Application of Membrane Technology to Retrofit Large-Scale Conventional Water Treatment Plant in Singapore

D.D. Ratnayaka**, M. F. Lee*, K.N.Tiew*, H.T. Chua*, D. Sanmuganathan*, D. H. K. Lim**, A.McNeil**, K.T. Teo*, T.W. Tan** and J.D.M.Currie**

*Public Utilities Board, 40, Scotts Road, #22-01, Singapore 228231, Singapore.
(E-mail: LEE_Mun_Fong@pub.gov.sg, TIEW_King-Nyau@pub.gov.sg, CHUA_Hock_Thak@)pub.gov.sg, Devaraj_SANMUGANATHAN@pub.gov.sg)
**Black & Veatch, 390, Havelock Road, #04-01, Singapore 169662, Singapore.
(E-mail: ratnayakad@bv.com, limDHK@bv.com, Alastair.McNeil@w2wa.com.au, tanteckwee@gmail.com, CurrieJDM@bv.com)

Abstract
This paper describes the first stage of a major upgrade to the Chua Chu Kang Water Works (CCKWW) in Singapore which included the retrofitting of immersed membrane filters to replace rapid gravity sand filters. CCKWW has a total capacity of 364,000 m^3/d and treats a blend from several reservoirs of varying quality using Pulsator® clarifiers, rapid sand filters and ozonation. In 2000 Black & Veatch were commissioned to develop a design that would improve the quality of the plants final water, particularly in the total removal of algae, microanimals and the reduction of THMs. The design recommended the replacement of the existing sand filters with MF/UF membrane filters and the use of enhanced coagulation in the clarifiers. The design also recommended discontinuing with the ozone treatment to produce a biologically stable water, chloramination for THM control and lime and carbon dioxide dosing to improve chemical stability of the water.

In order to maximize the use of existing assets at the plant the immersed membrane filters were retro fitted into the existing rapid sand filter concrete tanks and the ozone contact tanks were converted into chlorine contact tanks. Due to the space constraints in the existing sand filter tanks an immersed membrane with a relatively high packing density of fibers suitable for clarified water was selected. Extended pilot trials were carried out with the membranes to not only ensure that the required water quality would be achieved but also to identify the optimum flux rate and membrane cleaning regime to suit the plants clarified water chemistry.

To reduce the plant energy usage, an innovative system using a siphon instead of pumps to drive the flow across the membranes at times of low flow or low membrane fouling was implemented. This mixed siphon and pump system is anticipated to reduce the need for pumping by at least 50% at normal plant flows.

Keywords
Immersed membrane, retrofitting, siphon, upgrading, water treatment

BACKGROUND

Choa Chu Kang Waterworks (CCKWW) was developed in two phases. The Phase 1 was commissioned in 1975 and the Phase 2 of a similar design and treatment capacity was commissioned in 1981. With the commissioning of the second phase, CCKWW was producing 364,000 m^3/d of drinking water which was the largest waterworks in Singapore at the time and the first to use ozone in the region. The treatment process is shown in Figure 1(a).

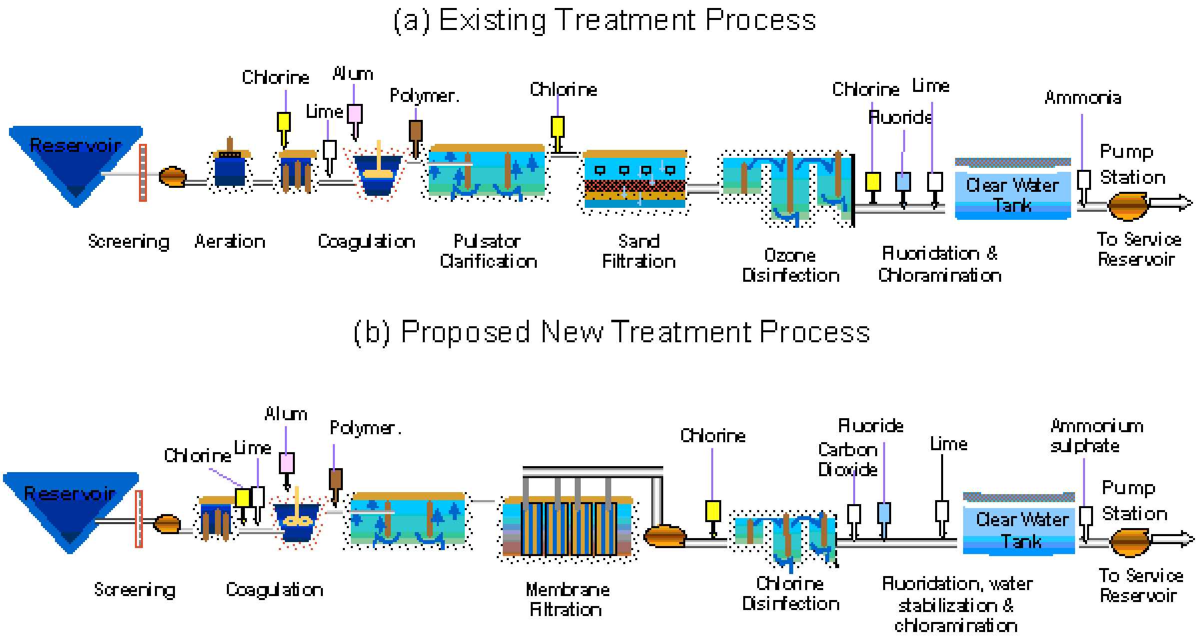

Figure 1. Comparison between (a) the existing treatment process and (b) the proposed new treatment process at CCKWW.

CCKWW receives raw water mainly from three reservoirs of the western catchment area of Singapore; namely Tengeh, Kranji and Pandan. The water quality of the three sources varies; Pandan is the best with respect to quality and the smallest in capacity, Kranji is the poorest with respect to organic quality while Tengeh can produce high concentration of turbidity. The raw water from the three reservoirs is blended at CCKWW to utilize the resources judiciously. With the existing treatment process train, CCKWW was able to produce drinking water of quality that comfortably meets World Health Organisation (WHO) guideline values (2004). Table 1 presents the typical characteristics of blended raw water received and final product water produced by CCKWW in 2007.

Table 1. Characteristic (average) of blended raw water and final product water of CCKWW in 2007.

Parameter	Blended Raw Water	Final Product Water	WHO Standards (2004)
pH	7.0-8.1	7.9-8.2	#
Turbidty (NTU)	9.2-45	0.1-0.3	5
Colour (true) (^{o} Hazen)	40-100	<5	15
Conductivity (μmho/cm^2)	165-194	243-285	#
Total alkalinity (mg $CaCO_3$/L)	30-43	23-30	#
Chloride (mg/L)	16-24	20-31	250
Fluoride (mg/L)	<0.10-0.15	0.5-0.69	1.5
Ammonia (mg/L as N)	<0.02-0.04	0.03-0.05	#
Nitrate (mg/L as N)	<0.05-0.35	0.14-0.43	50
Phosphate (mg/L as PO_4)	<0.02-0.03	<0.02	#
Sulphate (mg/L as SO_4)	13-17	52-64	250
Iron (mg/L)	0.19-1.14	<0.02	0.3
Manganese (mg/L)	0.006-0.154	0.002-0.004	0.4
Aluminum (mg/L)	0.07-0.62	0.02	0.2
Total organic carbon (mg/L)	7.0-8.1	1.9-2.3	#

no guideline value

UPGRADING OF CCKWW

CCKWW has been receiving raw water containing algae and mirco -animals in the order of 1000 per mL and 800 per mL, respectively. Algae are present in Kranji and Pandan sources which predominately consist of blue green algae and diatoms. Micro-animals present in the raw water include nematode worms, chironomid, chaoborid midges and zooplanktons which include water fleas such as copepod, cladocera, rotifers, and dinoflagellates, such as *Ceratium* and *Peridinum.* There are also protozoa such as *Arceila* and *Difflugia* present in the source. For convenience, all these organisms are reported as micro-animals in this report.

It is undesirable for algae and micro-animals to be present, even in very small numbers, in the drinking water. Algal debris and other organic slime (biofilm) that support animal growth and enter the distribution system could lead to infestation in the mains and service reservoirs. These could eventually give rise to drinking water quality problems such as taste and odour. At present, there are still no international or national standards or guidelines that limit the number of micro-animal and algae present in the drinking water.

In 2000, Public Utilities Board (PUB) of Singapore introduced the following goals in addition to the WHO guidelines (1993) for drinking water: (a) free of micro-animals; (b) free of algae; (c) dissolved organic carbon (DOC) as low as possible; (d) biologically and chemically stable. These goals present great challenges to CCKWW as the existing treatment process was already producing very good water quality with over 2-log and 3-log removal of the algae and micro-animals respectively.

For CCKWW to achieve algae and micro-animal free drinking water, three different options were considered and evaluated. These options included: (1) converting the existing mono-media sand (effective size of 0.9mm) filters to dual media filters with fine sand (effective size of 0.55 mm) and anthracite (effective size 1.3 mm); (2) microstrainers as polishing filters or (3) microfiltration /

ultrafiltration (MF/UF) membrane filters retrofitted in existing sand filters. Following a technical evaluation, membrane filtration was preferred as it could completely reject the algae and micro-animals in the raw water based on size exclusion. Moreover with the membrane price decreasing in recent years, retrofitting the existing sand filters with UF membrane filter was an economically attractive solution.

MF/UF membranes filter can be installed either as pressurised membrane where filtrate is pushed through the membrane by positive pressure or as immersed membrane where the filtrate is drawn through the membrane by suction. For this upgrading project, immersed membrane was preferred as it offered several advantages over the pressurised membrane. The existing sand filter tanks could be converted to accommodate the new immersed membrane tanks without any expansion in the plant footprint. Immersed membrane could also benefit from the existing hydraulic profile to achieve filtrate removal by siphon action at least part of the time. These factors can contribute to a lower capital and operation cost for the new membrane plant.

Besides the addition of immersed membrane filtration system, pre-chlorination was restricted to intermittent use to minimize the formation of disinfection-by-products. Enhanced coagulation was adopted to maximise TOC removal. The use of ozonation which resulted in poor biological stability of the water was discontinued. Chlorine was used for disinfection with chloramination used to control among others trihalomethane formation. Ozone reaction tanks were converted to chlorine contact tanks. Lime and carbon dioxide are dosed to provide a chemically stable water prior to distribution. The revised process treatment train for the upgraded plant is presented in Figure 1(b).

It was proposed to retrofit only the Phase 1 of the plant. The objective being to learn from the Phase 1 retrofit in the design, construction and installation and apply lessons learnt to the second retrofit. It would also give the plant operators the opportunity to familiarise with the operation of the plant.

PILOT STUDY

For this project, there was insufficient time for carrying out pilot trials before the plant design and the pilot trials had to be included as a post-tender 'proof-pilot'. In the tender specification, the successful membrane supplier was required to set-up a demonstration pilot plant within eight weeks of the award of contract. The pilot plant was required to be operated on CCKWW clarified water for a minimum period of eight months followed by further trials in 30 day cycles to test the clarified water derived by treating the individual raw water sources. The pilot trials also had to demonstrate that the maximum membrane flux is limited to 90 $L/m^2.h$ with a CIP frequency of not less than 30 days and the membrane recovery of more than 95%.

Based on technical and economic considerations, Zenon Zeeweed® 1000 immersed ultrafiltration membrane was selected as the replacement for the existing Phase 1 sand filters A pilot plant consisting of three modules of Zenon ZeeWeed® 1000 membranes (139.5m^2 of membrane surface area) was set up with the following specific goals: (1) demonstrate the membrane flux proposed for the full scale system resulting in a CIP interval of a maximum of 12 cleans per year; (2) demonstrate effective cleaning of the ZeeWeed® 1000 membranes and (3) demonstrate that periodic pressure decay tests may be used with ZeeWeed® Membrane Systems to provide verification of membrane integrity.

The pilot trials successfully showed that good filtrate quality can be produced with no detection of algae and micro-animals in the filtrate. The average filtrate turbidity was less than 0.025 NTU and the filtrate particle count was less than 10 counts/mL 99.9% of the time. The pilot trial also successfully demonstrated full scale process operating design condition at a maximum instantaneous flux of 77 L/m^2.h with all trains in operation (N condition) and at a maximum flux of 90 L/m^2.h with one train out (N-1 condition) while consistently maintaining a membrane recovery of 96%. There was no membrane failures throughout the piloting period as confirmed by a pressure decay rate of less than 4 kPa/2 minutes on every membrane integrity test performed. The filtrate pH in the range of 5.8 to 6.2 was found to have a lower fouling rate and at pH outside this range the fouling both organic fouling (TOC) and inorganic fouling (aluminium) increased. This probably is due to the fact that the optimal pH range for the upstream coagulation process was in the range of 5.8 to 6.2 and outside this range TOC removal declined due to under dosing of coagulant or aluminium fouling increased duE to over dosing of coagulant). Daily maintenance cleaning with 100 mg/L sodium hypochlorite could effectively control organic fouling during period of higher organic load. The ability of recovery clean using sodium hypochlorite and citric acid to restore membrane permeability with a cleaning interval of 30 days had also been demonstrated. The order of cleaning was found to be critical with the acid clean first providing superior recovery, probably due to the ability to achieve low pH if there is no residual hypochlorite present

MEMBRANE PLANT

Design

A total of eight trains of Zenon Zeeweed 1000 membranes were installed in the four filters to provide a treatment capacity of 182,000 m^3/d. Each membrane train consists of five membrane cassettes and each cassette can hold 60 membrane modules, giving a total of 300 modules per train. Extra space is also allocated in each train to allow for the addition of one more cassette. This provision is to cater for future conditions when the membrane flux has to be reduced due to deterioration in water quality or when treatment capacity has to be increased to meet higher water demand. Based on the findings from the pilot study, the immersed membrane system is designed to operate at a maximum instantaneous flux of 77 L/m^2.h with all trains in operation (N condition) and at a maximum flux of 90 L/m^2.h with one train out (N-1 condition). The overall design membrane recovery is 96%.

In general, clarified water from the upstream Pulsator clarifier passes through a 1-mm pore size fine screen before entering the membrane tanks. The membrane is operating in a batch mode with each cycle consisting of permeation followed by backwashing. The permeating duration of each cycle is controlled by the membrane recovery (96%) which can range between 30 and 40 minutes. During the 4 minutes backwashing with filtrate, continuous aeration is also provided to scour the membrane surface. At the end of the backwashing stage, the entire membrane tank content is drained off to remove all the accumulated solids. Once the membrane tank is empty, it is refilled with clarified water and the whole operating cycle is repeated. In order to recover the membrane permeability, chemically enhanced backwash (CEBW) with 100 mg/L of sodium hypochlorite will be carried out daily while cleaning-in-place (CIP) with 500 mg/L of sodium hypochlorite and 2000 mg/L of citric acid will be carried out once a month. The cleaning chemicals are neutralised by sodium bisulphite and sodium hydroxide to adjust the pH (6.5–8) and free residual chlorine concentration (<0.25 mg/L) before discharge.

Use of Mixed Siphon and Pump System

The design of the membrane filtration plant capitalizes on the existing structures and the hydraulic profile to draw the filtrate from the membrane by gravity. As shown in Figure 2, the hydraulic profile at 182,000 m^3/d of water production can provide a head difference of about 4.65 m between the membrane tank and the filtered water channel which is equivalent to a transmembrane pressure (TMP) of about 45kPa. This allows filtrate to be drawn from the immersed membrane by siphon action. The pilot trial in 2006 demonstrated that at the reduced flux rates corresponding to plant flows less than 90,000 m^3/d, the TMP would remain below 45 kPa for periods in excess of 30 days after a CIP. This allows the plant to operate only using siphonic action while feed water flow rates remain at or below about 50% of peak capacity. The siphonic action to draw water from the membranes was used in a large water treatment works for the first time at the Chestnut Avenue works, Singapore (Janson, 2004). CCKWW is the first large water treatment works to use mixed siphon-pump system.

With the fouling of the membrane or when higher treatment capacity is needed, a filtrate pump can be started to provide the additional TMP. By innovative use of either the siphon or pump for membrane filtration effectively, CCKWW membrane system can maximize membrane recovery to 96% with a low designed power consumption of 17.8 kWh/ML. The CIP regime for the membranes was programmed to allow cleaning intervals to be linked to the volume of flow treated rather than duration of operation. This design can minimize chemical usage for CEBW and CIP.

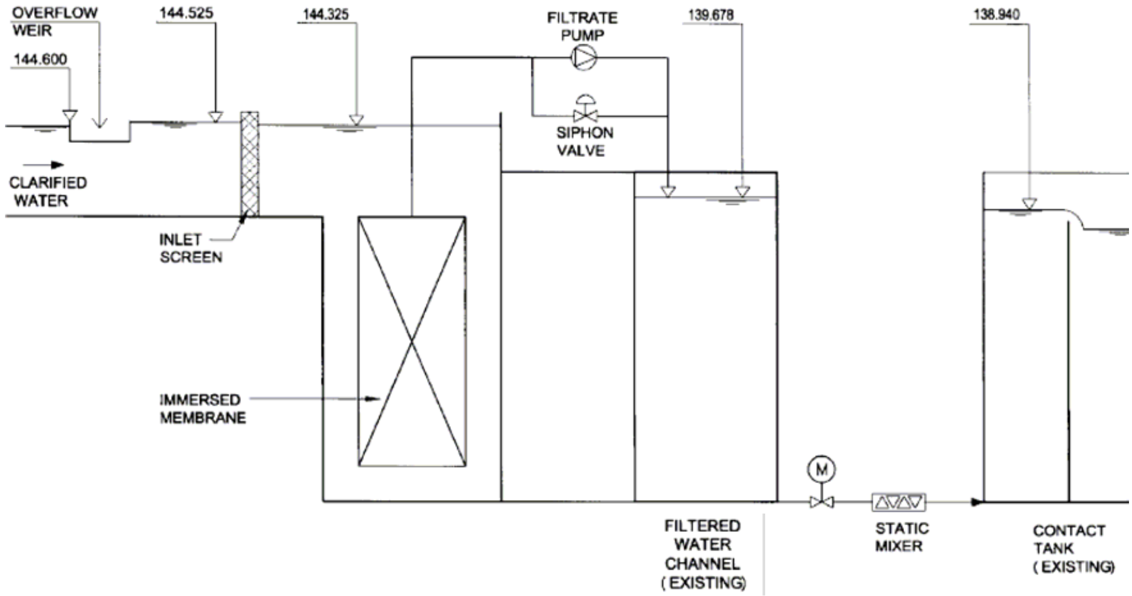

Figure 2. Simplified hydraulic profile of CCKWW (Phase 1) for water production of 182,000 m^3/d

Retrofitting Work

The upgrading of Phase 1 of CCKWW was divided into 2 main stages and took two years to complete. The main objective of Stage 1 was to separate the link between Phase 1 and Phase 2 which involved the separation of all the shared facilities such as the sand filter wash water building, the SCADA and PLC system. This was to ensure CCKWW could undergo retrofit work at Phase 1 with minimum disruption to Phase 2 drinking water production. Stage 2 mainly involved the retrofitting work to the existing Phase 1 process. This includes: (i) modification of sand filter for membrane filter system; (ii) modification of ozone contact tank to chlorine contact tank; (iii) provision of new chemical dosing system for carbon dioxide and ammonium sulphate; (iv) refurbishment of existing chlorine dosing and scrubber system; (v) provision of new control system and (vi) replacement of existing yard piping. All these works including the testing and commissioning was scheduled to be completed in one year. The retrofitted membrane plant was successfully commissioned in April 2008.

The existing Phase 1 sand filtration plant comprised of nine sand filters tank. Four sand filter tanks were retrofitted with eight membrane trains and its associated filtrate pumps. Three sand filters tanks are used to house the backwash water holding tanks, neutralisation tanks, and membrane washwater pumping station. The remaining two sand filter tanks are reserved for future membrane tanks if needed to meet higher water demand. It has been demonstrated that the existing sand filters tanks can be converted to an immersed membrane system with some filter tanks spare. In the case of CCKWW only four filters were required to be retrofitted with membranes to produce 182,000 m^3/day of drinking water and with two spare filters remaining empty the Phase 1 capacity could be increased to 273,000 m^3/day provided the remainder of works could accommodate the additional hydraulic capacity. Figure 3 shows two stages in converting the sand filter tanks into membrane filters tanks.

Figure 3. Comparison between the sand filter tank (before) and the retrofitted membrane tank (after)

MEMBRANE PLANT PERFORMANCE

Water Quality

Plant performance run was conducted since January 2008, as scheduled, to demonstrate the membrane recovery, energy consumption and chemical usage guaranteed by the contractor. The membrane plant was tested at various flow rates, ranging from 45,500 m^3/day to 182,000m^3/day, to verify its response to increases and decreases in water production demand. It was occasionally observed that slight deterioration in the clarified water quality occurred initially after a change in water flow rates. During this period, the membrane was able to produce very good quality filtrate even when the clarified water turbidity exceeded 1 NTU. Generally, the membrane plant has successfully demonstrated that high quality filtrate which meets the contract specification can be produced at different flow rates. There were also no algae and micro-animals detected in the membrane filtrate. Table 2 summarized the quality of the clarified water and the membrane filtrate observed during the plant performance run.

Table 2. Characteristic (average) of the clarified water and membrane filtrate

Parameter	Clarified Water	Membrane Filtrate
pH	6.1 ± 0.4	6.1 ± 0.3
Turbidty (NTU)	0.9 ± 1.3	< 0.1
Colour (True) (^{o} Hazen)	4.7 ± 1.6	< 2
Conductivity (µmho/cm)	239 ± 50	234 ± 50
Micro-animal (count/m^3)	3921 ± 5265	N.D.
Algae (count/mL)	68 ± 76	N.D.
Particle (2 – 5µm)	6.09 ± 0.36	6.10 ± 0.28

Power Consumption

One of the key design features of the membrane plant is to use the head available to achieve filtration by the siphon effect and minimise the energy consumption. During the performance run, the membrane plant can cope with the water production of ~~from~~ 27,800 to 91,000 m^3/day without the use of the membrane suction pumps. Only when the production reached above 136,500 m^3/day, the membrane suction pumps were partially used to provide the additional TMP. In terms of energy consumption, the new membrane plant can meet the designed power consumption of 17.8 kWh/ML from 27,800 to 91,000 m^3/day. Interestingly, it was found that the power consumption is not directly proportional to the water production. As shown in Table 3, the membrane plant is most energy efficient at a production of 91,000 m^3/day. Although the membrane suction pumps are not in use at lower production rate (27,800 m^3/day), similar amount of power is still needed to operate the air blower, recirculation pump and chemical pumps for backwashing and CEB. Thus, the membrane plant can use the energy more efficiently at 91,000 m^3/day production. When the membrane is operated at 136,000 m^3/day production or higher, membrane suction pumps are activated to draw the permeate from the membrane. This will inevitably add to the power consumed by the membrane plant as shown in Table 3.

Table 3. Power consumption at different production capacity

Production (1000 m^3/day)	Membrane Flux (LMH)	TMP (kPa)	Energy Consumption (kWh/ML)
45.5	34 to 76	-15 to -25	11.08
91	34 to 76	-20 to -30	6.68 to 7.46
136.5	34 to 76	-20 to -30	9.87
182	76 – 86	-34 to -40	13.71 to 14.35

CONCLUSION

CCKWW upgrading project was initiated to further enhance the water quality and to achieve micro-animal and algae free drinking water. Immersed ultra-filtration membrane retrofitted from the existing sand filters was selected as the process to achieve these objectives. Besides producing excellent drinking water quality, the new membrane plant is also innovatively designed for energy and chemical efficiency in operation. Upon successful commissioning, the upgrading project at CCKWW would be the largest retrofitted membrane plant (182,000 m^3/day) in the Asia Pacific Region and the second largest in the world and the first to use a mixed pump- siphon system.

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