Development of Advanced Wastewater Treatment and Reclamation System

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Recycling and the reuse of industrial wastewater has always been an important need for water-scarce regions such as Singapore. This will also be beneficial to emerging countries such as India, China, the Middle East, etc., as it will not only provide water to meet increasing population growth, but also reduce environmental pollution. With that goal in mind, a demonstration plant to test industrial wastewater treatment processes was set up in Singapore in 2013. This test plant is situated at the Jurong Water Reclamation Plant (JWRP), where wastewater from the Jurong Industrial Estate will be treated. In this test, Mitsubishi Heavy Industries Mechatronics Systems, Ltd. (MHI-MS) has demonstrated the stability of the treatment process, where the treated water has a constant CODCr level of 100 mg/l or less. In addition, high water recovery ratios of 60% using a reverse osmosis (RO) membrane system and 75% using a capacitive deionization system were obtained in spite of the highly variable qualities of the incoming industrial wastewater. This report presents the results of this demonstration test, as well as future plans for testing.

1. Introduction

As city functions develop in emerging countries such as India, China, Singapore, as well as those in the Middle East and Africa, environmental pollution resulting from the discharge of untreated urban wastewater has become a serious issue, giving rise to the necessity for wastewater treatment in urban areas. Emerging countries also face environmental pollution resulting from the discharge of untreated wastewater, giving rise to the necessity for wastewater treatment. In order to meet such needs, it is necessary to combine advanced water reclamation treatment technologies with existing wastewater treatment technologies.

Cooperating with Mitsubishi Heavy Industries, Ltd. (MHI) and Mitsubishi Heavy Industries Engineering & Services Private Ltd. (MIES), MHI-MS Installed a demonstration test plant with a throughput of 48 m^3/d to process untreated industrial wastewater at the Jurong Water Reclamation Plant (JWRP) owned by the Public Utilities Board (PUB) of Singapore. The demonstration test commenced in September 2013.

2. Overview and processes of demonstration test of wastewater treatment at industrial park

Figure 1 is a flow diagram of the wastewater treatment system. Despite the highly variable qualities of the incoming industrial wastewater, the system can operate steadily and even at a high water recovery ratio (i.e., the quantitative ratio of the obtained desalinated water to the wastewater). It

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consists of two main processes: wastewater treatment and desalination. In order to maintain the stable operation of the desalination treatment process, it is necessary to maintain the stable operation of the upstream wastewater treatment process. This in turn will ensure a constant supply of industrial water and NEWater (a brand name that collectively denotes reclaimed water of high quality, produced by purification treatment using advanced desalination technology). Below is an overview of the treatment processes.

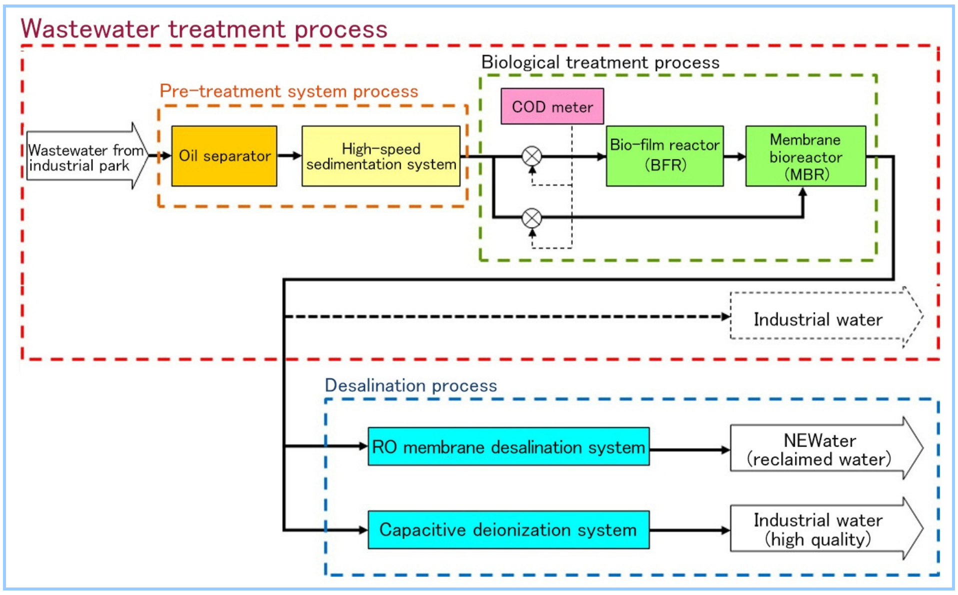

Figure 1 Flow diagram of wastewater treatment system at industrial park

2.1 Wastewater treatment process

Wastewater treatment is mainly comprised of two processes; the pre-treatment system process and the biological treatment process.

(1) Pre-treatment system process

The main purpose of the pre-treatment system process is the removal of inhibitors prior to biological treatment. The methods used for removal/treatment are chosen appropriately depending on the target substances. In order to prevent the disruption of the subsequent biological treatment, floatable components (e.g., oils and solvents) are separated through a process of floatation using oil separators, while heavy metals (e.g., Cu, Zn and Ni) and suspended solids (SS) are removed by sedimentation techniques. The high-speed sedimentation system used in this process (**Figure 2**) is a proprietary technology of MHI-MS. It is highly compact and exhibits excellent capacity for SS removal compared with conventional sedimentation systems.

Figure 2 High-speed sedimentation equipment

(2) Biological treatment process

The biological treatment process is performed mainly to remove organics (based on the chemical oxygen demand (COD), biochemical oxygen demand (BOD), etc.) contained in the pre-treated water (inhibitors have been removed prior to the biological process).

In this process, two types of biological treatment methods are used: bio-film reactor (BFR) and membrane bioreactor (MBR). These treatment systems are illustrated in **Figure 3**. BFR is a fixed bio-film process in which organics are aerobically treated through the use of oxygen and nutrients by microorganisms attaching to the packing surface of the fixed bed in the tank, i.e., the decomposition of organics. Because of this attachment to the packing surface, the bacterial flora is unlikely to change and a certain number of bacteria can be maintained. Thus, BFR is a treatment method that has the capability to adhere to the change in load. On the other hand, MBR is an aerobic treatment process in which biological flocs, i.e., activated sludge, are used to decompose the organics. This treatment retains the sludge, i.e., mixed liquor suspended solids (MLSS) at levels higher than the standard biological treatment, i.e., activated sludge treatment, by adopting microfiltration (MF) instead of sedimentation separation. This makes it possible to operate the system under high organic volumetric loading, which results in the reduced size of the bioreactor.

This process is designed to ensure the stable treatment of the highly variable qualities of incoming industrial wastewater by combining BFR, which has the capability to adhere to the change in load, with MBR, which can operate under high-load conditions.

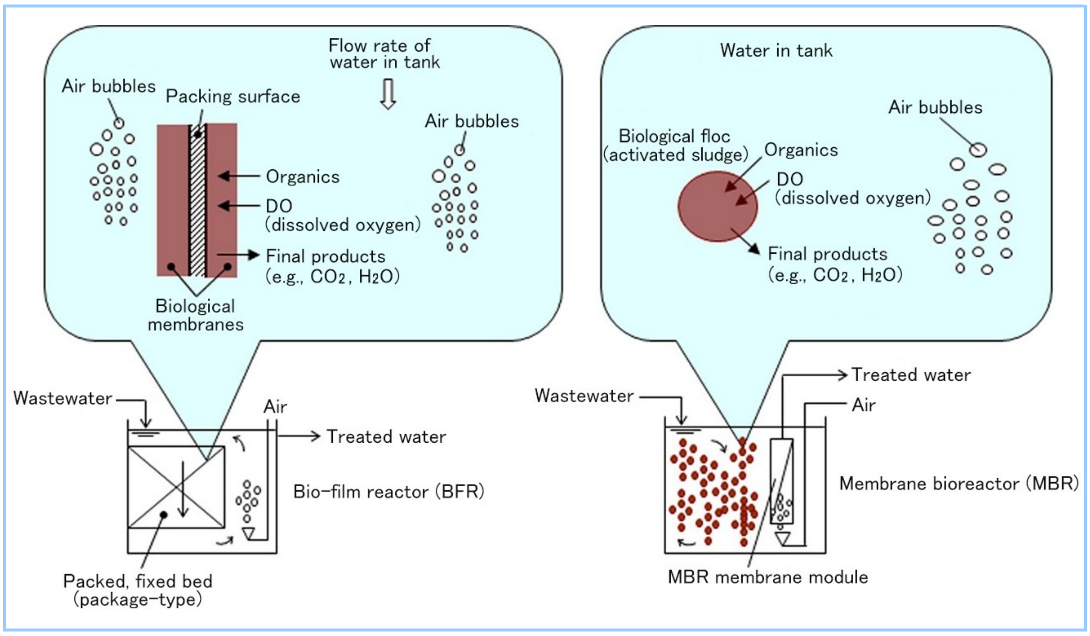

Figure 3 Biological treatment processes (BFR and MBR)

2.2 Desalination process

In the desalination process, two treatment methods have been adopted: the RO membrane system and the capacitive deionization system.

(1) RO membrane system

The RO membrane system is a method that is technically established. An RO membrane is a semi-permeable membrane with a porous diameter of less than 1 nm. Water molecules will pass through the RO membrane through the application of pressure greater than the osmotic pressure, allowing pure water through while holding back the majority of contaminants such as ions, salts and low-molecular organic compounds (**Figure 4**).

(2) Capacitive deionization technology

Capacitive deionization technology is known as a next-generation desalination technology that is still under development. It uses a pair of electrodes with large specific surface areas to create a small electrical field to deionize the water. The area between the electrodes is filled with the water to be desalinated and anions are adsorbed onto the anode and cations are adsorbed onto the cathode (**Figure 5**).

Figure 4　RO membrane desalination equipment

Figure 5　Capacitive deionization equipment

This process is designed to obtain the stable operation of the desalination system and determine the maximum ratio of water recovery using treated water with certain qualities that has undergone the aforementioned wastewater treatment process.

3. Demonstration test results of wastewater treatment at industrial park

Shown below are the test results of the demonstration wastewater treatment plant.

3.1 Wastewater treatment process

(1) Evaluation of high-speed sedimentation system performance

The SS levels in the industrial park wastewater fluctuate significantly, while the designed level is 300 mg/l. In spite of the severe test conditions with a continuous inflow of wastewater that substantially exceeds the designed SS level of 300mg/l, an SS removal rate of more than 80% has been demonstrated under the influence of chemical dosing. The injection rate for the flocculant, $FeCl_3$ is 100 mg/l and that of the polymer coagulation aid is 2 mg/l (**Figure 6**).

The linear flow velocity (LV) of the high-speed sedimentation system compared with a conventional sedimentation tank is approximately 8-fold, and therefore the installation area of the sedimentation tank can be expected to decrease to nearly one-eighth.

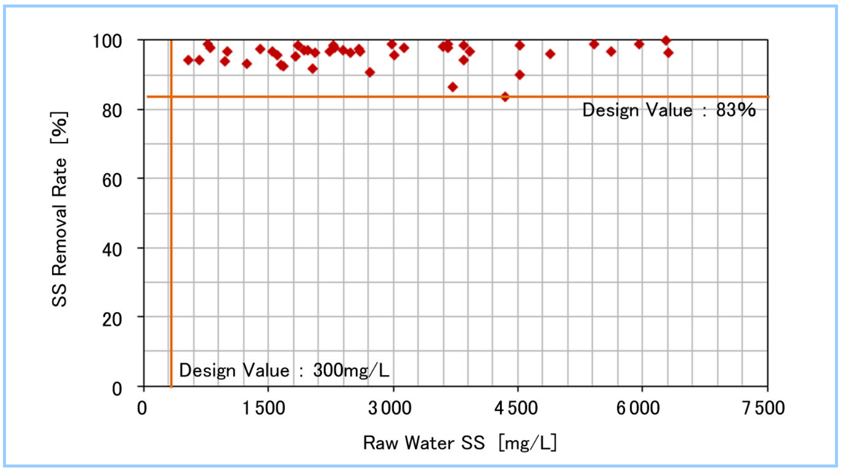

Figure 6　SS removal performance of high-speed sedimentation system

(2) Evaluation of BFR Performance

Although the COD_{Cr} (dichromate chemical oxygen demand test used to measure the organic matter in the water) levels in the pre-treated water fluctuate considerably, they are equal to or below the designed level (1,000 mg/l). This occurred when BFR operates below the designed load condition of 1.5 kg-COD_{Cr}/m^3·d (volumetric loading per biofilm).

As shown in **Figures 7** and **8**, BFR is able to produce treated water with a COD_{Cr} level of 300 mg/l or less within a load fluctuation range of 0 to 1.5 kg-COD_{Cr}/m^3·d, thus demonstrating its extensive removal capability over a wide range of volumetric loading.

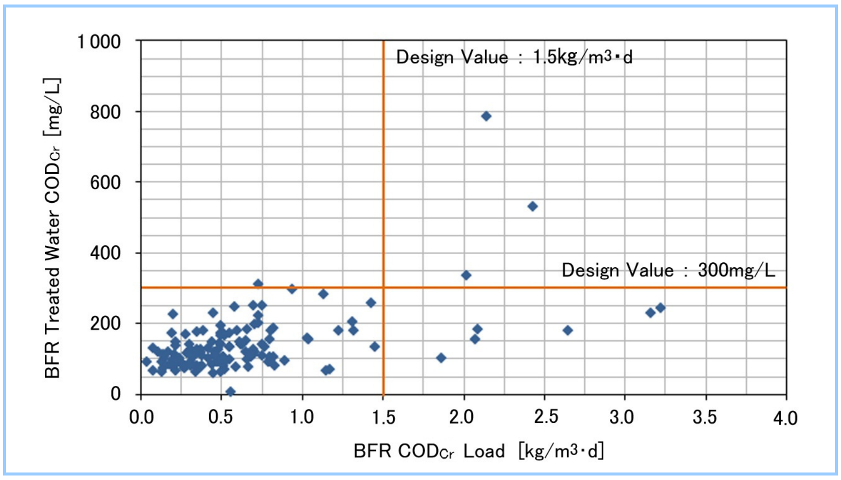

Figure 7 Relationship between COD_{Cr} space loading and quality of treated water (BFR)

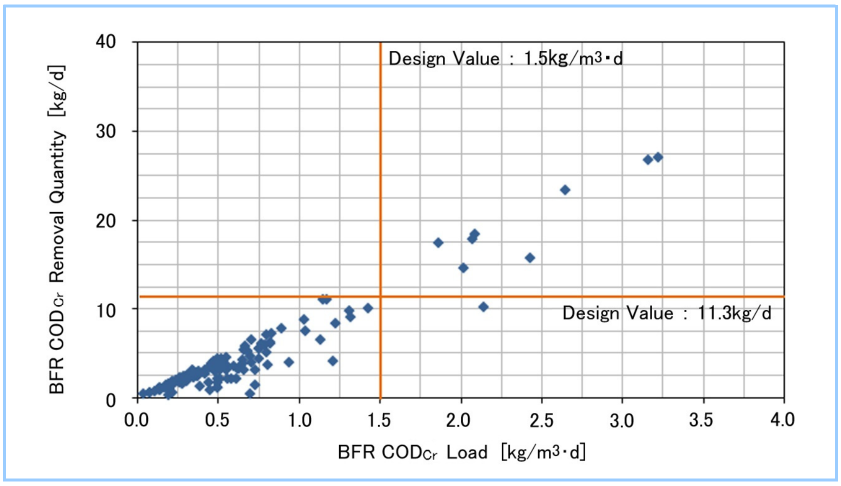

Figure 8 Relationship between COD_{Cr} space loading and removed COD_{Cr} quantity (BFR)

(3) Evaluation of MBR Performance

Similar to BFR, under an operating condition of the designed load (space loading per tank capacity) of 2.4 kg-COD_{Cr}/m^3·d, MBR has demonstrated the capability to remove $COD_{Cr.}$ Treated water produced by MBR has a CODCr level of 100 mg/l or less (which is the minimum specification for COD level for reclaimed water in Singapore) (**Figure 9**).

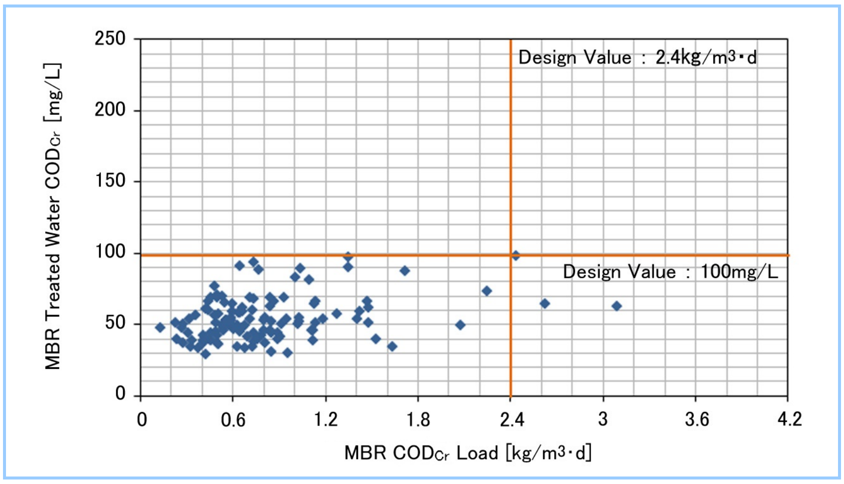

Figure 9 Relationship between COD_{Cr} space loading and quality of treated water (MBR)

The removal of COD_{Cr} tends to increase as the volumetric loading rises under the operating condition of a space loading range of 0 to 2.4 kg-CODCr/m^3·d. This indicates its removal capability to produce treated water of satisfactory quality even under high loads (**Figure 10**).

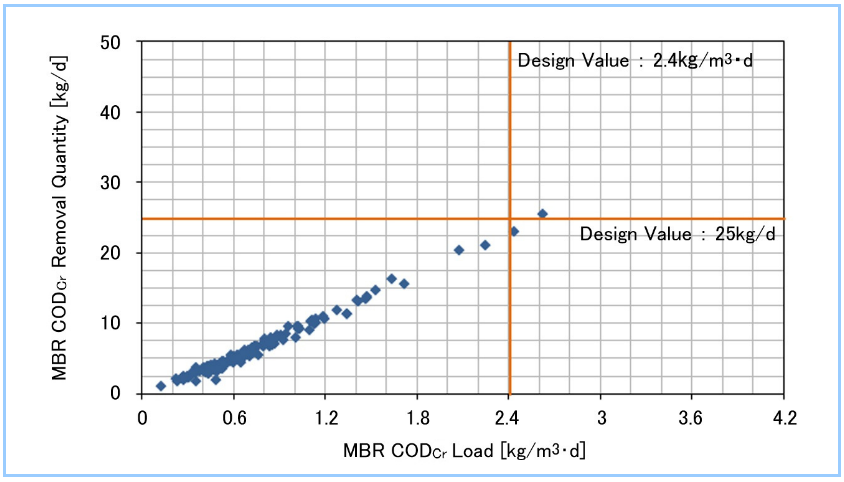

Figure 10 Relationship between COD_{Cr} space loading and removed COD_{Cr} quantity (MBR)

Therefore, it has been demonstrated that by combining BFR and MBR (i.e., excellent load following capability and operability under high loads, respectively), stable biological treatment operation is possible. Furthermore, MBR can produce good quality treated water to be fed continuously to the downstream desalination process.

3.2 Desalination process

(1) Evaluation of RO membrane system performance

Although it is not easy to realize it, the recovery ratio can be increased to 60% as described in Section 3.1 where the upstream wastewater treatment process can be maintained under continuous stable operation. As shown in **Table 1**, the quality of RO permeated water satisfies the stringent criteria of NEWater in Singapore, which indicates the satisfactory performance of the RO system.

Table 1 Quality of RO permeated water and NEWater quality control criteria

Item	Unit	RO feed water	RO permeate water	NEWater quality criteria
pH	—	7-8	6.5-7.5	7.0-8.5
Ca^{2+}	mg/L	30-55	≤1	(Total Hardness) <5mg/L as $CaCO_3$
Mg^{2+}	mg/L	30-40	≤0.5	
NH_4^+	mg/L as N	≤5	≤0.4	<0.5
M-Alk	mg/L as $CaCO_3$	100-280	5-10	<50 *1
Cl^-	mg/L	600-800	≤17	<20 *2
PO_4^{3-}	mg/L	≤6	≤1.5	—
F^-	mg/L	15-35	≤0.4	<0.5
TDS	mg/L	1 700-2 300	40-80	<90 *3
Conductivity	μS/cm	2 800-3 400	70-140	<150 *4
BOD_5	mg/L	0-25	≤3	—

Water recovery ratio	60%

*1 : Total Alkalinity
*2 : Applicable when 350 < Cl- in RO feed water ≤550
*3 : Applicable when 1,000 < TDS in RO feed water ≤ 1,330
*4 : Applicable when 1,580 < RO feed water Conductivity ≤ 2,100

(2) Evaluation of capacitive deionization system performance

Continuous stable operation of the upstream wastewater treatment process has allowed the capacitive deionization system to achieve a water recovery ratio of 75%. Although the treated water of the capacitive deionization system is unable to meet the NEWater quality criteria, it is able to meet the industrial water quality criteria (**Table 2**).

Table 2 Quality criteria of capacitive deionization water and industrial water

Item	Unit	Feed water of capacitive deionization	Capacitive deionization water	Industrial water quality criteria
pH	—	7-8	6.5-8	6.5-7.2
Ca^{2+}	mg/L	30-55	≤10	(Total Hardness) 100-250mg/L as $CaCO_3$
Mg^{2+}	mg/L	30-40	≤10	
NH_4^+	mg/L as N	≤5	≤1	<5
M-Alk	mg/L as $CaCO_3$	100-280	75	30-80
Cl^-	mg/L	600-800	100-350	100-500
PO_4^{3-}	mg/L	≤6	≤4	1-4
F^-	mg/L	15-35	5-20	—
TDS	mg/L	1 700-2 300	600-900	350-1 300
Conductivity	μS/cm	2 800-3 400	750-1 050	600-1 600
BOD_5	mg/L	0-25	≤5	1-5

Water recovery ratio	75%

4. Future test schedule

The future test plans are summarized below.

(1) Cost reduction for operation and facilities

Cost reduction for the operation and facilities of the system will be carried out by a few methods such as optimizing the chemical consumption of the high-speed sedimentation system and examining the influence of an increase in flux (the amount of permeated water per unit membrane area) on the performance of the biological treatment process (MBR).

(2) Determining the optimum operating condition of desalination system

The stable operation of an RO membrane system with a water recovery ratio of 60% has been demonstrated. We will optimize the chemical consumption for the RO system. The maximum water recovery ratio in the capacitive deionization system will be determined by changing the operating parameters while maintaining stable operation.

5. Conclusion

At the Jurong Water Reclamation Plant, a demonstration system with a throughput of 48 m^3/d used to process untreated industrial wastewater has been installed. The demonstration test commenced in September 2013 to treat wastewater from the Jurong Industrial Estate. The purpose of this plant is to demonstrate the viability of advanced water treatment/recycling technology. In this demonstration test, despite the highly variable quality of the industrial wastewater, the system was able to operate stably. In addition, a higher water recovery ratio was achieved. For future testing, we will study the maximum water recovery ratio of the capacitive deionization system, and at the same time attempt to further reduce operational and facility costs to make the technology practical for commercial purposes.