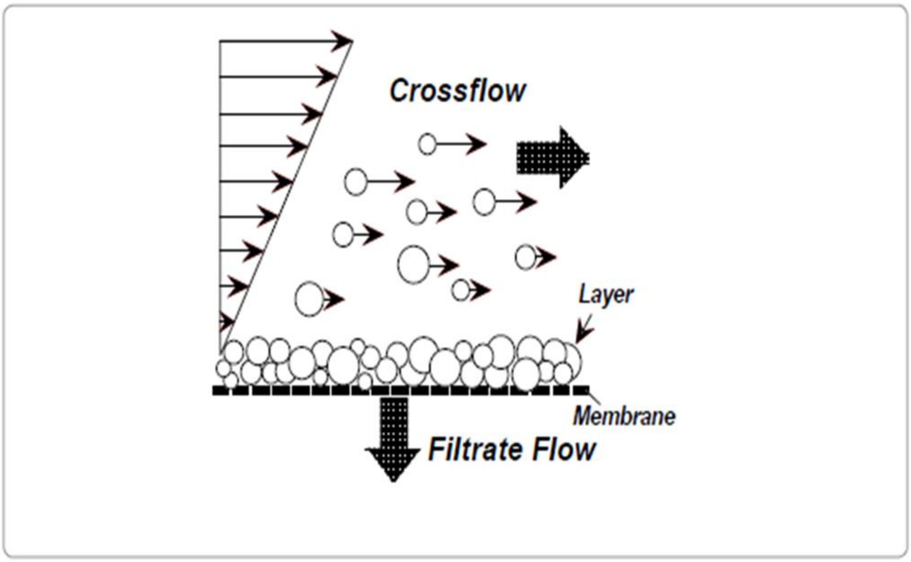

Figure 2.7 Crossflow filtration diagram **(44)**

With a high pressure pump, feed water is continuously pumped at elevated pressure to the membrane system and will be split into a low saline and purified product, called permeate, and a high saline or concentrated brine, called concentrate or reject. The mechanism of separation by NF and RO is quite different except that with NF, less pressure is needed because of larger membrane pore size (0.05 - 0.005 µm) **(38)**. NF membranes have lower rejection of monovalent ions when compared to RO, typical rejection efficiency of monovalent ions and divalent ions by NF is 30-80% and 70-95%, respectively **(23)**. RO membranes reject monovalent ions at 90-99.9% while rejection divalent ions at higher efficiency **(23)** .

2.8.2 Parameters affecting performance of NF/RO

The main performance parameters of a NF and RO process are permeate flux and salt rejection. Normally, the performances of membrane systems are mainly affected by variable parameters including; feed water salt concentration (salinity of feed water), feed pressure, feed water temperature, permeate recovery ratio and membrane compaction and fouling **(44)**.

(1) Feed water temperature

When all other parameters are kept constant and temperature increases, the salt passage (permeate salinity) and permeate flux will increase by the relation in Equation 2.1 **(44)**. It is due to the changing in rate of diffusion through membrane, and also results in lower salt rejection or higher salt passage. This is due to a higher diffusion rate for salt through the membrane. **(44)**.

$$J_{25} = J_T \bullet TCF \qquad \text{Equation 2.1}$$

Where J_{25} : Normalized permeate flux at 25 ^{0}C ($m^3/m^2.h$)

J_T : Actual permeate flux at temperature T ($m^3/m^2.h$)

TCF : Temperature correction factor which derived as Equations 2.2 and 2.3

$$TCF = \exp\left[2640\left(\frac{1}{298} - \frac{1}{273+T}\right)\right] ; T \geq 25^0C \qquad \text{Equation 2.2}$$

$$TCF = \exp\left[3020\left(\frac{1}{298} - \frac{1}{273+T}\right)\right] ; T \leq 25^0C \qquad \text{Equation 2.3}$$

Where T : Feed water temperature (^{0}C)

(2) Feed water salinity

The fluctuation of feed water concentration during NF/RO operation might be due to seasonal change of feed water salinity. Because of osmotic pressure is a function of the type and concentration of salts or organics contained in feed water, while salt concentration increases, so does osmotic pressure (Equation 2.4), and the amount of driving pressure necessary to reverse the natural direction of osmotic flow. The effect of increasing of feed water salinity could result in declining of both permeate flux (Equation 2.5) and salt rejection (Equation 2.7) **(44)**. As long as different feed water compositions will not require a change in the system recovery ratio, changing feed water composition will affect only the required feed pressure and permeate water salinity **(45)**.

(3) Feed Pressure

Feed water pressure affects both the water flux and salt rejection of RO membranes. With the increasing of effective feed pressure, the permeate salinity will decrease, while the permeate flux will increase (Equation 2.5) **(44)**. Because RO membranes are imperfect barriers to dissolved salts in feed water, there is always some salt passage through the membrane. As feed water pressure is increased, this salt passage is increasingly overcome as water is pushed through the membrane at a faster rate than salt can be transported **(44)**.

$$\pi = 2RT \sum(M_i) \qquad \text{Equation 2.4}$$

Where π : Osmotic pressure (bar)

$\sum(M_i)$: Sum of Molarity concentration of all constituents in a solution (mol/L)

R : Gas constant (0.08315 L.bar/mol.K)

T : Temperature (K)

$$J_w = A_w\ (TMP - \pi) \qquad \text{Equation 2.5}$$

Where A_w : Membrane permeability of water (m^3/m^2.h.bar)

TMP : Tran membrane pressure (bar) which derived as Equation 2.6

$$TMP = \left(\frac{P_f - P_c}{2}\right) - P_p \qquad \text{Equation 2.6}$$

Where P_f : Pressure at feed side (bar)

P_c : Pressure at concentrate side (bar)

P_p : Pressure at permeate side (bar)

$$J_s = B(C_f - C_p) \qquad \text{Equation 2.7}$$

Where J_s : Salts flux (kg/m^2.h)

B : Salt permeability coefficient (m/h)

C_f : Salinity of feed water (kg/m^3)

C_p : Salinity of the permeate (kg/m^3)

(4) Permeate recovery ratio

The ratio of permeate flow to feed flow is known as recovery ratio. Reverse osmosis occurs when the natural osmotic flow between a dilute solution and a concentrated solution is reversed through application of feed water pressure, while percentage recovery is increased (and feed water pressure remains constant), the salts in the residual feed become more concentrated and the natural osmotic pressure will increase until it is as high as the applied feed pressure. This can negate the driving effect of feed pressure, slowing or halting the reverse osmosis process and causing permeate flux and salt rejection to decrease and even stop **(44)**.

(5) Membrane compaction and fouling

Deposition of impurity (organic and inorganic substances) on membrane surface and/or blockage of feed channels which could result in non-reversible membrane degradation are called membrane fouling. Membrane fouling somehow ends up with increasing of pressure drop, flux declined, membrane degradation, or even complete destruction of membrane elements **(45)**. Table 2.5 below demonstrates a summary of the impact influencing RO/NF’s performance. Therefore, it is of necessary to pretreat water before being fed to a membrane.

Table 2.5 Parameters influencing NF/RO performance **(44)**.

Increasing of	Permeate Flux	Salt Passage
Feed water salinity	Decrease	Increase
Feed pressure	Increase	Decrease
Feed water temperature	Increase	Increase
Permeate recovery ratio	Decrease	Increase
Membrane fouling	Decrease	Decrease

2.9 Pretreatment for Membrane Processes

In wastewater recycling applications, RO can hardly function on its own without any protection from the fouling materials. Appropriate pretreatment must be provided to achieve stable performance of RO membranes **(46)**. The main purpose of pretreatment process is to remove anything that could hamper subsequent treatment processes. In addition, it will improve membrane desalination process efficiency and extend the life span of the system by preventing or minimizing bio-fouling, scaling, and membrane plugging. Depending on the quality of the feed water, several processes could be required. Table 2.6 shows the description of each pretreatment process.

Table 2.6 Pretreatment process and Its utilization **(23, 47)**

Pretreatment Process	**Descriptions**
Chemical pretreatment	
- Chlorination	Infect bacteria, microorganisms, protozoan, etc.
- Coagulation and flocculation	Remove colloidal particles organic and inorganic complexes.
- Acidification - Anti scalant	Reduce calcium, magnesium, barium, carbonates and strontium sulfates scale formation.
- Sodium bisulfite	Remove chlorine, $KMnO_4$ which destroy membrane.
- Lime soda or soda ash	Reduce hardness levels by precipitation.
- Magnesium salts	Reduce silica levels by precipitation.
Physical pretreatment	
- Sand Filtration (SF) - Multimedia filtration (MMF)	Filter clay, suspended solids, particle substance by traditional pressure operation.
- Activated carbon	Adsorb organic *chemicals* and filter particle substances.
Membrane pretreatment	
- Micro filtration (MF) - Ultra filtration (UF)	Filter clay, suspended solids, virus, microorganism, and particle substance by high pressure operation.

2.9.1 Conventional pretreatment

To prevent fouling problem in membrane, chemical pretreatment is used for reducing the turbidity, COD, BOD, organic and inorganic values followed by a fast filtration process like SF or MMF filter. This multistep pretreatment process is called conventional pretreatment, applied in most water treatment plants **(48)**.

Polyaluminium chloride (PACl) is often study to be chemical coagulant for pretreatment blowdown water from power plant **(6, 21, 49)**. Furthermore, previous studies showed that the application of PACl and poly acrylamide (PAM) with MMF filter pretreatment was effective enough to treat feed water for RO **(21)**.

In principle of conventional process, most solids suspended in water possess a negative charge; they consequently repel each other. This repulsion prevents the particles from agglomerating, causing them to remain in suspension. Coagulation and flocculation occur in successive steps intended to overcome the forces stabilizing the suspended particles, allowing particle collision and growth of flocs, which then can be settled and removed by sedimentation and filtered out of the water. Figure 2.8 shows the diagram of conventional system.

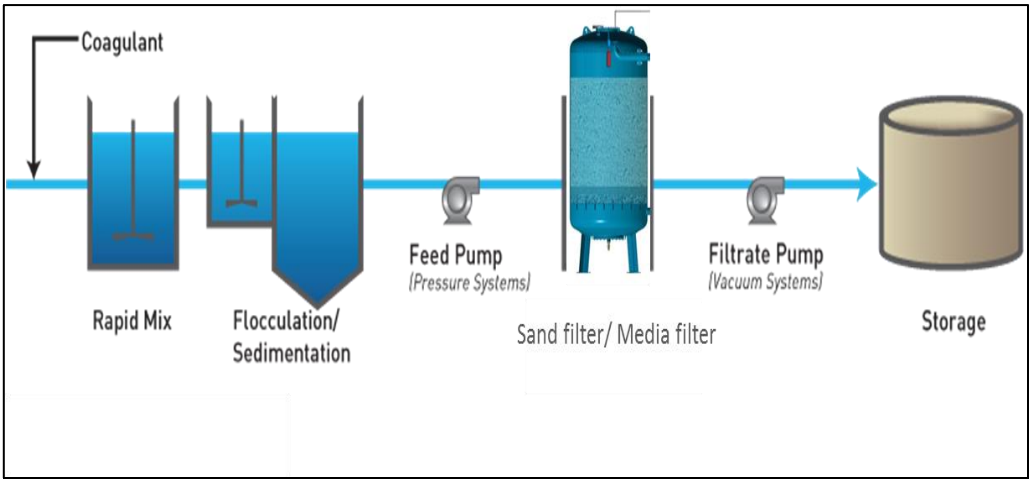

Figure 2.8 Conventional pretreatment systems **(50)**

Firstly, chemical coagulant, PACl is added to the water to destabilize small particles suspended in the water. Once the charge is neutralized, the small-suspended particles are capable of sticking together. The slightly larger particles formed through this process are called microflocs but are still too small to be visible to the naked eye. A rapid-mix to properly disperse the coagulant and promote particle collisions is needed to achieve good coagulant and formation of the microflocs. Over-mixing does not affect coagulant but insufficient mixing will leave this step incomplete. Proper contact time in the rapid-mix chamber is typically 1 to 3 minutes **(48)**.

The coagulated water would discharge to flocculation and at the entry to the flocculation tanks, flocculant chemical (PAM) would be added to aid the process. A gentle mixing stage increases the particle size from submicroscopic microfloc to visible suspended particles. The floc size continues to build through additional collisions and interaction with inorganic polymers formed by the coagulant to help bridge, bind, and strengthen the floc, add weight, and increase settling rate. Design contact times for flocculation range from 15 or 20 minutes **(48)**. Figure 2.9 showed the process of coagulation/flocculation of PACl and PAM.

Flocculated water would be transfer to sedimentation basin to settle the flocs, the times for sedimentation range from 60-120 minutes **(48)**. Thus, treated water passing through the gravity filters filled with sand granular medium for the single media filter and with anthracite (coal) / sand for the dual media filter.

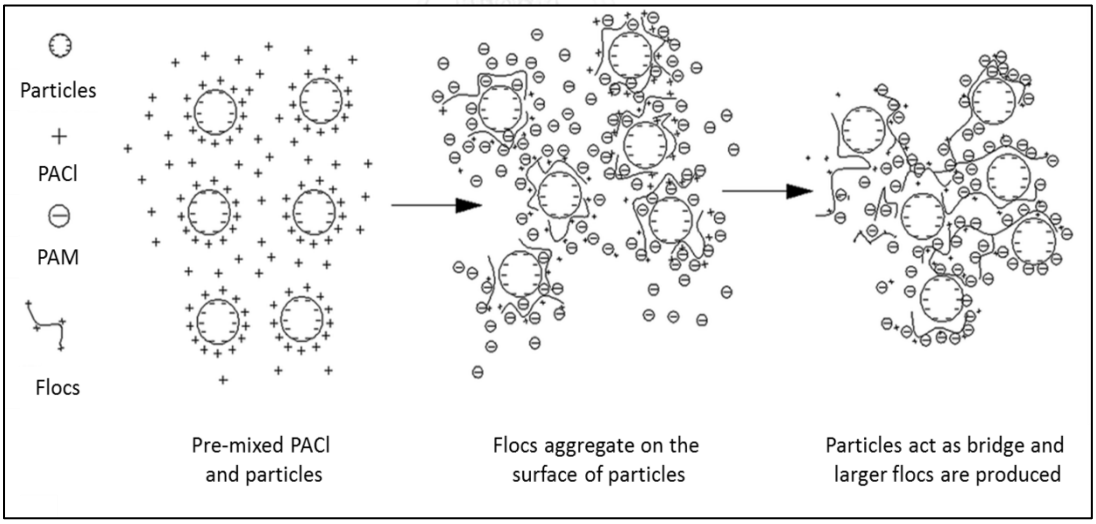

Figure 2.9 Schematic diagram of coagulation/flocculation process **(48)**

2.9.2 MF and UF membranes pretreatment principle

MF and UF membranes are continuing to become a go-to process for RO/NF pretreatment to reduce fouling in the process, replacing conventional treatment methods **(51)**. The principle of MF and UF is a physical separation, which dissolved solids, turbidity and microorganisms are removed by the size of the pores in the membranes.

The pore size of MF is 0.1 – 10 μm while UF is 0.001 – 0.1 μm **(51)**. Substances that are larger than the pores in the membranes are fully removed. Substances that are smaller than the pores of the membranes are partially removed, depending on the properties of the selective layer on the membrane

MF and UF have several advantages such as complete particle removal, short treatment time and low demand space **(52)**. However, the researchers showed that the treated water from UF is better quality than treated water from MF **(53, 54)**. Membrane filter processes are associated with membrane fouling, which can decrease the process performance. For reduce this problem, traditional pressure filter like SF **(18)** or MMF **(16)** are applied before MF or UF as pre-filter process to decrease the particle fouling on MF and UF membrane. The addition of SF and MMF is not an obligation; in fact there is no report of improving performance by investing in such additional steps **(16, 18)**

CHAPTER 3
RESEARCH METHODOLOGY

3.1 Introduction

In this work, a water treatment unit to treat discharged cooling water from a co-generation power plant was designed. The quality and characteristics of feed water collected from cooling tower were identified. In order to screen the suitable water treatment technologies, both operational constraints, and feasibility was used as the criteria. The selected treatment techniques were tested in a laboratory scale based on the evaluations of constituents present in the discharged water. Experimental works were separated in to 2 parts as shown in Figure 3.1.

1) Pretreatment process
    1.1) Conventional pretreatment
    1.2) UF Membrane pretreatment
2) Membrane treatment process
    2.1) Nano filtration
    2.2) Reverse osmosis

After the study of appropriate method and condition for pretreatment and treatment system were obtained, the treatment unit was designed for the effective operation of the discharged water treated system.

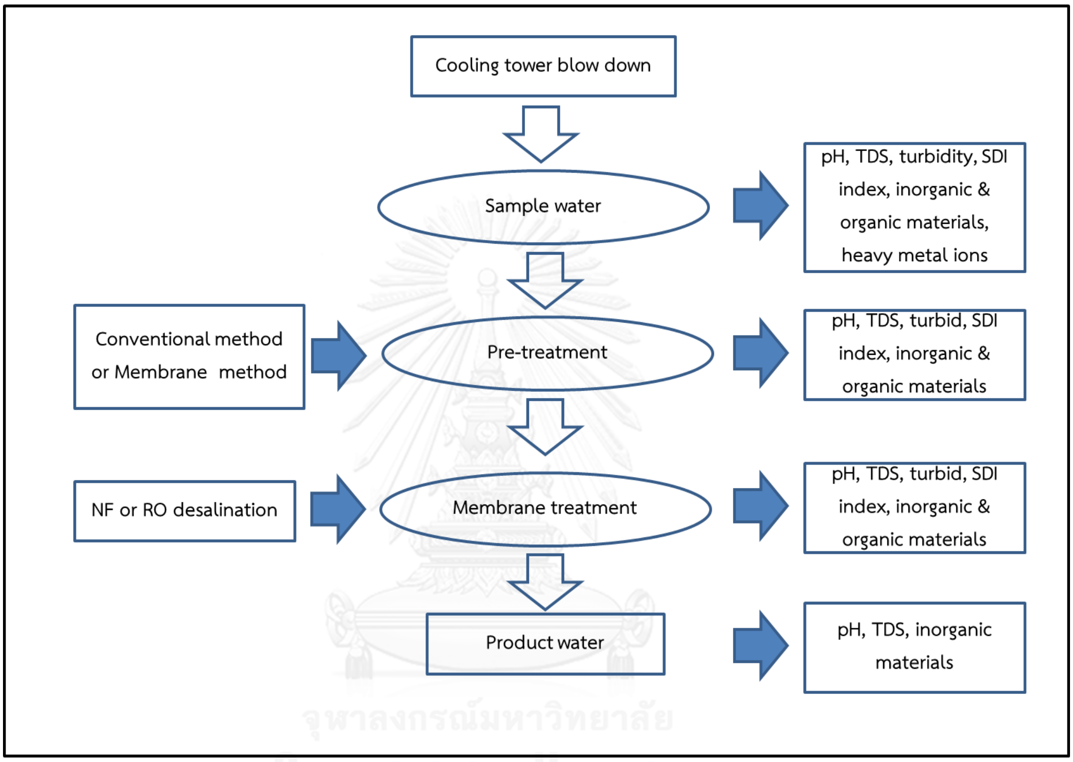

Figure 3.1 Experimental plan diagram

3.2 Sample Water

In a co-generation power plant, cooling towers (shown in Figure 3.2) are used in cooling systems to cool down and remove the heat from processes. Tap water is used as the source for a make-up water with an average conductivity of 350 - 400 μS/cm. Around 1,500 m^3 per day of blowdown water from the cooling towers are removed to keep the concentration stable.

Figure 3.2 One of cooling tower units in co-generation power plant

Blowdown water was drained from the drain pit of the cooling tower and fed to the chemical and physical pretreatment system. The quality of water was rich of organic and inorganic components, which were the major foulant of membrane desalination system.

3.3 Conventional Pretreatment

(a) Chemical pretreatment

The discharged water from cooling tower was collected in the 500 Liter tank as sample water. The jar test method was conducted according to the standard jar test procedure at room temperature (25-28°C) **(55)**. The proper chemical coagulant and coagulant aid with the most effective dosage were determined based on the best flocculation time and the most floc settled out. Supernatant sample was taken out for measuring water characteristics, such as turbidity and SDI.

In this study, the use of a commercial coagulant, poly aluminium chloride (PACl), was tested. PACl is in a powder form with the formula of $Al_2\ (SO_4)_3.18H_2O$, supplied by Interpretive, China. For the flocculants, cationic polyacrylamide (CPAM) and anionic polyacrylamide (APAM) were purchased from Interpretive, China. The coagulant and flocculant dosages were determined using a jar-test apparatus (JLT 4, VELP-Scientifica, Italy). The test conditions were summarized in Table 3.1.

Table 3.1 Conditions of jar test for coagulation-flocculation process

Condition of jar testing	**Value**	**Step**
Speed of rapid mixing (rpm)	200	Mixing the coagulants
Duration of rapid mixing (min)	1	
Speed of slow mixing (rpm)	20	Form the floc
Duration of slow mixing (min)	15	
Settling time (min)	60	Settle the floc

Firstly, PACl was added in the raw water at varied concentrations. The solution was mixed with a rapid mixing rate at 200 rpm for 1 min, and a slow mixing rate at 20 rpm for 15 min. Then it was set for 60 min for sedimentation. Afterwards, the supernatant was collected using a syringe from about 2 cm below the water surface to measure the turbidity.

To investigate the effect of different flocculant, APAM and CPAM, the flocculant was added into the testing solution to get the final concentration of the flocculation in testing solution of 1 mg/L at 45 seconds after the rapid mixing step had started. The PACl concentration was fixed to be constant. The characteristic of floc formation and the residual turbidity at various setting time of each flocculants type were observed. The experiments were test in triplicate for the accuracy of the results. The diagram and procedure of chemical pretreatment process was shown in Figure 3.3 and Table 3.2.

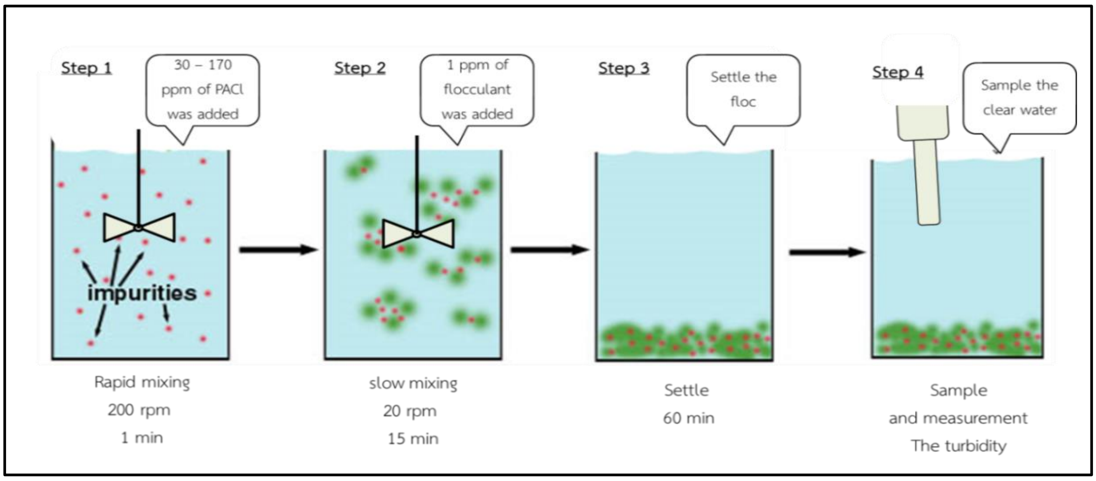

Figure 3.3 Chemical pretreatment process diagrams

Table 3.2 Procedure of chemical pretreatment process

Investigation	**Step 1**	**Step 2**	**Step 3**	**Step 4**
Dosage of PACl	Varied amount of PACl	No chemical added	60 min sedimentation	Measurement turbidity
Type of floculant	Fixed dosage of PACl (optimal value for lowest turbidity)	Add 1 ppm of Cationic PAM	60 min sedimentation	Measurement turbidity every 5 min and observe the floc size
		Add 1 ppm of Anionic PAM	60 min sedimentation	Measurement turbidity every 5 min and observe the floc size

(b) Physical pretreatment

Multimedia filter system was applied after the chemical pretreatment process. The experiments were carried out with a clear PVC column (4.0 cm in diameter and 45 cm in length) packed with 12 cm filter depth of anthracite layer, 8 cm of fine sand layer, and 5 cm of coarse sand layer from top to bottom, respectively (Figure 3.4). The bottom layer was supported by a 5 cm of gravel layer. This filter medias were conducted according to the standard multimedia filter test procedure **(56)** and the characteristics of each media layer are summarized in Table 3.3 . The filter medias were washed with deionized water and dried before used.

Deionized water was pumped through the column before the filtration experiment. The supernatant solution of the settling sample (from coagulation-flocculation experiments) was withdrawn from the beaker and transferred to another glass beaker as the raw water for filtration experiments. The raw water was continuously stirred at 100 rpm during the filtration experiment, and it was fed into the column at a constant flow rate of 15 L/h, which is the recommended flux for rapid filtration procedure **(56)**. The filtrate water was collected for further water quality analysis.

Table 3.3 Physical properties of filter media used

Property/Media	**Particle size range (mm)**	**Specific gravity**
Anthracite	0.8 – 1.6	1.5
Fine sand	0.1 – 0.2	4.0
Coarse sand	0.5 – 1.0	4.0
Gravel	5.0 – 7.0	-

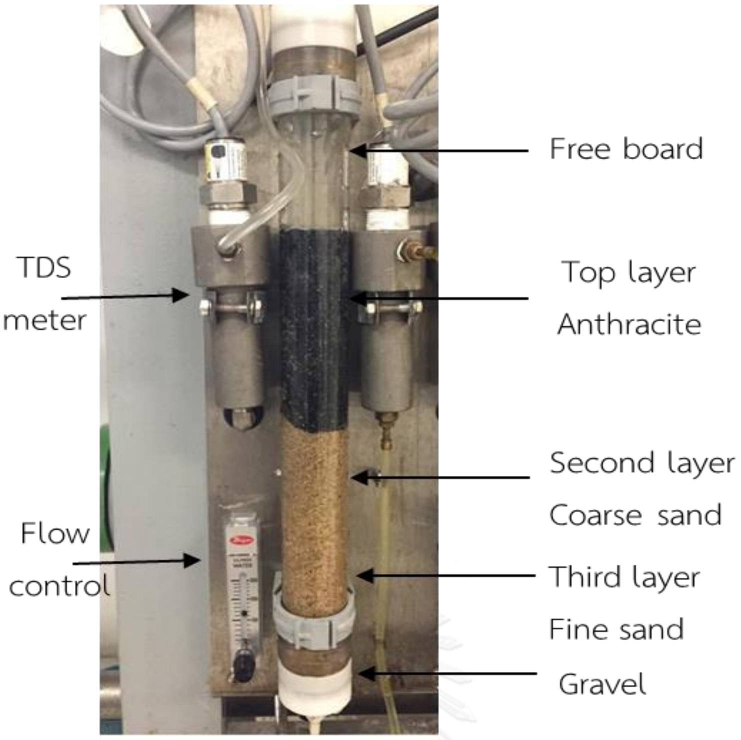

Figure 3.4 Multimedia filter for physical pretreatment test

3.4 Membrane Filtration Pretreatment

For comparison the effectiveness of chemical and physical pretreatment processes by chemical coagulation/flocculation and multimedia filter, the ultra-filtration (UF) were selected to be tested. The discharged water from cooling tower was collected in the 500 Liter tank as sample water and directly fed to the pretreatment membrane after the pre-filter process with 5 micron of cartridge filter (Polypropylene, PP filter). The dead end UF system especially designed for research purpose was used. UF-1812-PS-50K, hollow fiber configurations were purchased from VIFIL Company. Membranes specifications are given in the Table 3.4.

Table 3.4 Characteristics of MF and UF membrane

Parameters	**Cartridge filter**	**UF**
Company name	Aquatek (USA)	VIFIL (USA)
Model	-	UF1812-PS 50K
Membrane polymer	Polypropylene	Polysulfone
Configuration	Tubular	Hollow fiber
Pore size	5 micron	0.03 micron
Active area	-	2.22 m^2
pH range	0-14	0-14
Maximum applied pressure	3 bar	3 bar
Size	2’’ diameter x 10’’ length	

Filtration experiments were carried out at room temperature. The feed pressure was fixed at 2 barg, the flow rate of treated water was measured in order to calculate the flux as well as the turbidity. The samples were collected every 10 minutes for 1 hour or until the steady state flow was reached and the quality of treated water was characterized.

3.5 Membrane Treatment Process

The feed water for the membrane unit was synthesized by keeping its quality and components to be the same as those received from the selected pretreatment process. Table 3.5 provides the chemical lists used for the synthetic blowdown water.

Table 3.5 Chemical compositions of the synthetic cooling tower blowdown water

No.	Chemical name	MW	Supplier	Simulate salts ion	Ion
1	CaCl*18H20	160	Sigma Aldrich	Calcium ion	2+
2	MgCl*18H20	180	Sigma Aldrich	Magnesium ion	2+
3	NaHCO	160	Sigma Aldrich	Bicarbonate ion	1-

A cross flow lab-scale desalination system especially designed for research purpose was used. AMI NF-1812-36 membrane (spiral wound configuration) and Filmtec TW-1812-50 RO membrane (spiral wound configuration) were purchased from Applied Membrane Company and Dow-Filmtec Company, respectively. Both membrane specifications were given in the Table 3.6.

Table 3.6 Characteristics of NF and RO membrane

Parameters	**NF (57)**	**RO (58)**
Membrane company name	AMI	DOW-Filmtec
Model	NF-1812-36	TW-1812-50
Membrane polymer	polyamide TFC	polyamide TFC
Configuration	Spiral wound	Spiral wound
Salt rejection (NaCl)	50%	96-98%
Active area	0.32 m^2	0.32 m^2
Maximum applied pressure	20 bar	10 bar
Feed water pH range	4-11	2-11
Maximum feed water turbidity	1 NTU	1 NTU
Maximum feed water SDI_{15}	5	5
Maximum feed water chlorine	0.1 ppm	0.1 ppm
Size	1.8'' diameter x 12'' length	

The filtration was tested in total recycle mode. The total volume of the system was 8 Liters and both permeate and concentrate line were returned to the feed tank in order to keep a constant concentration. A high pressure pump was used to circulate the feed solution through the membrane module and a valve was installed at the concentrate outlet to adjust the pressure and the volumetric flow rate. A schematic representation of the equipment was illustrated in Figure 3.5

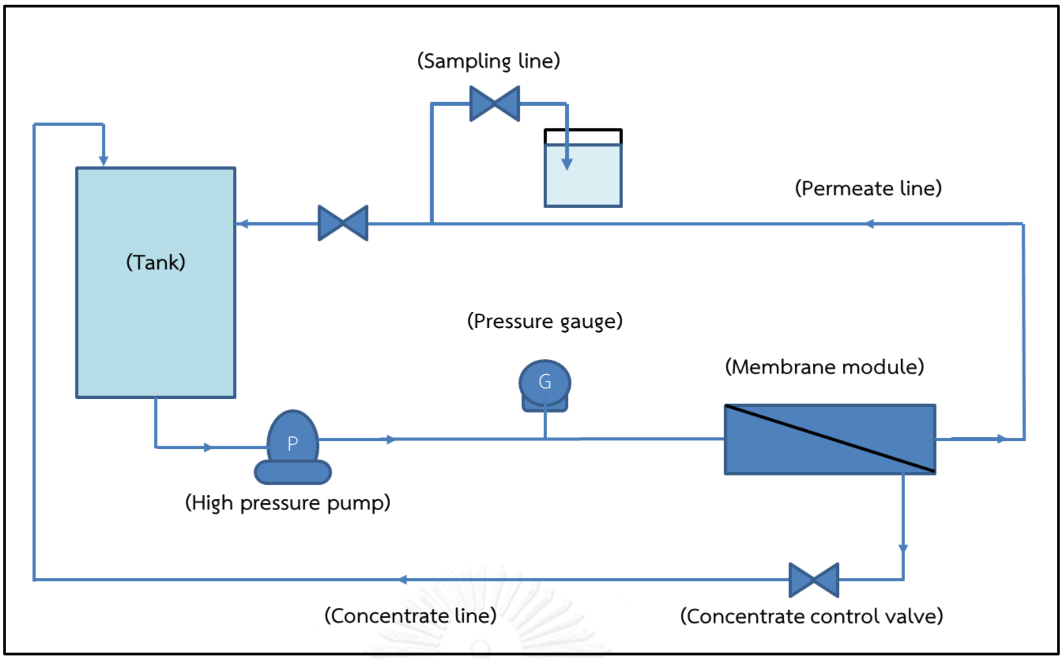

Figure 3.5 Schematic representation of the NF/RO setup

Filtration experiments were carried out at different pressure and temperature of 25°C. The feed pressure was varied at different values, the flow rate of permeate and concentrate were measured in order to calculate the flux and hydraulic permeability as well as the salt concentration. The samples were collected from permeate line every 10 minutes for 1 hour or until the steady state flow was reached.

3.6 Calculating parameters

3.6.1 Flux (J_w)

The permeate flux was determined by measuring the volume of the permeate in a given time interval by the relation in Equation 3.1

$$J_w = \frac{Q_P}{A} \qquad \text{Equation 3.1}$$

Where J_w : Permeate flux ($m^3/m^2.h$)

Q_P : Permeate flow rate (m^3/h)

A : Effective membrane area (m^2)

3.6.2 Rejection (R)

The salt rejection describes the quantity of salt removed from the feed water stream by the semi-permeable membrane as shown Equation 3.2.

$$R = \left(\frac{C_f - C_p}{C_f}\right) 100\% \qquad \text{Equation 3.2}$$

Where R : Rejection rate (%)

C_P : Concentration of permeate water (mg/L)

C_f : Concentration of feed water (mg/L)

3.6.3 Recovery

Recovery calculates percent of the membrane feed water which is converted into permeate as shown in Equation 3.3.

$$Y = \frac{Q_p}{Q_f} \qquad \text{Equation 3.3}$$

Where Y : recovery

Q_f : Feed flow rate (m^3/h)

3.6.4 Concentration Factor

The concentration factor is related to RO/NF systems recovery, when salt solubility limits are a concern, the concentration factor must be considered in the brine stream by Equation 3.4.

$$CF = \frac{1}{(1 - Y)} \qquad \text{Equation 3.4}$$

3.6.5 Osmotic pressure

Osmotic pressure is the pressure required to prevent the flow of water across a semi-permeable membrane separating two solutions having different ionic strengths using the equation 2.1. A useful “rule of thumb” is for every 100 mg/L of

TDS difference between feed and permeate, 1 psi (0.069 bar) of osmotic pressure exists **(59)**.

3.6.6 Trans Membrane Pressure (TMP)

The TMP is defined as the pressure gradient of the membrane, or the average feed pressure minus the permeate pressure by the relation in Equation 2.6. The feed pressure is often measured at the initial point of a membrane module and equals around 4 to 20 times of osmotic pressure **(60)**.

3.6.7 Membrane permeability (A_W)

The membrane permeability with the pure water and electrolyte solution can be obtained from the slope of the plot of J_W versus the TMP using the Equation 2.5.

3.7 Analytical Methods

The analytical methods given in Table 3.7 were used to determine the properties of raw water and effluent of each process.

Table 3.7 Analytical method for water analysis

No	**Parameters**	**Units**	**Methods**	**APHA 2012 Reference Method (61)**
1	pH	-	pH meter	2110
2	Conductivity	µS/cm	Conductivity meter	2510 (B)
3	TDS	mg/L	Conductivity meter	2510 (A)
4	TSS	mg/L	Dry at 103 – 105 ^{0}C	2540 (D)
5	Turbidity	NTU	Nephelometric	2130 (B)
6	SDI	-	Membrane filter	4189 (D)
6	COD	mg/L	Colorimetric	5220 (D)
7	BOD	mg/L	Colorimetric	2510 (A)
8	Alkalinity	mg/L $CaCO_3$	Titration	2320 (B)
9	Hardness	mg/L $CaCO_3$	EDTA Titration	2340 (C)
10	Calcium	mg/L $CaCO_3$	EDTA Titration	3500-Ca (B)
11	Chloride	mg/L Cl^-	Argentometric	4500 Cl^- (B)
12	Silica	mg/L SiO_2	Molybdosilicate	4500 SiO_2 (B)
13	Sulfate	mg/L SO_4^{2-}	Turbidimetric	4500 SO_4^{2-} (B)
14	Free Chlorine	mg/L Cl_2	Photometer	4500 Cl (G)

3.8 Unit design and Feasibility Study

The design of treatment system was done by using the result from selected pretreatment data and membrane treatment data from lab scale experiment. For case study of this power plant, the initial capacity of the treatment unit was 1,500 m^3/d using safety factor of 1.3 to avoid the high investment cost and operation and maintenance cost (O&M costs) as for future plant expansion the treatment unit was thus designed at 2,000 m^3/day flow capacity.

Capital and O&M costs of water treatment plants are essential for planning and design of the treatment facilities. These costs were used to evaluate the financial and economic benefits of the project. The accuracy of the estimate depends upon how well the variables and uncertainties within the scope of the project are defined and understood **(62)**. Various components of the capital and O&M costs are shown in Figure 3.6.

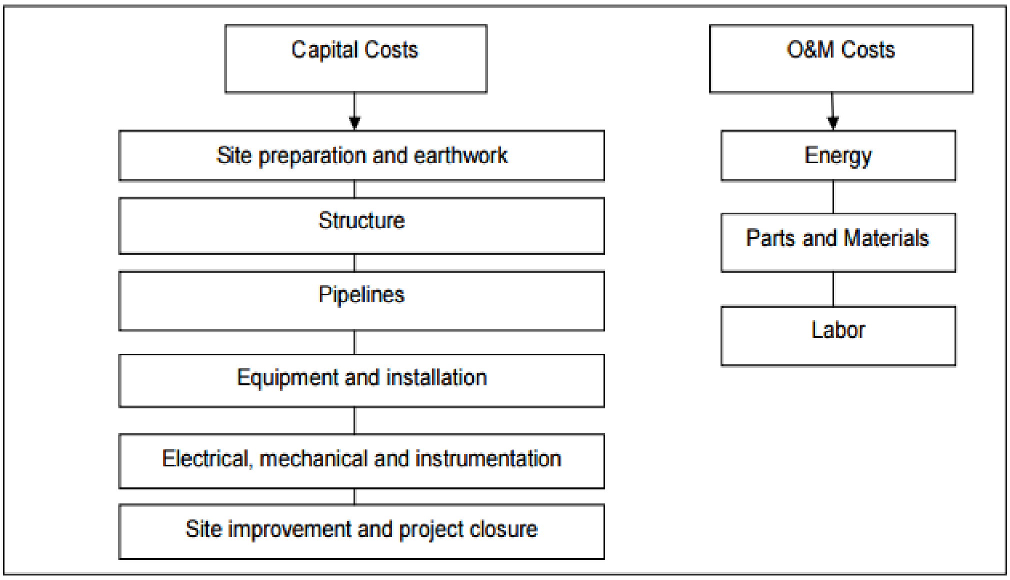

Figure 3.6 Components of capital, and operation and maintenance costs **(62)**

In this case study, the capital costs of rapid mixing, slow mixing, clarifier (for sedimentation), and multimedia filter depend on unit size and were calculated by an Qasim's equation model **(63)** and USEPA's cost curve **(64, 65)**. Membrane pretreatment and membrane desalination system were designed using the flux and permeability values from the experiment. The cost of this system depends on unit size, calculated by an estimating model, Suratt's equation model **(66)** and WATER's program **(67)**. The cost information of whole system was estimated and updated to actual year cost by ENR's construction and building cost index **(68)**. However, electricity cost and labor cost were evaluated from the domestic price in year 2016. All cost information in US currency was converted to Thai Baht currency with average exchange rate, one USD equal to around 35 Thai Baht (October 2016) **(69)**.

CHAPTER 4

RESULTS & DISCUSSIONS

In this chapter, the results which reflect to the objectives listed in Chapter I were divided into three main parts, the experimental study of pretreatment and membrane desalination of blowdown water, the decision making for selection the suitable pretreatment systems, and the design of blowdown treatment unit and its feasibility study.

Part I Experimental study of pretreatment and membrane desalination of blowdown water

4.1 Quality of discharged cooling tower water

Table 4.1 shows the annually averaged values of some important parameters in cooling tower blowdown water, which discharged from a co-generation power plant. However, based on the guidelines for feed water quality for membrane process like NF and RO in Table 3.7, this discharged water needs to be pretreated to reduce some parameters. Turbidity is an important parameter to indicate the suspended solid and colloidal particles that can cause fouling in membrane. The turbidity of the feed water for membrane has to be less than 1.0 NTU **(23, 70).** In addition, SDI index is the best method to tell the feed water quality of membrane unit **(6, 53)** and it should be less than 5 **(6, 23, 70, 71)**. Furthermore, the presence of chlorine could damage membrane and must be kept at less than 0.1 ppm **(72)**. Furthermore, COD, hardness and silica representted the organic and inorganic foulants for membrane **(21, 23)**.

From Table 4.1 it was clearly seen that the turbidity and SDI of the discharged water were over the limited values and must be removed before being fed to the membrane unit.

Table 4.1 Discharge water quality from cooling tower

No	Parameter	Unit	Value range	Annual value	NF and RO feed water Control
Overall characteristics					
1	pH	-	8.7 – 8.9	8.8	2-11
2	Conductivity	µS/cm	1,148-1,814	1,459	-
3	TDS	mg/L	688-1,130	969	-
4	TSS	mg/L	5-12	9	-
5	Oil and Greece	mg/L	< 1	<1	-
6	BOD_5	mg/L	2.0-3.4	2.6	-
7	COD	mg/L	19-47	35	-
8	Turbidity	NTU	1.8-5.4	3.5	<1
9	SDI	-	16-19	18	<5
Salt ions					
10	Total Alkalinity	mg/L $CaCO_3$	260-430	380	-
11	Calcium	mg/L $CaCO_3$	250-395	325	-
12	Magnesium	mg/L $CaCO_3$	115-180	145	-
13	Sulphate	mg/L SO_4	95-175	135	-
14	Chloride	mg/L Cl	115-340	205	-
15	Silica	mg/L SiO_2	10-80	50	-
16	Total Iron	mg/L Fe	0.02-0.15	0.08	-
17	Phosphate	mg/L PO_4	0.2-1.0	0.6	-
18	Chlorine	mg/L	<0.1	<0.1	<0.1
19	Heavy metals				
	- Manganese	mg/L	<0.03	<0.03	-
	- Copper	mg/L	0.01 – 0.03	0.02	-

4.2 Pretreatment of Feed Water

4.2.1 Conventional pretreatment

Coagulation and flocculation are the conventional pretreatment methods used to separate suspended and colloidal organic and inorganic particles from raw water. The effective application of coagulation and flocculation depends upon the characteristic of suspended particles such as charge, size, shape, and density **(48)**. Most suspended solids in water normally have a negative charge that repels each other when they come close together. This makes it hard to clump together and settle out of the water, unless proper coagulation and flocculation is used.

Coagulation and flocculation processes occur in sequential steps, allowing particle collision and growth of floc. This is then followed by sedimentation. In addition, for the efficient treatment the right dosages of coagulants and flocculants need to be determined.

a) Effect of PACl dosage on turbidity removal

The effect of coagulant dosage on the turbidity of pretreated water was illustrated in Figure 4.1 and 4.2.

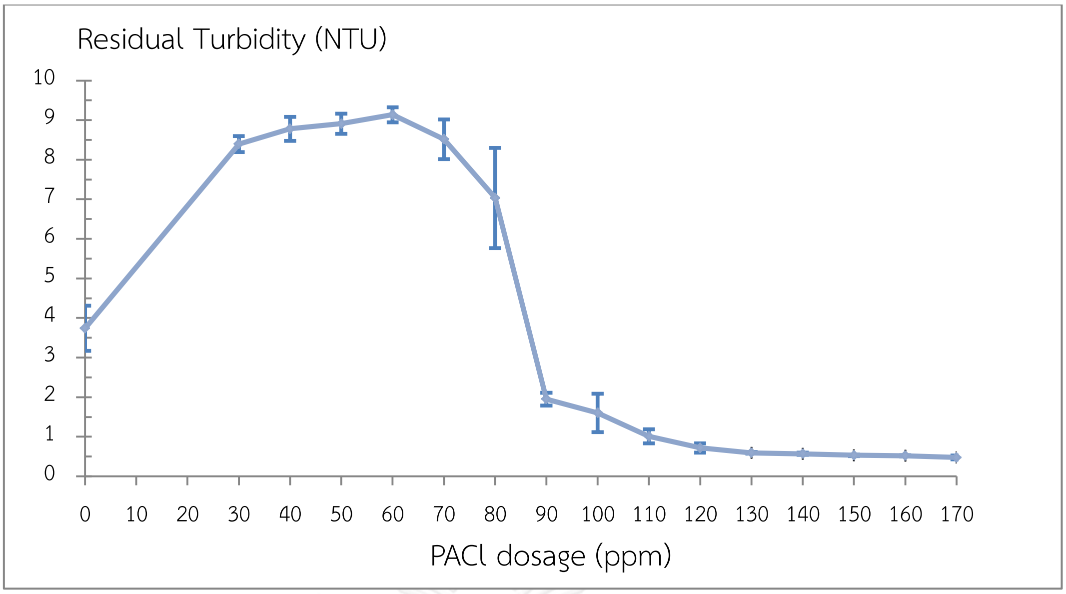

Figure 4.1 Residual turbidity vs PACl dosage

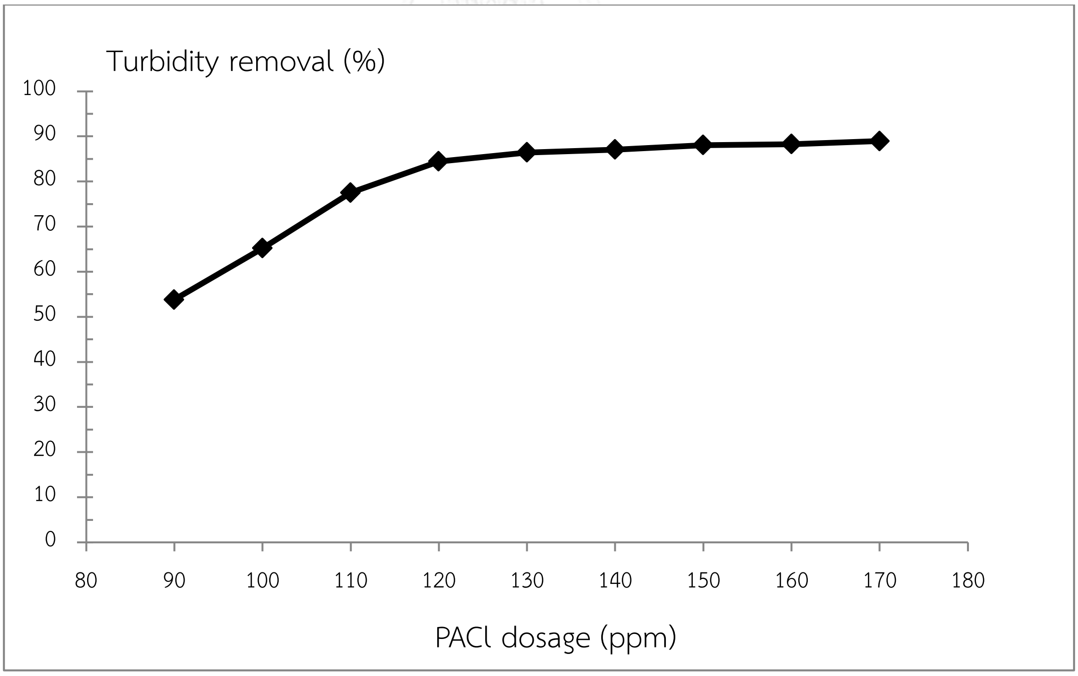

Figure 4.2 Percent turbidity removal vs PACl dosage

The residue turbidity gradually increased with the PACl addition, but then started to fall at PACl dosage of 60 ppm and got to a steady value at around 0.5 NTU at 120 ppm PACl dosage. The increasing trend of turbidity when 10-60 ppm of the coagulant was added might be attributed to the increase in suspended particles from the chemical addition itself. In addition, the small coagulant addition was not efficient enough to destabilize the colloidal particles, more coagulant chemicals may need to be added. Once the charge is neutralized, the small particles are capable of sticking together and water surrounding the newly formed micro-flocs should be clear. The optimum dosage of PACl was defined as a value above which there is no significant increase in removal efficiency with further addition of the coagulant. The optimum dosage of PACL for discharge cooling water in this study was 120 ppm, but 150 ppm of PACl was selected to be our operating dosage to ensure the effective removal of the suspended particles in the case of fluctuation of feed water quality. This dosage can reached the turbidity lower than 1.0 NTU which is the requirement of feed water for membrane processes. Approximately 0.4 NTU and 88% of turbidity removal could be achieved.

b) Effect of Flocculant Chemical on Settling Time

Two types of flocculant, CPAM and APAM, were added to the jar at slow stirring step and their effects were compared. The settling behavior of coagulant aids was investigated at dosage of 1.00 ppm and selected PACl dosage at 150 ppm. Figure

4.3 shows the residual turbidity at various settling time of sample water from coagulation-flocculation process with and without flocculant. It can be clearly observed that the addition of a small amount of the flocculant could significantly reduce the settling time of coagulation-flocculation process, which could reduce the sedimentation time for settling step.

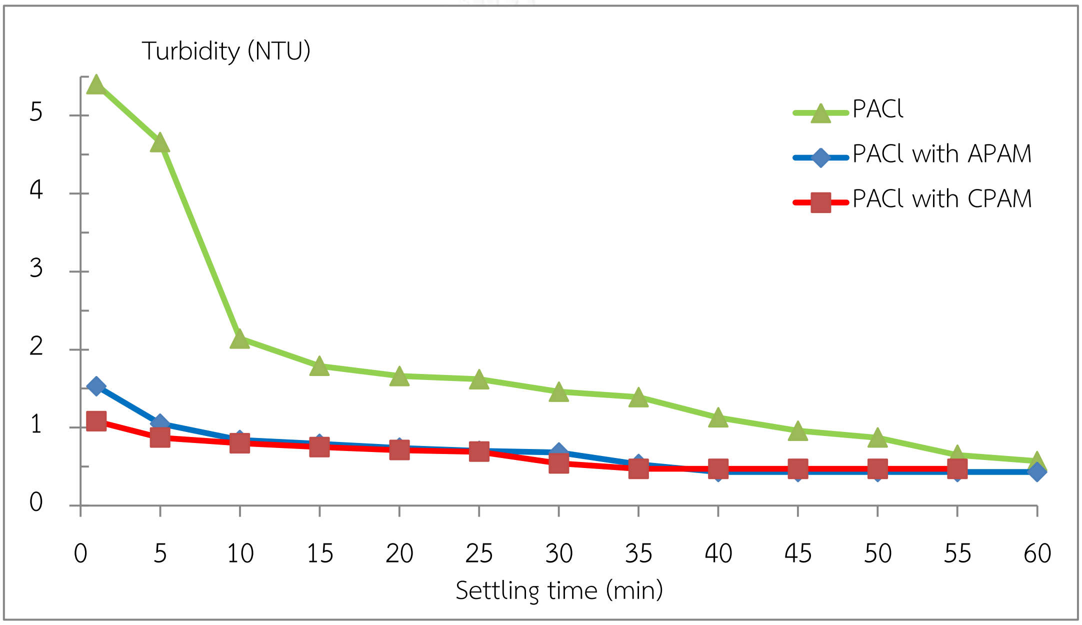

Figure 4.3 Residual turbidity at settling time of each pretreatment

Both polymers were added to help the flocs to bridge and bind together and also to strengthen their interaction, forming bigger flocs with heavier weight and accelerating their settling rate. From 4.4, both polymers showed no significant difference in reducing turbidity of the raw water with similar settling rate. However, from Figure 4.4, the flocs from the mixture of PACl and APAM were larger than those from PACl and CPAM. This added a big advantage in the following separation step of the flocs for PACL/APAM over the PACL/CPAM system **(73)**. This may be because the anionic PAM neutralized the positive charge of PACl coagulants and helped them form the larger flocs that can be visible with agglomerate sizes in the range of 0.1 to 2.0 mm **(74)**. APAM was thus selected to be the flocculant for the conventional treatment process that required 45 minute of settling time to reduce the turbidity of blowdown water down to 0.41 NTU.

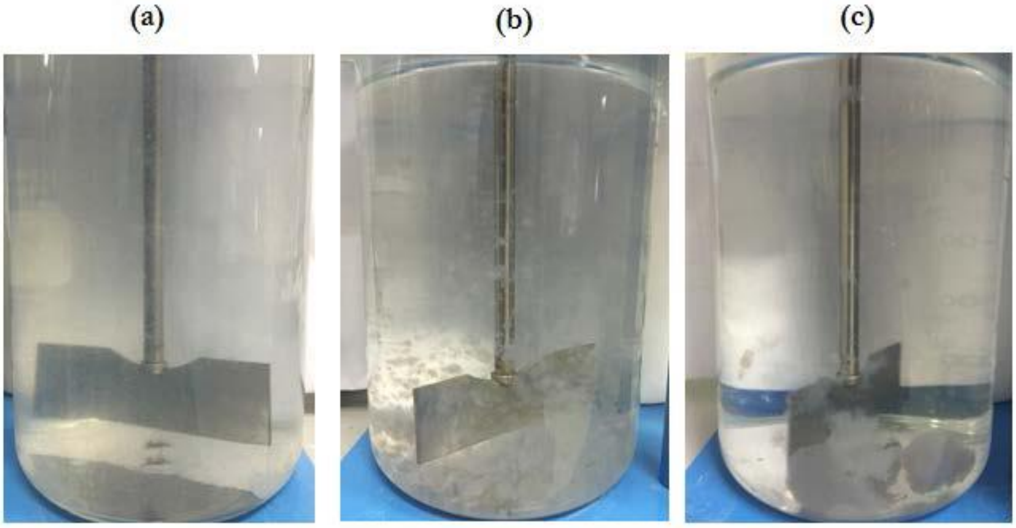

Figure 4.4 Characteristic of floc formation at the first minute of settling step
(a) PACl 150 ppm (b) PACl 150 ppm + CPAM 1.00 ppm
(c) PACl 150 ppm + APAM 1.00 ppm

c) Effect of media filtration pretreatment

When only filtration was used as the pretreatment for the raw water, the residual turbidity remained unchanged (see Table 4.2). It should be noted that the low value of turbidity (0.4 NTU) to meet the requirement for membrane separation process can already be achieved by coagulation and flocculation steps. However, the SDI value still exceeded the control value required by membrane separation process and it is of necessary to further complete the pretreatment with the multimedia filtration. Only when the combination of pretreatments using the multimedia filter after chemical pretreatment process, the pretreated water could meet feed water quality with low turbidity and low SDI value for membranes.

Table 4.2 Raw and effluent water qualities from each pretreatment step.

Parameter (unit)	**pH**	**Turbidity (NTU)**	**COD (mg/L)**	**Hardness (mg/L)**	**Silica (mg/L)**	**SDI**
Required quality	**-**	**<1.0**	**-**	**-**	**-**	**<5**
Raw water	8.8±0.1	3.74±0.57	33±3	440±8	38±1	18.1±0.1
Filtration	8.8±0.1	2.46±0.98	31±3	340±8	23±1	14.2±0.5
PACl	8.2±0.1	0.64±0.08	23±1	447±5	25±2	19.1±0.1
PACl + APAM	8.3±0.1	0.56±0.09	21±1	443±5	27±2	18.8±0.1
PACl + CPAM	8.2±0.1	0.59±0.04	20±1	440±8	24±2	18.9±0.2
PACl + Filtration	8.3±0.1	0.75±0.06	21±1	350±16	19±1	13.3±0.4
PACl + APAM + Filtration	8.3±0.1	0.41±0.05	20±1	452±2	25±3	4.1±0.5
PACl + CPAM + Filtration	8.2±0.1	0.42±0.04	21±1	445±4	24±1	4.5±0.3

Figure 4.5 shows the surface of used polymer filter (polyamide membrane with pore diameter at 0.45 µm) from SDI measurement of water from different pretreatments. For the raw blowdown water, the dark brown color was observed on the membrane filter (Figure 4.5 a), implying that the water contained high amount of suspended particles and colloidal. This raw water was not suitable for feeding to membrane separation process. When the water was pretreated by coagulation and flocculation chemical, the tiny particles are combined and settled out by gravity; this was clearly observed from the reduced observable cake-layer on the filter (Figure 4.5 b). The membrane surface after pretreatment with coagulation/flocculation and multimedia filtration had a more whitish appearance, indicating less foulants remaining (Figure 4.5 c) and can be used for membrane pretreatment process.

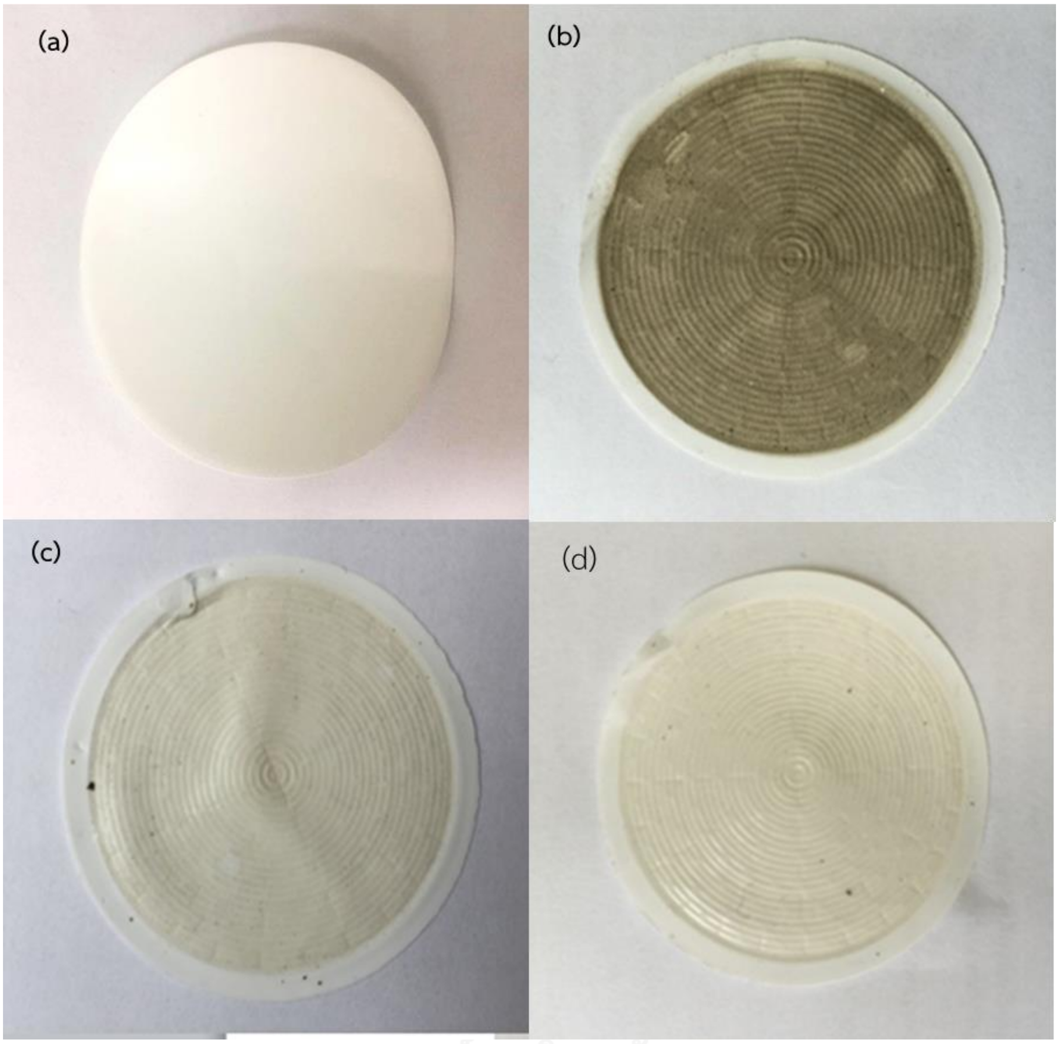

Figure 4.5 Used filter from SDI test of raw water and water for pretreatment by (a) new membrane (b) after raw effluent, (c) after treatment by coagulation-flocculation (APAM), (d) after treatment by coagulation-flocculation (APAM) and multimedia filtration

The results obtained for the pretreatment study showed that the combination of coagulation/flocculation (APAM) with multimedia filtration was the most effective method that could pretreat raw water to meet the required quality of the feed for the NF/RO systems.

4.2.2 Membrane pretreatment process

For the membrane pretreatment, the large particles in blowdown water was filtrated out by 5 µm polypropylene pre-filter before the UF membrane filter tests. The UF experiment was carried out for 1 hour of operation time. Feed pressure was fixed at 3 barg and every ten minute sample was collected to check turbidity of permeate water. The result of flux and turbidity was shown in Figures 4.6 and 4.7.

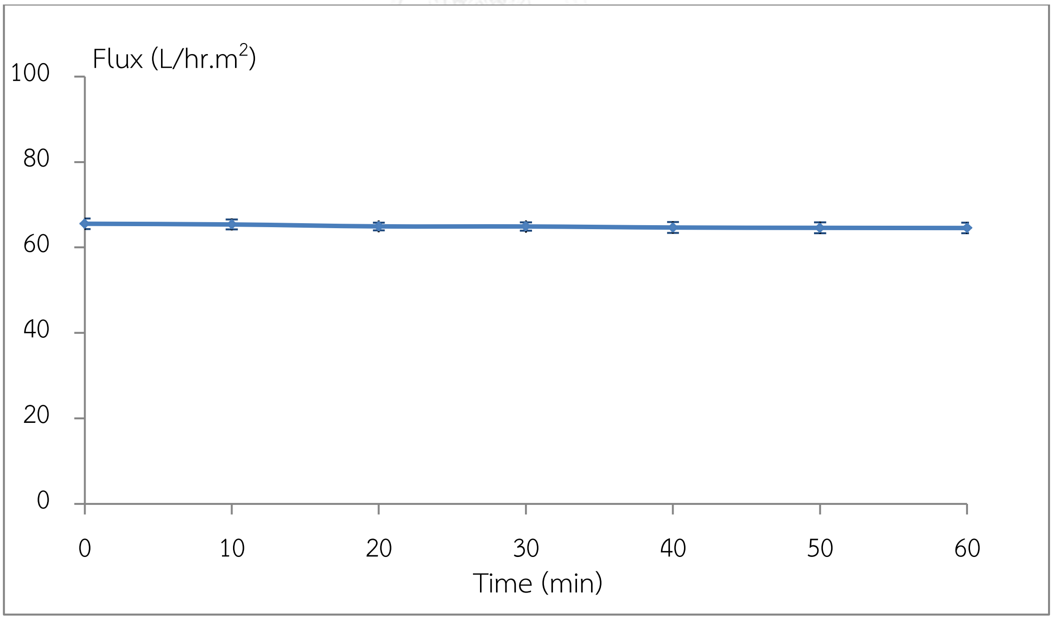

Figure 4.6 Operation flux of UF membranes

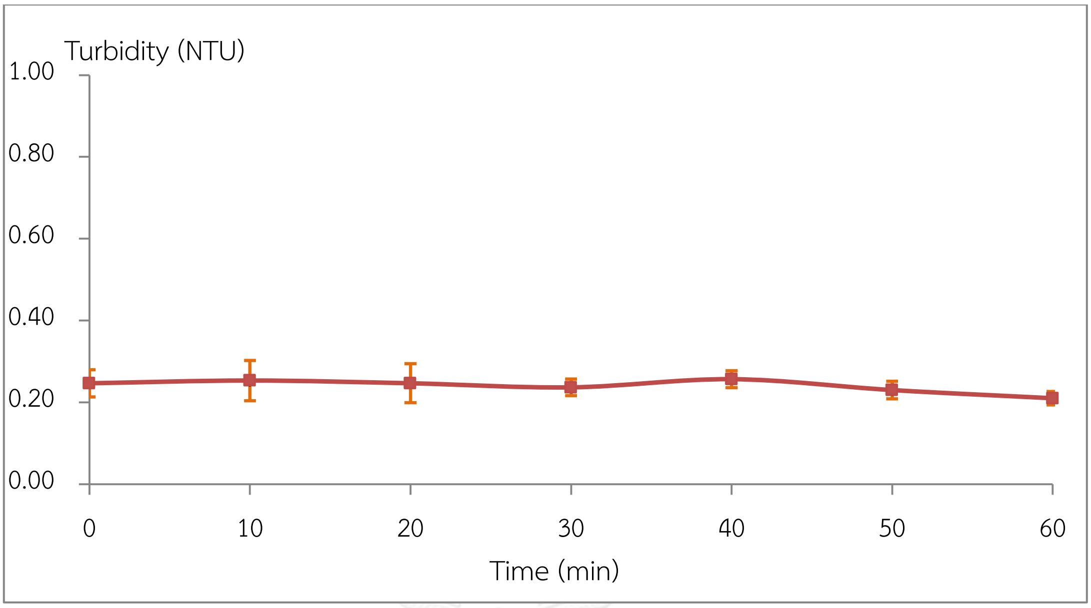

Figure 4.7 Turbidity of treated water form UF membrane

From Figure 4.6, at constant trans-membrane pressure the flux of treated water was relative stable at the average value around 65 L/hr.m^2. In fact, for the longer operation, normally the gradual flux decline should be observed. Dow, the membrane producer, recommended to do membrane cleaning cycle to prolong the lifespan of the membrane by a short back-washing every 30 minutes and by chemical cleaning with liquid chlorine, HCl acid, and NaOH basis every 12 hour **(75)**.

Water samples after the membrane pretreatment step were collected and analyzed, as the result; average turbidity and SDI by prefilter is about 1.56 NTU and 16.9. On the other hand, average turbidity and SDI of pre-treated water from the UF was only 0.24 NTU and 2.7, which was good enough as RO feed. However, other parameters like pH, COD, hardness and silica values were not changed. The water qualities after membranes pretreatment were summarized in Table 4.3.

Table 4.3 Raw water and effluent water qualities from UF pretreatment membrane

Parameter	**Raw water**	**Pre-filter**	**UF membrane**	**Required quality**
pH	8.8±0.1	8.7±0.1	8.7±0.1	**2-11**
Turbidity (NTU)	3.74±0.57	1.56±0.48	0.24±0.03	**<1.0**
COD (mg/L)	33±3	30±1	30±1	**-**
Hardness (mg/L)	440±8	440±2	441±5	**-**
Silica (mg/L)	38±1	35±1	37±2	-
SDI	18.1±0.1	16.9±0.1	2.7±0.5	< 5.0

Compared to the conventional pretreatment, membrane pretreatment showed to be more efficient. Figure 4.8 shows the surface of used polymer filter from SDI measurement of the pretreated water from 5 micron pre-filter and UF filter. The membrane surface was quite clean with only small area of black droplets (Figure 4.8 c), indicating only small amount of foulants remaining.

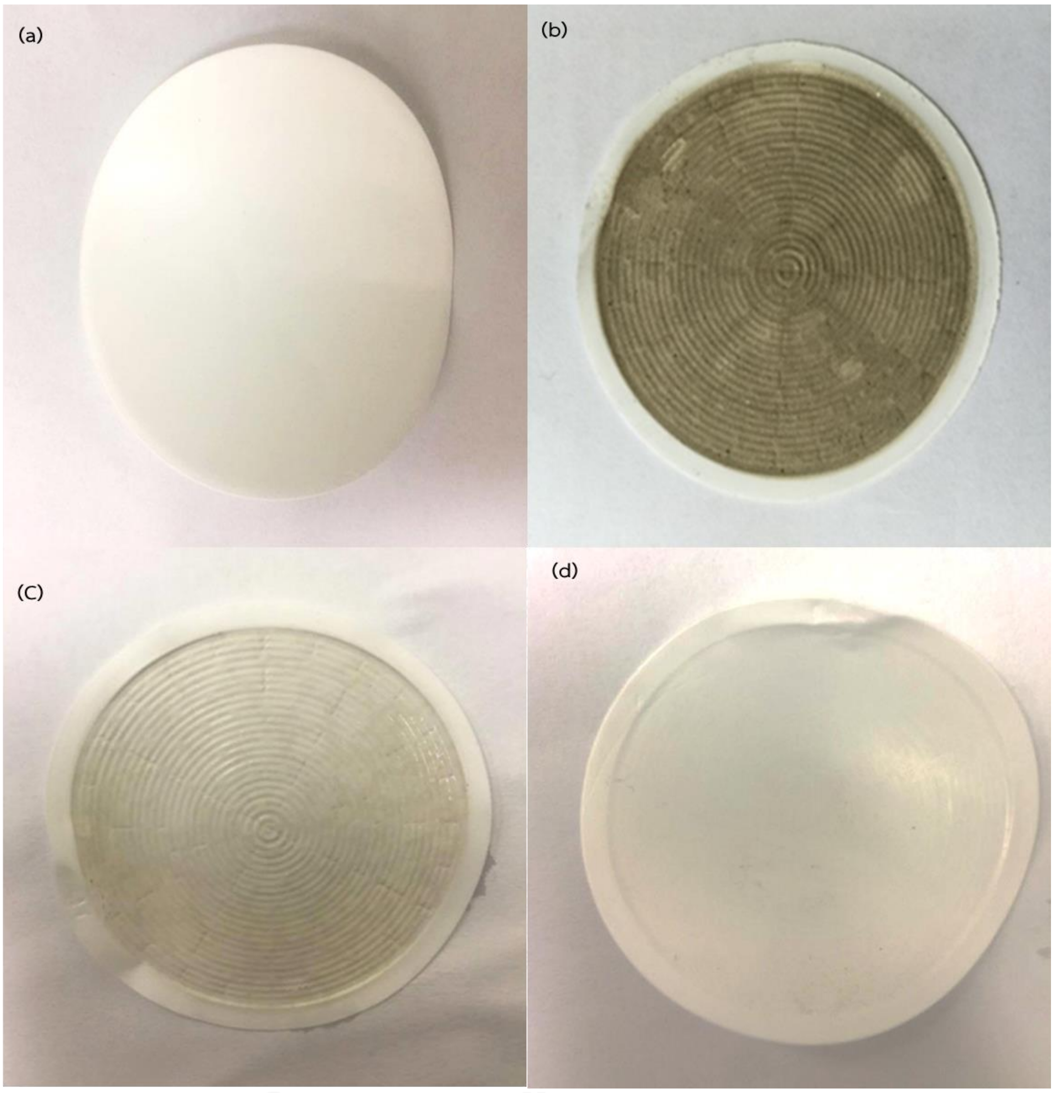

Figure 4.8 Used filter from SDI test of raw water and water for pretreatment by (a) new membrane (b) raw water effluent (c) after 5 micron pre-filter (d) after treatment by UF membrane

4.3 NF/RO membrane treatment process

Feed water for membrane process was synthesized to have the same composition as the pretreated water from the UF method. Two types of membranes, NF and RO, were used and compared. Water flux of the membranes was measured under different operation pressures and was presented in Figure 4.9. The fluxes increased linearly with the increased operation pressure. The linear evolution of fluxes with the transmembrane pressure shows that Darcy's law is valid (Equation 3.7). This linear behavior is described by a slope which corresponds to water permeability.

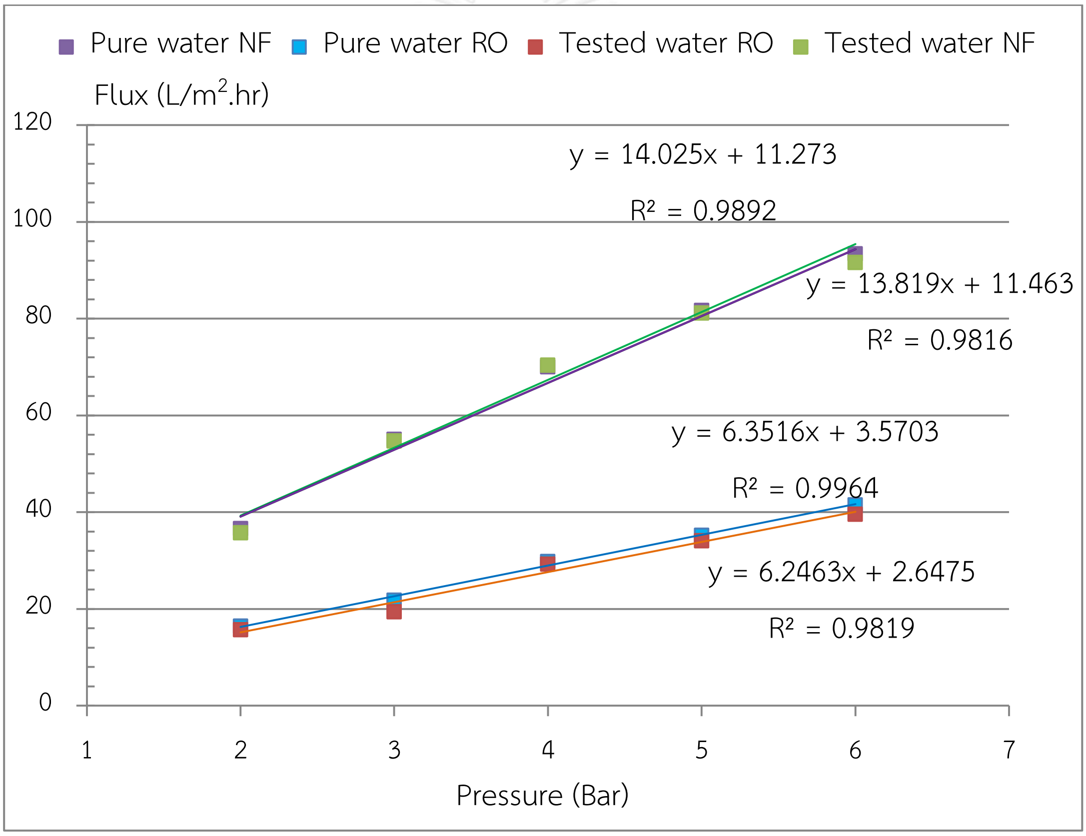

Figure 4.9 Effect of TMP on the permeate flux of pure water and tested water for NF and RO membrane

From Figure 4.9, the NF membranes exhibited higher permeate flux values to pure water compared to the RO membrane. The higher slope means the higher permeability characteristic, which generally indicates a high porosity. On the other hand, the lower slope value was obtained for the examined RO membrane, which is expected due to its denser selective layer. The molecular weight cut off (MWCO) of the investigated membranes and permeability values, which are proportional to the pores size of membranes, was given in Table 4.4.

The rejection of the investigated membranes for synthesis water was plotted against the different trans-membrane pressures as shown in Figure 4.10. In RO, the salt rejection remained considerably constants with increasing operating pressure, because the ion permeation is only a function of feed concentration and is independent of the operating pressure **(76)**. On the other hand, in NF membrane the rejection increased gradually with the applied pressure. This could be explained by considering salts transport through the membrane as a result of diffusion and convection due to concentration and pressure gradients across the membrane. At a low operation pressure, diffusion contributes substantially to the salts transport resulting in a lower retention while increasing pressure, the salts transport by diffusion becomes relatively less important, so that salts retention is higher **(77)**.

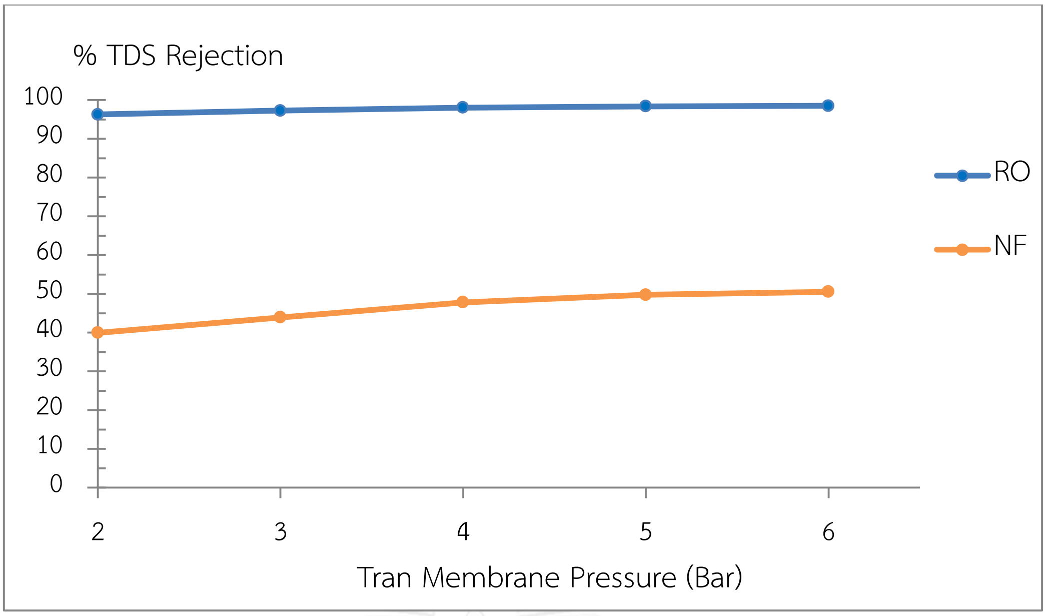

Figure 4.10 TDS rejection as a function of TMP for NF and RO membranes

The RO membranes as expected showed the best performance on salts rejection with almost 98 %. For the NF membrane, 50 % of salts rejection was obtained; this because the MWCO of membrane is larger than diameter of salts. The RO membrane can be used to treat blowdown water from cooling tower in this power plant. Based on this result, the selected pressure for operating RO unit is 7 bar.

Table 4.4 Values of MWCO and membrane permeability of the membranes

Membrane Type	**MWCO* (Dalton)**	**Membrane permeability (L/hr.m^2.bar)**	**TDS rejection (%)**	**TDS of The Treated water (mg/L)**
NF	200	14.03	50.5	514
RO	90	6.352	98.5	19

*Values were obtained from the literature (**40)**

From the data in Table 4.4, TDS 514 ppm of treated water from NF membrane was higher than TDS value of tap water quality in this power plant (around 200-300 ppm) and higher than criteria TDS for cooling tower make-up water, which should not be more than 500 ppm **(34)**. Unlike the treated water from RO membrane, 19 ppm of TDS was achieved and can be used for further design

Part II Decision making for selection the suitable pretreatment systems

Several factors including removal efficiency, cost, and area require were taken into account in order to make the decision for the suitable and most economic pre-treatment systems for the blowdown water pre-treatment unit. Figure 4.12 compares the steps required in conventional and membrane pre-treatment before being feed to the RO membrane. For conventional pretreatment, 150 ppm of PACl coagulant was dosed into the raw water and mixed through a baffle plates for 1 minute, and afterwards 1 ppm of APAM flocculant was added and kept mixing for 15 minute to form dense flocs. The flocs was then allowed to settle in sedimentation clarifiers for 1 hour. The clarified water was fed to the media filters with filtration rate of 8 L/hour.m^2, which was the recommended filtration rate for a media filter.

In the case of UF system, the process started with 5 µm pre-filters for screening large particulate before UF membrane. The filtration flux of UF is 65 L/hour.m^2. Therefore, 17 of UF membrane modules (77 m^2 per module) were required to treat 2000 m^3 of blowdown water per day.

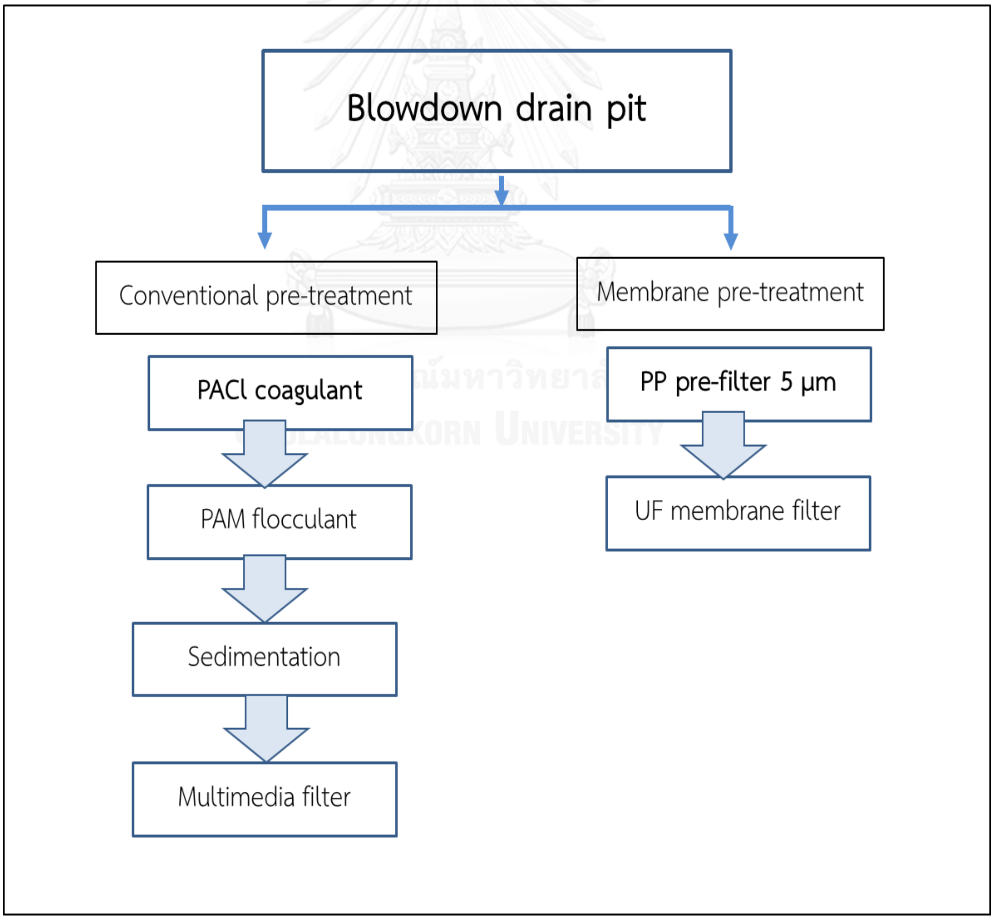

Figure 4.11 Process diagram of conventional and membrane pretreatment

From the design flow rate, 2,000 m^3/day of blowdown water from power plant, an economic analysis of the comparative conventionally versus membrane (UF) pretreated system for RO plant was evaluated. The cost data and economic analysis are summarized in Table 4.5 and 4.6, respectively.

Table 4.5 Comparative cost for conventional and membrane pretreatment systems (The costs in this Table is 2016's costs, See Appendix D)

Pretreatment type	**Conventional**	**UF**
Investment cost (Million Baht, MB)		
- Pre-filter	-	0.39
- Rapid mixer basin	1.79	-
- Slow mixer basin	4.68	-
- Sedimentation basin	5.13	-
- Filtration system and chemical feed system	21.2	-
- Membrane cleaning equip.	-	4.4
- UF Membrane system	-	28.19
Total capital cost (MB)	**32.80**	**32.98**
Fixed O&M cost (MB/year)		
- Materials	0.065	0.319
- Media filter replacement	0.042	-
- Membrane replacement	-	0.376
Variable O&M Cost (MB/year)		
- Energy	0.069	0.157
- Chemical	0.997	0.080
- Labor	0.082	0.133
Total O&M Cost (Baht/year)	1.26	1.07

Table 4.6 Main design data and economic analysis for conventional and membrane pretreatment systems (See Appendix D)

Pretreatment type	Conventional	UF
Number of unit	1	1
Train feed capacity (m^3/day)	2,000	2,000
Construction area (m^2)		
- Rapid mixer basin	2	-
- Slow mixer basin	33	-
- Sedimentation basin	35	-
- Filtration unit	7	25
Filtration flux (L/hr.m^2)	8	65
Water losses (%)	6.6*	10**
Train product capacity (m^3/day)	1,868	1,795

*Water losses through sludge discharged and backwash filter **(52)**

** Water losses through sludge discharged and backwash filter **(52)**

Capital cost

The total investment in the 2,000 m^3/day pretreatment plant was estimated to be 32.8 million Baht for the case where conventional filtration was used and 32.98 million Baht for the plant used UF pretreatment. The total capital cost of UF system was only slightly higher than the conventional method (around 5% higher).

Operation & Maintenance (O&M) costs

From Tables 4.5 and 4.6, the total O&M cost of the conventional method was approximately 18% higher than those of UF system. The major O&M cost of the conventional method was contributed to the chemicals, while for the UF system was to electricity

Quality of treated water and the fluctuation of raw water quality

UF system has exhibited its ability to constantly produce low turbidity (high quality) of filtrate in comparison to conventional method. The key feature of UF is its capability to control the permeate quality by pore size. However the major drawback of UF in large-scale application is membrane fouling which is tedious to control and likely to happen when turbidity of raw water is increased. The control turbidity for UF membrane should be less than 200 NTU **(75)**. On the other hand, conventional pretreatment plants are settling the particles out of process and in the case of high turbidity of raw water, conventional pretreatment are preferred. However, the annual water quality of the power plant in this study is rarely fluctuated, so the UF pretreatment are preferred.

Water loss and waste disposal

Water losses are mainly due to sludge discharge, cleaning the filter media and UF membrane through backwash process. It has been reported in commercial-scale studies that water losses of UF membrane can be as high as 13.3% **(78)** to allow more frequent sludge discharge interval and backwash to alleviate membrane fouling. On the other hand, the conventional system water losses are within the recommended level of less than 7% **(79).**

However, sludge with chemical coagulant, aluminium, could lead to heavy metal accumulation in the environment and thus required further treatment and proper sludge management **(80)**. This was considering one of the major disadvantages of the conventional system.

Land required

The land required for a UF plant operating at a membrane pretreatment was only 30% of the area needed for a system used a conventional pretreatment. For plants limited in size especially in the case of power plant located in a community area, membrane system was preferred. The fact that UF membrane price has been decreasing and smaller land requirements have made this treatment process very affordable to be implemented in large-scale

The primary purpose of this study was to evaluate the sustainability of industrial-scale UF and conventional pretreatment systems in terms of commercial and environmental. The comparisons between both systems indicated that the UF system might eventually be more commercially viable than conventional systems. In addition, the membrane system could produce consistently good quality of filtrate with lower O&M cost, smaller land requirement, non-toxic sludge discharge and highly automated process with less manpower required. Therefore, in this work, UF membrane was selected to be pretreatment process before RO membrane desalination plant for blowdown water from power plant.

<u>Part III</u> Design membrane treatment plant

4.4 RO Membrane Desalination Unit Design

4.4.1 Design basis of the membrane treatment blowdown water from power plant

Based on experimental data in section 4.2 and 4.3, 19 mg/L of TDS in permeate water was too clean for cooling make up water and make the productivity of membrane treatment plant was very low. For this reason, blending stream has to use for increase the TDS of product water and product flow as well. Valuation blending flow rate stream showed in Equation 4.1 **(67)** below, where Q_B is Blending flow rate in cubic meter per day and the flow diagram showed in Figure 4.13.

$$Q_B = Q_f \times \frac{TDS_{Target}}{TDS_{Permeate}} \times \frac{TDS_{Feed}}{TDS_{Permeate}} \quad \text{Equation 4.1}$$

Where Q_B is Blending stream volumetric flow rate and

Q_f is Feed stream volumetric flow rate

However, TDS in brine stream are concern according to the standards for wastewater discharge from industrial plants (Ministry of Natural Resources and Environment) **(81)** which should not be more than 3,000 ppm. From this point, CF of RO unit from equation 3.4 should less than 3 and Y value or recovery ratio equal to 65 percent. Quantity and quality of RO desalination unit showed in Figure 4.13.

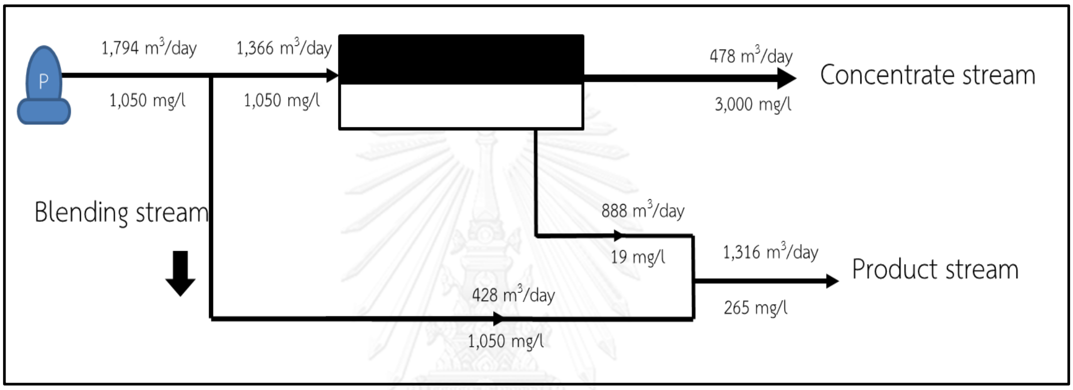

Figure 4.12 Flow diagram of RO membrane unit with blending stream

From Figure 4.13, membrane feed flow rate is 1,794 m^3/day which UF product water is used to calculate the number of membrane element via the membrane permeability value (6.352 Lph/m^2.bar). From this information, 1,280 m^2 of membrane area are used at 7 bar feed pressure, equal to 34.6 elements of BW30-400 membrane (8’’ diameter and 40’’ length) with active area of 37 m^2 per element. The design basis of membrane water treatment was shown in Table 4.7.

Table 4.7 Design basis of membrane water treatment plant

Parameter	**Description**
Design approach	- Continuous process
Design flow rate	- 2,000 m^3/day
Raw water quality	- Turbidity > 1 NTU - Suspended solid > 1 ppm - SDI > 15 - TDS ~ 1,050 ppm
Pretreatment type	- Cartridge filter pore size 5 µm - UF membrane pore size 0.03 µm
Pretreatment water quality	- Turbidity < 1 NTU - Suspended solid < 1 ppm - SDI < 5 - TDS ~ 1,050 ppm
Membrane treatment type	- RO element model BW30-400
Product water quality	- TDS ~ 365 ppm
Concentrate water quality	- TDS ~ 3,000 ppm
Disinfection of product water	- 1.0 ppm concentration of liquid chlorine

4.5.2 Process flow diagram

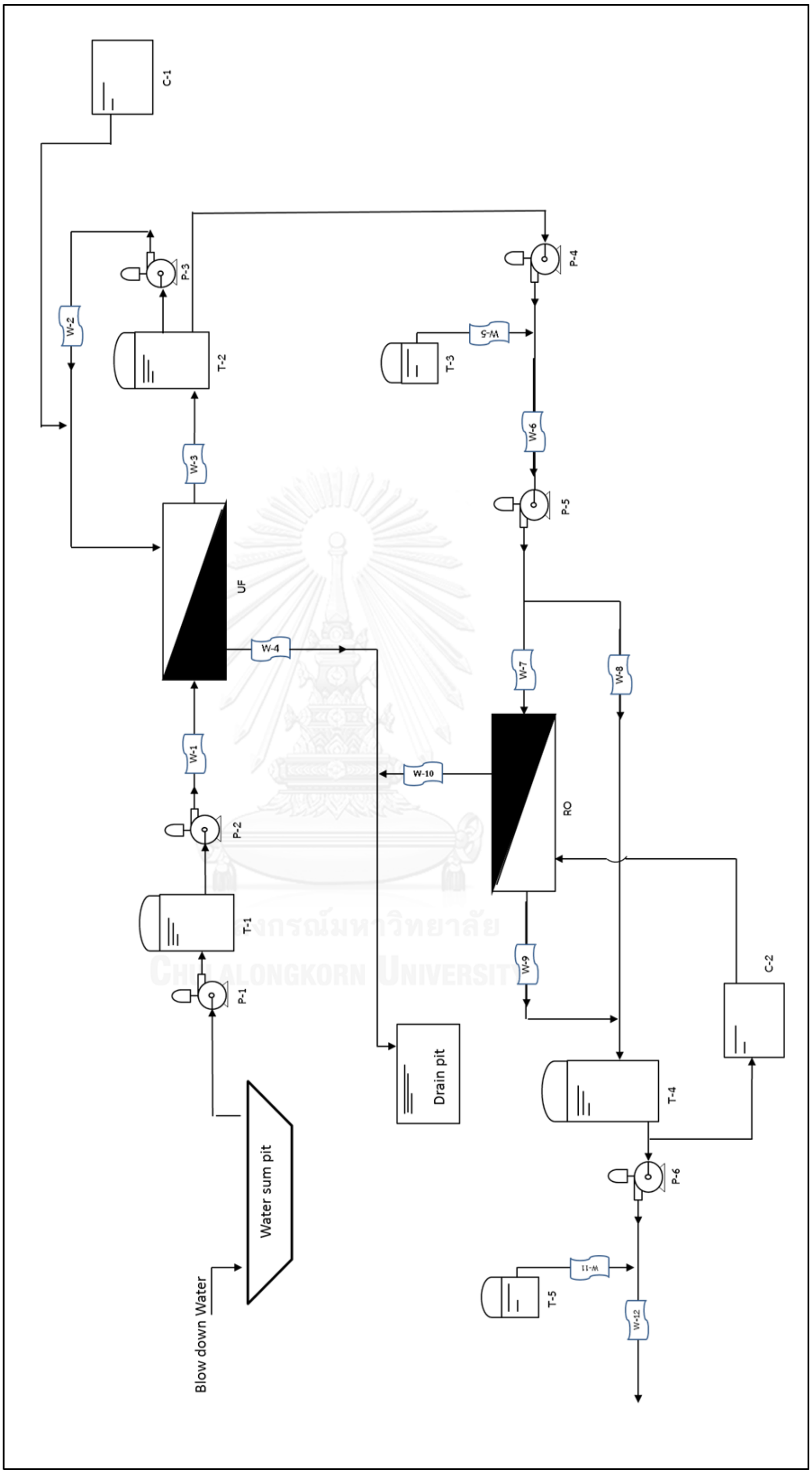

Figure 4.13 Process flow diagram of membrane treatment

4.4.3 Process description

Figure 4.14, showed the process flow diagram of the membrane treatment blowdown water from power plant. The production of the membrane treated water was a continuous process and can be simply described as follows.

Raw water

Raw water was fed from blowdown pit in power plant with design flow rate 2,000 m^3/day. The high values of turbidity and SDI were observed and cannot be fed directly to the membrane without pretreatment process to avoid the block up in membrane unit.

UF membrane pretreatment

Blowdown water was fed to feed tank and transfer to UF system by UF feed pump at constant pressure 3 bar (65 LPH of flux). The back wash pump was used to clean the membrane at pressure 3.1 bar every 30 minute as same as the chemically enhanced backwash (CEB) systems which conduct acid and caustic chemical to clean the membrane every 12 hour for prevent the fouling on UF membrane. The filtrated water was kept at filtrated water tank. Membrane system size can be calculated to 17 modules. Constructions were developed for complete UF plants include housing, structural steel, chemical tanks, piping, valves, flow meters, cartridge filters and also cleaning equipment.

RO membrane

After the pretreatment system, treated water was transferred from the holding tank to the high pressure pump by water transfer pump. The efficiency of the membrane elements may be impaired by scaling, then small quantities of anti-scale solution (recommended value 0.5 ppm), which prepared in a tank and then pumped by a diaphragm metering pump to the line was add-up. Membrane system size could be calculated to 36 modules. Constructions developed for complete RO plants include housing, structural steel, chemical tanks, piping, valves, high pressure pumps, pressure vessels, flow meters, cartridge filters and also cleaning equipment. The blending stream was used to achieve the higher TDS value and product water flow. The concentrate stream flow which TDS control of 3,000 ppm was rejected to the waste water drain pit.

Chlorine feed

To prevent the bacteria growth in product water, feed of small quantities (1.0 ppm) of sodium hypochlorite solution, which prepared in a day tank and then pumped by a diaphragm metering pump to the point of application. Construction is identical for chemical feed systems with capacity up to 500 kg/day.

4.4.4 Overall Flow and TDS balance

Overall volumetric flow and TDS balanced of the membrane treatment plant for cooling tower blowdown are summarized in Table 4.8.

Table 4.8 Flow and TDS balance for process flow diagram in Figure 4.14

Code	Flow (m^3/day)	TDS (ppm)	Stream	Remark
W-1	***2,000***	***1,050***	***UF Feed***	*Input stream*
W-3	2,000	1,050	UF Product	*In-Process stream*
W-2	206	1,050	UF Back wash	
W-5	0.01	10,050	Chemical dosing	
W-6	1,794	1,050	RO Feed	
W-7	1,366	1,050	RO Primary feed	
W-8	428	1,050	RO Blending	
W-9	888	19	RO Permeate	
W-11	0.02	12,750	Chemical dosing	
W-4	***206***	***1,050***	***UF Reject***	*Output stream*
W-10	***478***	***3,000***	***RO Reject***	
W-12	***1,316***	***265***	***RO Total Product***	

4.4.5 Equipment sizing

All equipment of the membrane treatment blowdown water from power plant are sized and summarized in Table 4.9.

Table 4.9 Equipment sizing (See Appendix D)

Equipment	**Code**	**Equipment function**	**Equipment specification**
Pump	P-1	Raw water transfer pump	- Size 8 Hp - Capacity 2,000 m^3/day - Pipe diameter 4 inch
Pump	P-2	UF feed pump	- Size 6.5 Hp - Pipe diameter 4 inch
Pump	P-3	UF back wash pump	- Size 6.5 Hp - Pipe diameter 4 inch
Pump	P-4	Transfer pump to High pressure pump	- Size 5 Hp - Pipe diameter 4 inch
Pump	P-5	High pressure pump	- Size 18 Hp - Pipe diameter 4 inch
Pump	P-6	Product water pump	- Size 14 Hp - Pipe diameter 4 inch
UF membrane	UF	UF membrane pretreatment	- Membrane diameter 22.5 cm^2 - Membrane module 17 modules - Filtration flux 65 L/hr.m^2

Table 4.9 Equipment sizing (continued)

Equipment	**Code**	**Equipment function**	**Equipment specification**
RO membrane	RO	Membrane desalination	- Membrane diameter 20.32 cm^2 - Membrane element 36 elements - Membrane vessel 9 vessels - Permeate flux 6.32 $L/hr.m^2.bar$
CEB tank	C-1	UF Chemical cleaning equipment	- Volume 0.5 m^3
CIP tank	C-2	RO Chemical cleaning equipment	- Volume 0.5 m^3
Feed tank	T-1	Raw water holding tank	- Volume 5 m^3
UF treated tank	T-2	UF treated water tank & Back wash water tank	- Volume 5 m^3
Chemical tank	T-3	Antiscale feed tank	- Volume 0.5 m^3 - Design dosing rate 10 L/day
RO permeate tank	T-4	RO permeate tank	- Volume 10 m^3
Chemical tank	T-4	Chlorine feed tank	- Volume 0.5 m^3 - Design dosing rate 20 L/day

4.5 Feasibility study capital and production cost

The total capital investment cost for 2,000 m^3 per day of maximum design flow which sum of the fixed capital investment and the working capital, indirect cost of UF and RO system showed in Table 4.10-4.11 below (See Appendix D). From these data, RO system occupied more than 50% of the total investment cost of system.

Moreover, all operation and maintenance cost from show in Table 4.12, which was estimated with 1,500 m^3 per day of operation flow rate, included chemicals consumption cost, power cost, membrane replacement cost, and maintenance cost for whole year round. Power cost and membrane cost for UF and RO system is the major cost of overall operation costs.

According to data from Table 4.10-4.12, the calculated cost of treatment per cubic meter of blowdown water daily when operate at 30 years plant life was 12.73 Baht per cubic meter. On the other hand, currently this plant was paying around 17 baht per cubic meter on tap water to use in cooling tower and it is profitable for the company to install these treatment systems.

Table 4.10 The total capital investment of the UF water treatment units (The costs in this table is 2016’s costs, see Appendix D)

No.	**Unit (Design at flow rate 2,000 m^3/day)**	**Construction Cost (Million Baht)**
1	UF system	-
	- Pump (Feed & Back wash)	1.32
	- Electricity system	5.20
	- Building	0.74
	- Membrane	0.94
	- Instrument & control	4.20
	- Piping	4.29
	- Cartridge filter	0.39
	- Membrane cleaning equipment	4.40
	- Site work	1.30
	- Contractor Engineering & Training	1.00
	Total capital investment	**23.78**
	Indirect capital costs	**-**
	- Interest during construction	**1.4**
	- Contingencies	**4.8**
	- A&E Fees, Project Management	**2.4**
	- Working Capital	**1.0**
	Total indirect capital investment	**9.60**
	Total capital cost	**33.38**

Table 4.11 The total capital investment of the RO water treatment (The costs in this table is 2016's costs, see Appendix D)

No.	**Unit (Design at flow rate 2,000 m^3/day)**	**Construction Cost (Million Baht)**
1	RO system	-
	- Pump	3.78
	- Electricity system	4.40
	- Building	1.30
	- Membrane	1.35
	- Instrument & control	4.20
	- Piping	3.97
	- Cartridge filter	0.23
	- Membrane cleaning equipment	4.40
	- Site work	1.50
	- Contractor Engineering & Training	1.00
	- Chemical feed system	1.61
	Total capital investment	**27.74**
	Indirect capital costs	
	- Interest during construction	**1.0**
	- Contingencies	**2.0**
	- A&E Fees, Project Management	**3.3**
	- Working Capital	**1.0**
	Total indirect capital investment	**7.3**
	Total capital cost	**35.04**

Table 4.12 Operation and maintenance costs of major system (The costs in this table is 2016's costs, see Appendix D)

No.	**Units**	**O&M Cost per year**
	(At flow rate 1,500 m^3/day)	**Cost (Million Baht)**
1	UF system	
	- Power feed pump	0.076
	- Power back wash pump	0.081
	- Membrane & Filter	0.130
	- Maintenance materials	0.48
	- Chemical	0.091
	- Labor & Lab fees	0.08
	- Insurance	0.133
	Total O&M costs	1.071
2	RO system	-
	- Power raw water pump	0.083
	- Power high pressure pump	0.18
	- Power transfer pump	0.054
	- Power product water pump	0.014
	- Membrane & Filter	0.22
	- Maintenance materials	0.47
	- Chemical	0.0508
	- Labor & Lab fees	0.133
	- Insurance	0.097
Total		**1.302**

* Electricity cost based on 2 Bath / KWatt-hr

** Labor cost based on 20,000 Bath / month

4.6 Profitability analysis

There are essentially three bases used for the evaluation of profitability;

(1) Time base (Payback period, PBP)

(2) Cash base (Cumulative Cash Ratio, CCR and Net Present Value, NPV)

(3) Interest rate base (Return on Investment, ROI)

For each of these bases, it can consider discounted and non-discounted techniques. Both types of techniques were presented in this work, and the considered plant will require the following basis.

Life time of plant	30	years
Plant start-up	At end of year 1	
Plan of feed water capacity	1,500	m^3/day
Working day	365	day/year
Total Investment cost	68,661,135	Baht
Total investment during year 1	100%	of investment cost
O&M Cost	2,299,857	Baht/year
Tap water cost (Product water)	17	Baht/m^3

The cumulative cash flow for the tap water production is illustrated in Table 4.13. Using this data, the cumulative cash flow diagram is drawn in Figure 4.14 below.

Table 4.13 Non-discounted & discount cash flow (All numbers is in million Thai Baht)

				Discount rate 0%		Discount rate 3%	
Year	Invest. Cost	O&M Costs	Net Profit	Cash flow	Cum. Cash flow	Cash flow	Cum. Cash flow
0							
1	(68.42)		(68.42)	(68.42)	(68.42)	(66.43)	(66.43)
2		(2.373)	3.756	3.756	(64.664)	3.540	(62.887)
3		(2.373)	3.756	3.756	(60.909)	3.437	(59.450)
4		(2.373)	3.756	3.756	(57.153)	3.337	(56.113)
5		(2.373)	3.756	3.756	(53.398)	3.240	(52.874)
6		(2.373)	3.756	3.756	(49.642)	3.145	(49.729)
7		(2.373)	3.756	3.756	(45.886)	3.054	(46.675)
8		(2.373)	3.756	3.756	(42.131)	2.965	(43.710)
9		(2.373)	3.756	3.756	(38.375)	2.878	(40.832)
10		(2.373)	3.756	3.756	(34.620)	2.795	(38.037)
11		(2.373)	3.756	3.756	(30.864)	2.713	(35.324)
12		(2.373)	3.756	3.756	(27.108)	2.634	(32.690)
13		(2.373)	3.756	3.756	(23.353)	2.557	(30.133)
14		(2.373)	3.756	3.756	(19.597)	2.483	(27.650)
15		(2.373)	3.756	3.756	(15.842)	2.411	(25.239)
16		(2.373)	3.756	3.756	(12.086)	2.340	(22.899)
17		(2.373)	3.756	3.756	(8.330)	2.272	(20.627)
18		(2.373)	3.756	3.756	(4.575)	2.206	(18.421)
19		(2.373)	3.756	3.756	(0.819)	2.142	(16.279)
20		(2.373)	3.756	3.756	2.936	2.079	(14.200)

Table 4.14 Non-discounted & discount cash flow (All numbers is in million Thai Baht)

				Discount rate 0%		Discount rate 3%	
Year	Invest. Cost	O&M Costs	Net Profit	Cash flow	Cum. Cash flow	Cash flow	Cum. Cash flow
21		(2.373)	3.756	3.756	6.692	2.019	(12.181)
22		(2.373)	3.756	3.756	10.448	1.960	(10.221)
23		(2.373)	3.756	3.756	14.20	1.903	(8.318)
24		(2.373)	3.756	3.756	17.96	1.848	(6.470)
25		(2.373)	3.756	3.756	21.71	1.794	(4.677)
26		(2.373)	3.756	3.756	25.47	1.741	(2.935)
27		(2.373)	3.756	3.756	29.23	1.691	(1.244)
28		(2.373)	3.756	3.756	32.98	1.641	0.397
29		(2.373)	3.756	3.756	36.74	1.594	1.991
30		(2.373)	3.756	3.756	40.49	1.547	3.538
31		(2.373)	3.756	3.756	44.25	1.502	5.040
Number in ( ) are negative cash flow							
CCR or NPV				44.25 MB		5.040 MB	
PPB or DPBP				18.2 Year		27.7 Year	
ROI or DROI				65 Percent		8 Percent	

Payback period (PBP)

Payback period is the time in which the initial cash outflow of an investment is expected to be recovered from the cash inflows generated by the investment. The formula to calculate payback period of a project for even cash flow per period from the project is in Equation 4.2.

$$\text{PBP} = \frac{\text{Initial Investment}}{\text{Cash inflow per Period}} \qquad \text{Equation 4.2}$$

From Table 4.19, it was found that the PBP is 18.2 years for non-discount rate and 27.7 years at discount rate at 3%.

Net Present Value (NPV) and Cumulative Cash Ratio (CCR)

CCR is the cash criterion for non-discounted technique, which is simply the worth of the project at the end of its life and showed in Equation 4.3.

$$\text{CCR} = \frac{\text{Sum of all positive cash flows}}{\text{Sum of all negative cash flows}} \qquad \text{Equation 4.3}$$

NPV is a formula used to determine the present value of an investment by the discounted technique. The formula for the discounted sum of all cash flows can be rewritten as Equation 4.4.

$$\text{NPV} = -C_0 + \sum_{i=1}^{T} \frac{C_i}{(1+r)^i} \qquad \text{Equation 4.4}$$

When $-C_0$ is a negative cash flow, and $\frac{C_i}{(1+r)^i}$ is cash flow with discount rate of each year. These two values considering that the money going out is subtracted from the discounted sum of cash flows coming in, the values would need to be positive in order to be considered a valuable investment. From Table 4.19, it was found that the CCR is 44.25 million Baht for non-discount rate, so this project would be estimated to be a valuable venture. The NPV is 5.040 million Baht at discount rate at 3% from the start of the project, which may not be worth investing in when expecting such profits.

Rate of Return on Investment (ROI)

ROI is used to measures a profitability ratio that calculates the profits of an investment as a percentage of the original cost. The ROI formula is calculated by subtracting the average cost from the total income and dividing it by the initial investment cost as in Equation 4.5.

$$\text{ROI} = \frac{\text{Average annual net profit}}{\text{Initial investment}} \qquad \text{Equation 4.5}$$

From Table 4.19, it was found that the ROI is 65% for non-discount rate, and 8.0% for discount rate at 3%. Generally, any positive ROI is considered a good return and means that the total cost of the investment was recouped in addition to some profits left over. A negative return on investment means that the revenues weren't even enough to cover the total costs.

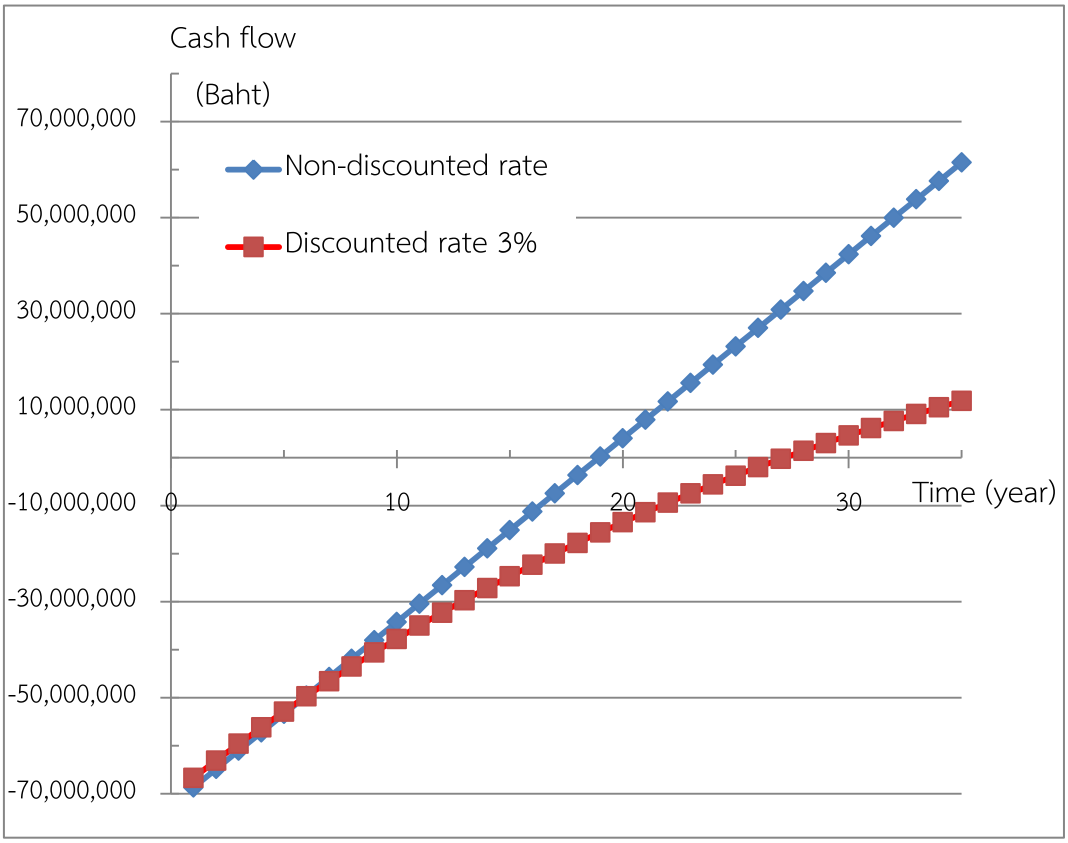

Figure 4.14 Cumulative cash flow diagrams for discounted and non-discounted rate

4.7 Sensitivity analysis

Similar to other industrial plant projects, factors and assumption used in estimation may fluctuate by different extents and lead to a variation in the economic performance of the entire project. Analysis on the major factors affecting the performance is therefore necessary in order to find out the implication of these factors on the profitability of the proposed plant. Figure 4.16 showed the results of the sensitivity analysis by varying five major factors. These factors include:

(1) Tap water cost

(2) Operation flow rate

(3) RO membrane cost

(4) Fixed cost

(5) Electricity cost

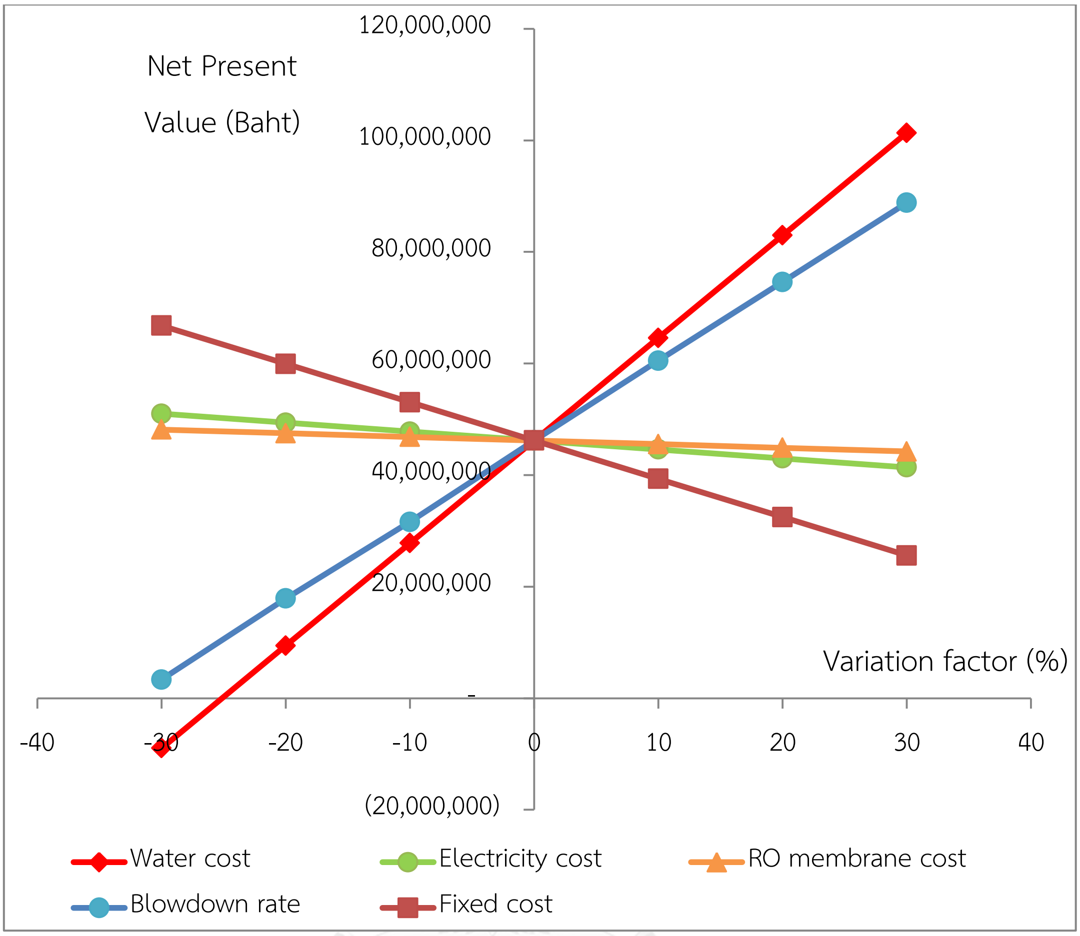

Figure 4.15 Sensitivity analyses in the variation factor of ± 30%

Tap water cost

In present, tap water price for this co-generation power plant is 17 Baht/m^3, which lower than the general industrial plant (25-35 Baht/m^3). As the matter of fact, increment of tap water price is likely to happen in the near future, because of the clean water shortage in Thailand. The variation of tap water price in the range of 11.9-22.1 Baht/m^3 may result in a difference of ±119 % to the NPV at the discount rate of 0%.

Blowdown water rate

The operation rate for treatment plant increased when blowdown water from power plant increased. The proposed plant was designed to support the blowdown water at a maximum rate 2,000 m^3/day and it seems to be possible to be operated at its full in the future because the demand of electricity and cooling load of the airport. The variation of operation flow in the range of 1,050–1,950 m^3 per day is result in a difference of ±93 % to the NPV at the discount rate of 0%.

Capital cost

Total capital cost of this project is estimated to be 68,661,135 Baht. If the lower fixed capital investment (lower cost of equipment) is possible, the NPV could be improved. The capital cost has been varied in the range of 48-89 million Baht, changing the NPV at the 0% discount rate of ±45 %.

RO membrane cost

Cost of RO membrane (model BW-300) for this project is 24,500 Baht/element, which is the average price in distributor companies in abroad and will be less by more import quantities in the future. The RO membrane price has been varied in the range of 17,150-31,850 Baht/element, changing the NPV at the 0% discount rate of ±4 %.

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APPENDIX A

Cooling Tower Blowdown Water Quality

Table A-1 Annual Quality of Cooling Tower Blowdown Water

No	**Parameters**	**Units**	**Month / year 2015**					
			July	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	pH	-	8.8	8.7	8.8	8.9	8.8	8.8
2	Conductivity	µS/cm	1,814	1,735	1,159	1,487	1,430	1,425
3	TDS	mg/L	1,111	1,130	906	1,110	1,052	1,006
4	TSS	mg/L	<5	<5	<5	<5	<5	<5
5	Oil and Greece	mg/L	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
6	BOD_5	mg/L	3.2	<2.0	<2.0	2.5	<2.0	<2.0
7	COD	mg/L	45.3	18.9	29.7	34.1	39.5	31.8
8	Turbidity	NTU	1.84	3.39	2.30	3.13	5.35	3.53
9	T-Alkalinity	mg/L*	345	260	400	400	325	405
10	Calcium	mg/L*	355	250	395	325	320	315
11	Magnesium	mg/L*	135	160	145	135	115	160
12	Sulphate	mg/L	156	142	111	128	137	174
13	Chloride	mg/L	253	338	158	307	205	218
14	Silica	mg/L	10	19	45	74	78	79
15	Total Iron	mg/L	0.10	0.09	0.1	0.14	0.13	0.15
16	T-PO4	mg/L	0.73	0.45	0.99	0.15	0.16	0.83
17	Manganese	mg/L	0.03	0.02	0.02	0.02	0.02	0.02
18	Copper	mg/L	0.01	0.03	0.01	0.01	0.01	0.02
19	Chlorine	mg/L	<0.1	0.1	<0.1	<0.1	<0.1	<0.1

* mg/L as $CaCO_3$

Table A-1 Annual Quality of Cooling Tower Blowdown Water (continued)

No	Parameters	Units	Month / year 2016					
			Jan	Feb	Mar	Apr	May	June
1	pH	-	8.9	8.9	8.8	8.8	8.8	8.8
2	Conductivity	µS/cm	1,431	1,556	1,148	1,537	1,348	1440
3	TDS	mg/L	978	1,008	688	990	834	815
4	TSS	mg/L	12	<5	<5	5	<5	<5
5	Oil and Greece	mg/L	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
6	BOD_5	mg/L	3.4	2.0	2.3	2.0	<2.0	<2.0
7	COD	mg/L	45	40	31	29.4	22.3	47
8	Turbidity	NTU	2.63	3.68	4.81	4.10	3.92	2.98
9	T-Alkalinity	mg/L*	420	430	425	395	360	376
10	Calcium	mg/L*	320	280	355	345	329	320
11	Magnesium	mg/L*	130	150	140	125	181	168
12	Sulphate	mg/L	107	160	95	144	147	113
13	Chloride	mg/L	180	190	115	156	142	192
14	Silica	mg/L	57	62	50	67	64	26
15	Total Iron	mg/L	0.04	0.04	0.02	0.02	0.14	0.02
16	T-PO4	mg/L	0.75	0.69	0.99	0.65	0.26	0.30
17	Manganese	mg/L	0.02	0.02	0.02	0.02	0.02	0.02
18	Copper	mg/L	0.01	0.01	0.01	0.01	0.01	0.02
19	Chlorine	mg/L	<0.1	0.1	<0.1	<0.1	<0.1	<0.1

*mg/L as $CaCO_3$

APPENDIX B

Preparation of Synthesis Cooling Water

Step 1: Specification of cooling water requirement

No.	**Parameters**	**Value**	**Unit**
1	Volume	4	Liter
2.	Alkalinity	400	mg/L as $CaCO_3$
3	Calcium	300	mg/L as $CaCO_3$
4	Magnesium	150	mg/L as $CaCO_3$

Step 2: Specification of chemical

No.	Chemical	Equivalent weight	Ion	Equivalent weight	Atomic weight
1	$NaHCO_3$	84.01	Bicarbonate	61.00	61.00
2.	$CaCl_2$•$2H_2O$	147.02	Calcium	20.01	40.02
3	$MgCl_2$•$6H_2O$	203.30	Magnesium	12.20	24.30

Step 3: Change mg/L as $CaCO_3$ to mg/L as each ion (Eq. weight of $CaCO_3$ is 50)

3.1 $NaHCO_3$ 400 mg/L as $CaCO_3$ equal to (400 x 61) / 50 = 488 mg/L as bicarbonate

3.2 $CaCl_2$•$2H_2O$ 300 mg/L as $CaCO_3$ equal to (300 x 20) / 50 = 120 mg/L as calcium

3.3 $MgCl_2$•$6H_2O$ 150 mg/L as $CaCO_3$ equal to (150 x 12.2) / 50 = 36.6 mg/L as magnesium

Step 4: Weight of each ion as required concentration

4.1 Bicarbonate: (488 ppm as bicarbonate x 4 Liter)/1,000 = 1.95 g

4.2 Calcium: (120 ppm as calcium x 4 Liter)/1,000 = 0.48 g

4.3 Magnesium: (36.6 ppm as magnesium x 4 Liter)/1,000 = 0.15 g

Step 5: Weight of each chemical

5.1 $NaHCO_3$: (1.89 gram of bicarbonate x 84.01) / 61.00 = 2.60 g of $NaHCO_3$

5.2 CaCl2•2H2O: (0.48 gram of bicarbonate x 147.02) / 40.02 = 1.76 g of $CaCl_2$•$2H_2O$

5.3 $MgCl_2$•$6H_2O$: (0.15 gram of bicarbonate x 147.02) / 40.02 = 0.55 g of $MgCl_2$•$6H_2O$

Step 6: Weight each chemical in table 2 as in Step 5

Step 7: Dissolve in demineralization water and adjust volume to 4 liters in volumetric flask

Step 8: Specification of cooling water requirement in step 1 are done

APPENDIX C

SDI (Silt density index) Determination

SDI (Silt density index) determination

In this experiment Rizon Manual SDI Test Kit model HAK-120 (Horizon Environmental Technology, Co., Ltd) was used to determine SDI index.

Calculation: $SDI_5 = (1 - t_0 / t_5) \times (100 / 5)$

When: t_0 is necessary time (sec) to collected 500 ml of water at the begin (t_0) of filtration test

t_5 is necessary time (sec) to collected 500 ml of water at 5 minute (t_5) of filtration test

Table C-1 SDI of conventional pretreatment

Run1				
No.	**Pretreatment**	**t_0 (Sec)**	**t_5 (Sec)**	**SDI**
1	Feed water	13	148	18.2
2	Multimedia filter	12	38	13.7
3	PACl 150 ppm	24	561	19.1
4	PACl 150 ppm + APAM 1 ppm	26	443	18.8
5	PACl 150 ppm + CPAM 1 ppm	28	531	18.9
6	PACl 150 ppm + MMF	11	31	12.9
7	PACl 150 ppm + APAM 1 ppm + MMF	10	13	4.6
8	PACl 150 ppm +CPAM 1 ppm + MMF	13	17	4.7

Table C-1 SDI of conventional pretreatment (continued)

Run2				
No.	**Pretreatment**	t_0 (Sec)	t_5 (Sec)	**SDI**
1	Feed water	19	191	18.0
2	Multimedia filter (MMF)	16	61	14.8
3	PACl @ 150 ppm	22	512	19.1
4	PACl @ 150 ppm + APAM 1.0 ppm	25	465	18.9
5	PACl @ 150 ppm + CPAM 1.0 ppm	33	621	18.9
6	PACl @ 150 ppm + MMF	16	51	13.7
7	PACl @ 150 ppm +APAM 1.0 ppm + MMF	14	17	3.5
8	PACl @ 150 ppm +CPAM 1.0 ppm + MMF	15	19	4.2

Table C-2 SDI of UF membrane pre-treatment

Run1				
No.	**Pretreatment**	t_0 (Sec)	t_5 (Sec)	**SDI**
1	5 micron filter	12	80	17.0
2	UF filter	9	10	2.2
Run2				
No.	**Pretreatment**	t_0 (Sec)	t_5 (Sec)	**SDI**
1	5 micron filter	13	79	16.8
2	UF filter	9	10	2.4
Run3				
No.	**Pretreatment**	t_0 (Sec)	t_5 (Sec)	**SDI**
1	5 micron filter	12	79	16.9
2	UF filter	8	10	3.4

APPENDIX D

Cost Calculation for Pretreatment Systems

Table D-1 Cost indices data for conventional pretreatment systems

Cost Indices Categories:	**Used For**	**January 2016 (68)**	**October 1978 (67)**	**Cost ratio**
ENR Construction Cost Index				
Construction Cost	Manufactured & Electrical Equipment	10,132.55	2,850.66	3.55
ENR Building Cost Index				
Building Cost	Housing	5,561.76	1,721.13	3.23
Skilled Labor	Excavation and Site work, Labor	9,705.74	2,465	3.94
ENR Materials Cost Index				
Materials	Piping & Valves	3,035.31	1,267.1	2.40
Materials	Maintenance Materials	3,035.31	1,267.1	2.40
Cement	Concrete	1,14.5	48.27	2.37
Steel	Steel	49.5	15.73	3.15
Additional information				
Electricity Cost (Based Cost)	2 Baht/KWh			
Labor Cost for O&M	20,000 Baht/month			
Exchanged rate	35 Baht/Dollar			

Table D-2 Package pressure filtration cost calculations

Cost calculations	**Value**	**Units**	**Remark**
Design flow	2,000	m^3/day	

Filtration rate	4.9	gallon/min.ft^2	From lab experiment
PACl dose rate	150	mg/L	From lab experiment
PAM dose rate	1.0	mg/l	From lab experiment
Cost PACl	8,015	Baht/ton	Kurita-gk chemical
Cost PAM	164,990	Baht/ton	Kurita-gk chemical
Calculated PACl dose rate	9.38	kg/hr.	
Calculated PAM dose rate	0.06	kg/hr.	
(Oct 1978) Capital Cost*:	**151,596**	**Dollar**	Capital cost **(64)**
Update Capital cost			
Cost calculations	**Percent**	**Cost (MB)**	**Remark**
Manuf. & Electrical Equip.	0.62	12	Update costs **(64)**
Housing	0.25	4.3	
Excavation, Site Work & Labor	0.11	2.3	
Piping and Valves	0.01	1.3	
Steel	0.00	-	
Concrete	0.01	1.3	
(Dec 2016) Capital Cost:	**1.00**	**21.2**	**2016's Costs**
Operation & Maintenance Cost			
Power (25,937 KWh/year)	0.052	MB/year	O&M costs **(64)**
Maintenance Material	0.0016	MB/year	
Labor (73 hr/year)	0.0073	MB/year	
PACl chemical cost / year	0.88	MB/year	
PAM chemical cost / year	0.12	MB/year	
(Dec 2016) O&M Cost:	**1.0609**	**MB/year**	**2016's Costs**

*Include 2 chemical feed systems (PACl and PAM)

Table D-3 Rapid mixing system cost calculations

Cost calculations	Value	Units	Remark
Design flow	2,000	m^3/day	

G value	300	ft-lb/sec.ft^3	From lab experiment
Retention Time	1	min.	From lab experiment
Assumed Depth	1.5	m	Assume value
Calculated Settling Area	0.93	m^2	
Design Settling Area	2.00	m^2	
Design Volume: V	3.00	m^3	Application range 3-550 **(65)**
(Oct 1978) Capital Cost:	**14,404**	**Dollar**	Equation 1 **(65)**
Update Capital cost			
Cost calculations	**Percent**	**Cost (MB)**	**Remark**
Manufactured & Electrical Equip.	0.60	1.1	Update cost components **(63)**
Housing	0.00	-	
Excavation, Site Work & Labor	0.21	0.42	
Piping and Valves	0.00	-	
Steel	0.12	0.19	
Concrete	0.07	0.08	
(Dec 2016) Capital Cost:	**1.00**	**1.79**	2016's Costs
O&M Cost			
Cost per year	**Cost**	**Units**	**Remark**
Power (5,090 KWh/year)	0.010	MB	O&M cost component **(63)**
Maintenance	0.0017	MB	
Labor (470 hr/year)	0.047	MB	
(Dec 2016) O&M Cost:	**0.059**	**MB/year**	**2016's Costs**

Equation 1: $239.7 \times (V^{\wedge 1.055}) + 13{,}640$

Table D-4 Slow mixing system cost calculations

Cost calculations	**Value**	**Units**	**Remark**
Design flow rate	2,000	m^3/day	
G value	20	ft-lb/sec.ft^3	From lab experiment
Retention Time	15	min.	From lab experiment
Assumed Depth	1.5	m	Assume value
Calculated Settling Area	13.9	m^2	
Calculated Volume	20.8	m^3	
Design Volume: V	50.0	m^3	Application range 50-28,000 **(65)**
<u>(Oct 1978) Capital Cost:</u>	**38,795**	**Dollar**	Equation 2 **(65)**
Update Capital cost			
Cost calculations	**Percent**	**Cost (MB)**	**Remark**
Manufactured & Electrical Equip.	0.35	1.7	Update cost components **(63)**
Housing	0.00	-	
Excavation, Site Work & Labor	0.29	1.6	
Piping and Valves	0.00	-	
Steel	0.21	0.90	
Concrete	0.15	0.48	
<u>(Dec 2016) Capital Cost:</u>	1.00	4.68	**2016's Costs**
O&M Cost			
Cost per year	**Cost**	**Units**	**Remark**
Power (330 KWh/year)	0.00066	MB/year	O&M cost components **(63)**
Maintenance	0.032	MB/year	
Labor (99 hr/year)	0.0099	MB/year	
<u>(Dec 2016) O&M Cost:</u>	**0.04257**	**MB/year**	**2016's Costs**

Equation 2: 5,610.0 x ($V^{\wedge 0.494}$) x EXP (0.000024 x V)

Table D-5 Rectangular clarifier system cost calculations

Cost calculations	Value	Units	Remark
Design flow rate	2,000	m^3/day	
Retention Time	40	min.	
Assumed Depth	2.5	m	
Calculated Settling Area	22.22	m^2	
Design Settling Area: A	25.0	m^2	Application range 20-450 **(63)**
(Oct 1978) Capital Cost:	**43,720**	**Dollar**	Equation 3 **(63)**
(Oct 1978) O&M Cost:	**2,138**	**Dollar**	Equation 4 **(63)**
Update Capital cost			
Cost calculations	**Percent**	**Cost (MB)**	**Remark**
Manufactured & Electrical Equip.	0.29	1.6	Update cost components **(63)**
Housing	0.00	-	
Excavation, Site Work & Labor	0.24	1.5	
Piping and Valves	0.10	0.37	
Steel	0.27	1.3	
Concrete	0.10	0.36	
(Dec 2016) Capital Cost:	**1.00**	**5.13**	**2016's Costs**
Update O&M cost			
Cost calculations	**Percent**	**Cost (MB)**	**Remark**
Materials	0.16	0.029	O&M cost components **(63)**
Energy (2,983 Kwh/year)	0.04	0.0057	
Labor (173 hr/year)	0.80	0.017	
(Dec 2016) O&M Cost:	**0.0517**	**MB/year**	**2016's Costs**

Equation 3: 30,290 + (537.2 x A)

Equation 4: 8.4 x ($A^{\wedge 1.0386}$) + 1,900

Table D-6 Cost indices data for membrane treatment systems

Cost Indices Categories:	**Used For**	**January 2016 (68)**	**October 1978 (67)**	**Cost ratio**
ENR Construction Cost Index				
Construction Cost	Manufactured & Electrical Equipment	10,132.55	5,432.0	1.87
ENR Building Cost Index				
Building Cost	Housing	5,561.76	3,095.0	1.80
Skilled Labor	Excavation & Site work, Labor	9,705.74	5,735.3	1.69
ENR Materials Cost Index				
Materials	Piping & Valves	3,035.31	2,219.2	1.37
Materials	Maintenance Materials	3,035.31	2,219.2	1.37
Cement	Concrete	1,14.5	81.0	1.41
Steel	Steel	49.5	28.3	1.75
Additional information				
Electricity Cost (Based Cost)	2 Bath/KWh			
Labor Cost for O&M	20,000 Baht/month			

Table D-7 UF system cost calculations

Required flow & water quality	**Value**	**Unit**	**Remark**
Design flow rate	2,000	m^3/day	Plant production flow
Lab experimental data			
Temperature	25	^oC	From lab experiment
UF Permeation Flux	64.8	Lph/m^2	From lab experiment
Pore size	0.03	µm	
Operation pressure	3.0	bar	
Filtration area need	1,286	m^2	
UF Membrane data	**Value**	**Unit**	**Remark**
Model #	SFP 2880		Dow filmtec
Membrane Diameter	22.50	cm	Dow filmtec
Active surface area per module	77.0	m^2	Dow filmtec
Membrane life	10	year	Dow filmtec
Operation details	**Value**	**Unit**	**Remark**
Design feed pressure	30	psi	Dow filmtec
Back flush pressure	36	psi	Dow filmtec
Backwash Flow	100	Lph/m^2	Dow filmtec
Backwash Frequency	30	minute	Dow filmtec
Backwash and back flush duration	120	Second	Dow filmtec
CEB Frequency	720	minute	Dow filmtec
CEB Duration	15	minute	Dow filmtec

Table D-7 UF system cost calculations (continued)

UF Output Construction detail	**Value**	**Unit**	**Remark**
Number of Elements (Calculate)	16.7	module	Design 2,000 m^3/day
Number of Elements (Design)	17	module	Design 2,000 m^3/day
Max module per Skid	60	modules	Assumed value
Number of Skids	1	skids	
Reject flow	209.4	m^3/day	Equation 5 **(67)**
Recovery rate	0.90		Recovery rate
Design product flow rate	1,794	m^3/day	
Building Area	25	m^2	Equation 6 **(67)**
UF Feed pump			**Pump Style VST**
Height Difference	5	m	From pump to top of skid
Motor Efficiency	0.93		Assumed value
Pump Efficiency	0.80		Assumed value
Coupling Efficiency	1.00		Assumed value
Differential Pressure (Design)	310	kPa	
Capacity per pump (Design flow)	0.023	m^3/s	Equation 7 **(67)**
Pipe X-Sectional Area	0.009	m^2	Equation 8 **(67)**
Size	6.51	hp	Equation 9 **(67)**
UF Back wash pump			**Pump Style VST**
Height Difference	5	m	From pump to top of skid
Motor Efficiency	0.93		Assumed value
Pump Efficiency	0.80		Assumed value
Coupling Efficiency	1.00		Assumed value
Differential Pressure (Design)	310	kPa	
Capacity per pump (Design flow)	0.023	m^3/s	Equation 7 **(67)**
Pipe X-Sectional Area	0.009	m^2	Equation 8 **(67)**
Size	6.51	hp	Equation 9 **(67)**

Table D-7 UF system cost calculations (continued)

UF Cost calculations (2016)	**Cost (MB)**	**Cost index**	**Remark**
Total membrane cost	0.94	-	1,580$ per module [Dow]
Building area cost	0.74	-	857$ per m^2*
Construction cost			
- Electrical	5.2	Manf&Elect	614$ per m^3 (67)
- Instrumentation & Controls	4.2	Manf&Elect	65,000$ per skid (67)
- Feed pump	0.66	Piping	Equation 10 (67)
- Back Wash pump	0.66	Piping	Equation 10 (67)
- Process piping	2.1	Piping	Equation 11 (67)
- Yard piping	2.0	Piping	50,000$ per m^3 (67)
- Cartridge filters	0.39	Materials	Equation 12 (67)
- Concentrate treatment & piping	0.19	Piping	13$ per m^3 (67)
- Membrane cleaning equipment	4.4	Manf&Elect	67,000 $ per Skid (67)
- Cont. engineering & training	1.00	-	1,000,000 Baht**
- Site work	1.3	Sk. labor	14.53$ per m^3 (67)
Total direct capital cost	**23.78**	**MB**	
Indirect capital costs			
- Interest during construction	1.4	MB	6% of direct cost (67)
- Contingencies	4.8	MB	20% of direct cost (67)
- A&E Fees, Proj. Management	2.4	MB	10% of direct cost (67)
- Working capital	1.0	MB	4% of direct cost (67)
Total indirect capital cost	**9.5**	**MB**	Total 40%
Total capital cost	**32.98**	**MB**	**2016's cost**

Table D-7 UF system cost calculations (continued)

O&M Cost calculations per year (2016's costs)	**Cost (MB)**	**Cost index**	**Remark**
Chemical Costs			
Chlorine (per ton)	0.0047	-	**Interpretive Co.**
HCl 35% Acid (per ton)	0.0084	-	**Interpretive Co.**
NaOH 50% (per ton)	0.0084	-	**Interpretive Co.**
UF Energy Costs			
Feed pump (37,895 KWh/year)	0.076	-	
Backwash p. (40,422 KWh/year)	0.081	-	
UF Materials Costs			
Membrane Replace (per year)	0.13	Material	Equation 14 **(67)**
Repairs and Replace (per year)	0.23	Material	Equation 15 **(67)**
Cartridge Filters (per year)	0.25	Material	Equation 16 **(67)**
Insurance (per year)	0.091	Material	Equation 17 **(67)**
Cleaning chemical (per year)	0.080	-	Equation 18 **(67)**
UF Labor cost			
Labor (730 hour/year)	0.073		
Lab fee ***	0.060		
Total O&M Costs:	**1.093**	**MB/year**	**2016's cost**

* Assume 25,000 Baht/m^2 for building cost in Thailand

** Assume 1,000,000 Baht for Contractor engineering & training in Thailand

*** Assume 1,000 Baht/time, 6 times per year

Equation 5: (Backwash flow x Backwash duration / Backwash frequency)

Equation 6: (Design feed flow x 1.277244) / 100

Equation 7: (Primary treatment flow x 1,000 / 3.785) x (0.0013/10.734)

Equation 8: Capacity per pump (m^3/s) / 2.5

Equation 9: ((ΔHeight x gravity force) + (0.5 x Velocity)^2 + Δpressure) x Capacity per pump x 1,000 / (746 x Motor eff. x Pump eff. x Coupling eff.$^{-1}$)

Equation 10: (85,000 x (Hp/100 $^{0.65}$) x [cost index]

Equation 11: 15.852 x (Primary treatment flow / recovery) x [cost index]

Equation 12: 112,836 x ((Primary treatment flow / 24 / 3,600) $^{0.8031}$) x 1.2 x [cost index]

Equation 13: (Concentration (ppm) x Primary treatment flow / recovery x [cost index] + 20,000

Equation 14: (Number of operate elements x cost per element) / membrane life time (year)

Equation 15: (0.5% x Total construction cost) x [cost index]

Equation 16: (23,097 x (Plant production flow / 24 / 3,600 / recovery) - 6.245) x 12

Equation 17: (0.2% x Total construction cost) x [cost index]

Equation 18: (Number of operate elements x cleaning rate) x (pi x membrane radius (cm)^2 x 102) x 1.15 x (0.001 x cost of NaOH (per kg) + 0.001 x cost of NaOCl (per kg) + 0.05 x cost of HCl (per kg)) / 1,000

Table D-8 RO system cost calculations

Required flow & water quality	**Value**	**Unit**	**Remark**
Design flow rate	1,794	m^3/day	UF production flow
Feed TDS	1,050	mg/l	Equal to 1,570 uS/cm
Target TDS	265	mg/l	Equal to 395 uS/cm
Recovery rate	0.65		
Lab experimental data	**Value**	**Unit**	**Remark**
Test solution TDS	1,100	mg/L	From lab experiment
Product TDS	19	mg/L	From lab experiment
TDS rejection	98.3	%	From lab experiment
Temperature	25	°C	From lab experiment
Permeation membrane	6.35	Lph/m^2.bar	From lab experiment
Membrane data	**Value**	**Unit**	**Remark**
Model #	BW30-400		Dow filmtec
Membrane Diameter	20.32	cm	Dow filmtec
Active surface area / module	37.00	m^2	Dow filmtec
Membrane life	4	year	3-6 years [Dow]
Cleaning rate	6	time/year	
Output flow & water quality	**Value**	**Unit**	**Remark**
Applied pressure	7	bar	
Element productivity	39.5	m^3/day	Per element
Primary treatment flow	1,366	m^3/day	
Bypass flow for blending	428	m^3/day	
Permeate flow	888	m^3/day	
Total product flow	1,316	m^3/day	
Concentrate flow	478	m^3/day	
Concentrate TDS	3,000	mg/l	

Table D-8 RO System Cost Calculations (continued)

Output Construction detail	**Value**	**Unit**	**Remark**
Number of Elements (Calculate)	34.6	elements	
Number of elements per vessel	4	elements	
Number of Pressure Vessels	9	vessels	
Number of Elements (Design)	36	elements	
Max Vessels per Skid	60	vessels	Assumed value
Number of Skids	**1**	skids	
Building Area	44	m^2	Equation 5 **(67)**
Raw water transfer pump			**Pump Style VST**
Height Difference	10	m	From pump to basin
Motor Efficiency	0.94		Assumed value
Pump Efficiency	0.75		Assumed value
Coupling Efficiency	1.00		Assumed value
Differential Pressure	100	kPa	Operating pressure
Capacity per pump (2,000 m^3/d)	0.021	m^3/s	Equation 6 **(67)**
Pipe X-Sectional Area	0.008	m^2	Equation 7 (67)
Size	8	hp	Equation 8 **(67)**
High Pressure Feed Pump			**Pump Style VST**
Height Difference	5	m	From pump to top of skid
Motor Efficiency	0.95		Assumed value
Pump Efficiency	0.90		Assumed value
Coupling Efficiency	1.00		Assumed value
Differential Pressure	1,000	kPa	Design at max P 10 bar
Capacity per pump	0.023	m^3/s	Equation 6 **(67)**
Pipe X-Sectional Area	0.009	m^2	Equation 7 **(67)**
Size	27	hp	Equation 8 **(67)**

Table D-8 RO System Cost Calculations (continued)

Transfer Pumps (to HPP)	**Value**	**Unit**	**Pump Style VST**
Height Difference	3	m	Assumed value
Motor Efficiency	0.94		Assumed value
Pump Efficiency	0.75		Assumed value
Coupling Efficiency	1.00		Assumed value
Pressure Differential	100	kPa	Assumed value
Capacity per Pump	0.021	m^3/s	Equation 6 **(67)**
Pipe X-Sectional Area	0.008	m^2	Equation 7 **(67)**
Size	5	hp	Equation 8 **(67)**
Product water pump			**Pump Style VST**
Height Difference	25	m	Assumed value
Motor Efficiency	0.94		Assumed value
Pump Efficiency	0.75		Assumed value
Coupling Efficiency	1.00		Assumed value
Pressure Differential	100	kPa	Assumed value
Capacity per Pump	0.021	m^3/s	Equation 10 **(67)**
Pipe X-Sectional Area	0.008	m^2	Equation 11 **(67)**
Size	14	hp	Equation 12 **(67)**

Equation 6: (Primary treatment flow x 1,000 / 3.785) x (0.0013/10.734)

Equation 7: Plant production flow (m^3/day) x 24 / 3,600

Equation 8: Capacity per pump (m^3/s) / 2.5

Equation 9: ((ΔH x g) + (0.5 x Velocity) ^{2} + Δp) x Capacity per pump x 1,000 / (746 x Motor eff. x Pump eff. x Coupling eff. $^{-1}$)

Table D-8 RO system cost calculations (continued)

Cost calculations	Cost (MB)	Cost index	Remark
Total membrane cost	0.88	-	700\$/ element **[Dow]**
Membrane skid cost	0.47	Housing	1,500\$/vessel **[Pentair]**
Building area cost	1.3	-	857\$ per m^2*
Construction cost			
- Electrical	4.4	Manf&Elect	614\$ per m^3 **(67)**
- Instrumentation & Controls	4.2	Manf&Elect	65,000\$ per skid **(67)**
- Raw water transfer pump	0.78	Piping	Equation 10 **(67)**
- High pressure pump	1.3	Piping	Equation 10 **(67)**
- Transfer pump	0.60	Piping	Equation 10 **(67)**
- Product water pump	1.1	Piping	Equation 10 **(67)**
- Process piping	1.6	Piping	Equation 11 (67)
- Yard piping	1.9	Piping	50,000\$ per m^3 **(67)**
- Cartridge filters	0.23	Materials	Equation 12 **(67)**
- Conc. treatment & piping	0.47	Piping	13\$ per m^3 **(67)**
- Membrane cleaning equip.	4.4	Manf&Elect	67,000 \$ per Skid **(67)**
- Cont. engineering & training	1.0	-	1,000,000 Baht**
- Site work	1.5	Sk. labor	14.53\$ per m^3 **(67)**
Antiscale feed system	0.77	Manf&Elect	Equation 13 **(67)**
Chlorine feed system	0.84	Manf&Elect	Equation 13 **(67)**
Total direct capital cost	27.74	**MB**	**2016's cost**
Indirect capital costs			
- Interest during construct	1		5% of direct cost **(67)**
- Contingencies	2		6% of direct cost **(67)**
- A&E Fees, Project Manage.	3.3		12% of direct cost **(67)**
- Working capital	1		4% of direct cost (67)
Total indirect capital cost	**7.3**		**Total 27%**
Total capital cost	**35.04**	MB	**2016's cost**

Table D-8 RO System Cost Calculations (continued)

O&M Cost calculations (2016)	Cost (MB)	Cost index	Remark
Chemical Costs			
Anti-scale (per ton)	0.16	-	**LPE Co., Ltd.**
Chlorine (per ton)	0.0047	-	**Interpretive Co., Ltd.**
Citric Acid (per ton)	0.25	-	**LPE Co., Ltd.**
NaOH 50% (per ton)	0.0084	-	**Interpretive Co., Ltd.**
Energy Costs			
Raw water p. (37,025 KWh/year)	0.083		
HP p. (64,111 KWh /year)	0.18	-	
Transfer p. (24,414 KWh /year)	0.054	-	
Product w p. (82,500 KWh /year)	0.014	-	
Materials Costs			
Membrane Replace (per year)	0.22	Material	Equation 14 (67)
Repairs and Replace (per year)	0.24	Material	Equation 15 (67)
Cartridge Filters (per year)	0.23	Material	Equation 16 (67)
Insurance Replace (per year)	0.097	Material	Equation 17 (67)
Chemicals Costs			
Cleaning chemicals (per year)	0.0075		Equation 18 (67)
Anti-scale cost (per year)	0.041		1.0 ppm dose rate
Chlorine cost (per year)	0.0023		0.5 ppm dose rate
Lab fees (per year)	0.060		Assumed 10,000 Baht*
Labor for O&M (730 hr/year)	0.073		
Total O&M Costs:	**1.302**	**MB/year**	**2016's cost**

VITA

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