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A brief review on best available technologies for reject water (brine) management in industries

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ABSTRACT

The technological advancement in applications of membrane processes was efficiently explored in recent decades due to huge demand for potable water. However, relatively little improvements have been reported in the management and handling of the major by-product, called reject water or brine. The disposal or management of desalination brine (concentrate) is expensive and faces major environmental challenges. In spite of the scale of this economical and environmental problem, the options for brine management have been limited. This brief review presents an overview of the existing methods on brine treatment, minimization, and disposal practices based on the newest and most updated technologies. In addition, the review outlines the advantages and disadvantages of the most common treatment and disposal methods from an environmental perspective.

Keywords: Best Available Technologies, Brine Discharge, Brine Minimization Practices, Brine Treatment, Membrane Technology, Reject Water, Reverse Osmosis, Salt Recovery.

1. Introduction

With our increasing rates of population explosion and water exploitation, serious environmental attention needs to be paid on the use and reuse of water. Water is the key and most precious natural resource, no wonder it is called the elixir of life. With the increasing water scarcity, skyrocketing competition occurs among various sectors, such as industry, agriculture, and domestic sector. Especially for a developing and agrarian country like India, the demand for water supply is insusceptible. In addition, raising public awareness on water conservation strategies from both the state and central governments along with stringent environmental norms significantly increased the monitoring of water use in industries at all possible levels.

The intensifying demand of potable water led to several significant improvements in the application of membrane technology in water and wastewater treatment. Considerable expansion in membrane technology happened over the last three decades and it lowered the production costs. This further extends the applicability of this desalination technology at grass roots level. From smaller, pre-engineered industrial skidded designed membrane systems to large flow, custom membrane systems are available for water and wastewater treatment in present-day market to satisfy the need of various sectors. As a consequence, the huge generation of reject

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water (saline effluent from desalination plants or industry) is normally viewed as a severe environmental threat. The reject water disposal is considered as a major challenge in the engineering design of any desalination facility and often appears to be an afterthought in many desalination texts. The interplay of design objectives and regulatory restraints is complex yet surprisingly synergistic when it comes to the issues of reject water discharge.

Essentially, membranes allow partial water to pass through while rejecting the rest. Therefore, any feed stream sent to a membrane system can be classified into two streams called permeate and concentrate. The part of the stream that can pass through the membrane is called permeate (clean/product water). The part of the stream that is rejected by the membrane is called the concentrate (retentate) as shown in Figure 1. In general, the common perception about the concentrate represents concentrated slurry of undesirable contaminants in a wastewater or product clarification application. However, in an optimistic way one can view the concentrate as the desirable material in a product recovery or concentration context. Currently, four basic categories of membranes are in existence and they are categorized as follows: Microfiltration (MF) [0.1 µ–2.0 µ], Ultrafiltration (UF) [0.008 µ–0.1 µ], Nanofiltration (NF) [0.001 µ–0.01 µ], and Reverse Osmosis (RO) [30 Da–0.001 µ].

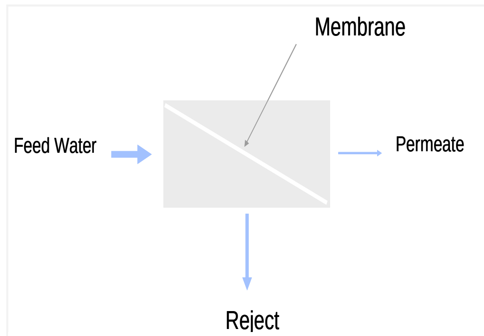

Figure 1: Membrane process for water and wastewater treatment

In general, the advanced treatment technology to generate the process water in industries consists of MF and RO, followed by ultraviolet (UV) disinfection with advanced oxidation (AO). While backwash waste produced from MF/UF facility can be recycled back to the wastewater treatment facility, the concentrate (reject) flow from the RO needs to be properly disposed. It is evident, therefore, that there is an urgent need for the development of a new process for the management of desalination brine that can be used by coastal as well as inland desalination plants.

The objective of this review is to make a thorough literature survey to identify technologies that could be used to develop multiple concentrate management alternatives that an industry could implement as a part of advanced water reclamation and reuse. This information will be used to develop and implement a decision analysis for concentrate management process selection after considering the associated capital and operation and maintenance (O&M) cost estimates with the estimation of life cycle costs (LCC) for each alternatives.

2. Evaluation of the Technologies

Concentrate management alternatives that can be applicable at any industrial facility can be categorized into three broad groups:

I. Wastewater Effluent Mixing
II. Volume Reduction Processes
III. Zero Liquid Discharge Technologies

2.1 Wastewater Effluent Mixing

Blending RO concentrate with secondary treated effluent from a wastewater treatment plant (WWTP) can be practiced to mitigate the impact of the high total dissolved solids (TDS) (or other solute) concentrate using the blending capacity of a lower-TDS stream. This combined stream can then be further discharged in accordance with existing permits or be applied to land. Implementation of this technique for reject water disposal is simple because no new equipments are needed. Only few pipelines have to be modified and so the implementation issues are minimal. As long as the blended flow complies with the existing permit requirements, a modified permit is not required at all.

2.2 Volume Reduction Processes

The concentrate volume reduction processes such as Electrodialysis Reversal (EDR), Vibratory Shear-Enhanced Processing (VSEP), and Enhanced Membrane System (EMS) already exist in industries installed at developed countries.

2.2.1 Electrodialysis Reversal (EDR)

Electrodialysis (ED) is a process that uses an electrical current to remove salt ions from a solution. It is based on the property that salts in solution are dissociated into positively and negatively charged ions. The ions are separated from the solution by passing a direct current between a cathode and an anode while passing water containing the ions across alternating pairs of cation-transfer and anion-transfer membranes. The result is the production of a demineralized product stream (from which ions have migrated) and a concentrate stream (to which ions have migrated). EDR is a variant of ED in which the cathode and anode positions are alternated several times per hour (polarity reversal). Polarity reversal assists in control of membrane fouling and allows operation at higher feedwater recovery with less scale control chemicals. It should be noted that, unlike other membrane processes used in drinking water and reuse, water does not flow through the EDR membranes, only ions. Consequently, particulates and poorly ionized solutes are not removed and no pathogen removal credits are given to ED/EDR under the Surface Water Treatment Rule.

2.2.2 Vibratory Shear-Enhanced Process (VSEP)

Conventional RO systems are subject to scaling by sparingly soluble salts and high concentrations of dissolved organic and colloidal matter. VSEP, a patented process of New Logic, was developed to reduce polarization of suspended colloids and sparingly soluble salts on the membrane surface by introducing shear to the membrane surface through vibration. Shear waves produced on the membrane surface keep the colloidal material in suspension, thereby minimizing fouling and prevent precipitating salts from accumulating on the membrane surface as scales. As a result, high throughput and water recoveries above that of a conventional membrane system can be achieved.

VSEP employs torsional oscillation at a rate of 50 times per second (50 hertz) at the membrane surface to inhibit diffusion polarization of suspended colloids. The suspended colloids are helped in suspension, where a tangential cross flow washes them away. The VSEP system consists of four components: a driving system that generates vibration, a membrane module, a torsion spring that transfers vibration to the membrane module, and a system that controls vibration. The vibration imparts a shear to the surface of the membrane to mitigate fouling and scaling that would occur in a conventional RO system. The membrane module houses a stack of flat membrane sheets (filter pack) in a plate- and frame-type configuration.

Unlike conventional RO systems, VSEP is not limited by the solubility of minerals or the presence of suspended solids. It can be used in the same applications as crystallizers or brine concentrators and is capable of high recoveries (up to 90%). The VSEP system can be configured employing either RO or NF membranes in a single-stage or multiple-stage arrangement. The configuration depends on the quality of the wastewater to be treated; water quality goals for the VSEP permeate, and target water recovery. VSEP outperforms conventional separation systems due to high filtration rates, fouling resistance, high solids, high efficiency, engineered dependability, compact design, convenient testing, and low cost.

2.2.3 Enhanced Membrane Systems (EMS)

EMS refers to the use of a nonconventional RO system to permit operation at higher recovery and at higher flux. One of the types of EMS is the patented High-Efficiency Reverse Osmosis (HERO™) system. This process uses ion-exchange softening to pretreat the conventional RO concentrate to reduce its scaling potential, followed by the high-pH operation of a three-stage RO system using standard spiral wound RO elements. Caustic is added to raise the pH to approximately 11 to retard silica scaling and biofouling. Historically, the HERO™ process has been applied for industrial use, for example, to treat cooling tower blowdown as a part of a zero liquid discharge treatment system.

EMS is a relatively new type of membrane system and will require approximately 6 months of pilot testing before implementation. Pilot testing could be complex because a mainstream RO pilot of sufficient capacity would be required to generate the concentrate as feed to the EMS pilot. One of the major drawbacks of the EMS is the complexity of the process (i.e. it requires chemical addition for softening, ion exchange, pH adjustment, and an RO system). Although softening, ion exchange, and RO are all proven technologies for drinking water applications, the combination of these technologies in the EMS requires a skilled staff to operate the facility. Capital and O&M costs are relatively high due to high energy and chemical consumption.

The product water quality is projected to be similar to VSEP permeate water quality because each technology uses RO membranes. Some of the EMS product water could potentially be blended with the RO permeate if it satisfies the Indian General Standards for Discharge of Effluents to surface water.

2.3 Zero Liquid Discharge Technologies

Processes capable of reducing the concentrate, either directly from the conventional RO or the volume-reducing processes to zero liquid discharge (ZLD), (i.e. sufficiently dry salt or other solid to be landfilled) were evaluated as a means for final concentrate disposal. Specifically, the analysis focused on mechanical evaporation, solar evaporation (evaporation ponds), and constructed wetlands. ZLD processes are considered in conjunction with wastewater effluent mixing and volume reduction technologies, where applicable.

2.3.1 Mechanical Evaporation

Mechanical evaporation can process concentrate by converting the water component into condensable water vapor, leaving behind a wet salt to be landfilled. Many different options for mechanical evaporation equipment exist. The most common combination of technologies used for this purpose is a vertical tube falling film brine concentrator followed by a forced-circulation crystallizer. This arrangement of evaporation equipment is typically the most economical and, therefore, selected for use as one ZLD alternative for RO concentrate treatment.

2.3.2 Vertical Tube Falling Film Brine Concentrator

High TDS and saturation of low-solubility scaling salts such as calcium sulfate ($CaSO_4$) and silica (SiO_2) limit the percentage of water that can be recovered in a conventional evaporator system. The brine concentrator uses a unique process called seeded slurry evaporation to overcome the limitation imposed on conventional evaporators by the saturation limits of low-solubility scaling compounds. The seeded slurry process involves establishing and maintaining slurry of $CaSO_4$seed crystals in the circulating brine in the evaporator.

With careful thermal and mechanical design, $CaSO_4$ and SiO_2 can precipitate preferentially on the recirculating seed crystals instead on the tubes. The ultimate concentration achievable in the brine concentrator is limited by the boiling point elevation of the brine, the relative concentrations of sulfate and chloride (e.g. the double salt, $CaSO_4$•Na_2SO_4 [glauberite], does not form), and the solubility of the sodium salts. The brine discharged from the brine concentrator is further concentrated in the crystallizer.

2.3.3 Brine Crystallizer

The crystallizer is a forced-circulation-type evaporator, which is specially designed to precipitate, grow, and handle crystals in the concentrate as water is continuously evaporated. Recirculated concentrate is pumped through the forced-circulation heat exchanger, where it is heated above its normal boiling temperature with steam. It requires 65–80 kWh of power per 1000 liters of crystallizer feed. Boiling of the concentrate in the heat exchanger is suppressed due to sufficient static head. The heated concentrate then enters a flash tank operating at a slightly lower pressure, causing flash evaporation of water and crystallization of salts in the brine.

High recirculation rates are used to keep the velocity on the heated surface high, avoiding the formation of scale on the heat transfer surface and increasing heat transfer efficiency. The slurry produced in the crystallizer is dewatered in the belt filter and the liquid portion is returned to the crystallizer for further concentration. When the salt cake accumulates on the belt filter to a predetermined level, an automatic sequence is initiated which advances the belt and dumps the salt cake into a hopper for disposal.

The primary obstacle in implementing mechanical evaporation for the disposal of RO concentrate is the size and complexity of the equipment. For example, a falling film brine concentrator for a 0.6 million liters-per-day (MLD) concentrate stream is approximately 25 meters in height. In addition, evaporators and crystallizers are relatively complex to operate and energy intensive compared with other ZLD methods.

Reliance on mechanical compressors results in lower reliability than other ZLD methods that are less mechanically intensive. Permit requirements for operation of volume reduction process equipment for membrane concentrate disposal are similar to other wastewater treatment processes. Implementation of a mechanical evaporator could require a variance due to the aesthetic impacts of the tower profile on the surrounding vistas.

2.3.4 Evaporation Ponds

Evaporation ponds rely on solar energy to evaporate water from the RO concentrate stream, leaving behind precipitated salts—which are ultimately landfilled. Evaporation ponds are most effective in arid and semiarid climates having high net evaporation rates. High net evaporation rates decrease the pond area required because evaporation occurs in less time. One major advantage of evaporation ponds is that the practicality of using evaporation ponds is not limited by RO concentrate quality.

In the most common case, RO concentrate is conveyed to the evaporation ponds where it is spread out over a large area and allowed to evaporate. For evaporation ponds systems, multiple ponds are constructed so that some ponds can be taken offline for periodic maintenance. Periodic maintenance includes allowing the evaporation pond to set idle to firm the consistency of the precipitated salts, cleaning the ponds by removing and transporting the precipitated salts to a landfill, and inspecting the protective lining system.

Factors affecting the feasibility of implementing evaporation ponds for RO concentrate disposal include membrane concentrate flow rate, geographical location, and site location. The RO concentrate flow rate is the primary factor affecting the area required for the evaporation ponds. The greater the flow of RO concentrates, the larger the area required for evaporation ponds. An estimate of the pond area required should take into account the reduced evaporation rate of a brine solution compared to typical lower-TDS water. A general guideline is to apply a factor of 0.7 to the evaporation rates. This reduces the evaporation rate by 30% to account for the lower evaporation rate of the concentrate solution.

Evaporation ponds must be lined to prevent seepage into the groundwater if the industry aimed to consider this as an injection well. However, installing a double liner with leachate collection system is needed to make treated reject water as lower concentrations of salt constituents than those found in the native groundwater. Another major concern with installation of evaporation ponds is the control of habitat, including water fowl. Large evaporation ponds are attractive to many birds. However, the required area for evaporation ponds will be high, if no volume reduction occurred before the evaporation ponds. Implementation of such a large pond area is neither feasible nor economically attractive in many instances. A hybrid method, incorporating volume reduction technologies (e.g. VSEP, EMS, and mechanical evaporation), should be used to reduce the evaporation pond area. A major advantage for constructing evaporation ponds in India is the higher evaporation rates due to the solar energy available throughout the year.

Table 1: Advantages and Disadvantages of Common Brine Treatment and Disposal Methods

Disposal method	***Advantages***	***Disadvantages***
Direct surface water discharge	✓ *Natural processes promote degradation* ✓ *Can accommodate large volumes* ✓ *Water body promotes dilution* ✓ *Low cost* ✓ *High dilution rates in the water body, possible dilution and blending with power plant discharge*	○ *Dilution depends on local hydrodynamic conditions* ○ *Good knowledge, monitoring and planning programs of receiving waters are required* ○ *Limited natural assimilation capacities cause adverse impacts on marine environment if exceeded* ○ *Thermal pollution, reduction of dissolved oxygen in receiving waters, eutrophication, toxicity, pH increase, damage of biota*
Discharge to a sewage treatment plant	✓ *Lowers the BOD of the resulting effluent* ✓ *Dilutes the brine concentrate* ✓ *Uses existing infrastructure*	○ *Can inhibit bacterial growth* ○ *Can hamper the use of the treated sewage for irrigation due to the increase in TDS and salinity of the effluent* ○ *Overload the existing capacity of the sewage treatment plant while diminish its usable hydraulic capacity*
Deep well injection	✓ *Viable for inland plants with small volumes of brine* ✓ *No marine impact expected*	○ *Cost efficient only for larger volumes* ○ *Needs a structurally isolated aquifer* ○ *Increases the salinity of groundwater*
Land applications	✓ *Can be used to irrigate salt tolerant species* ✓ *Viable for inland plants with small volumes of brine* ✓ *No marine impact expected*	○ *Requires large areas of land* ○ *Suitable for smaller discharge flows* ○ *Can affect the existing vegetation* ○ *Can increase the salinity of groundwater and underlying soil* ○ *Storage and distribution system needed*
Evaporation ponds	✓ *A viable option for inland plants in highly arid regions* ✓ *Possible commercial salt exploitation* ✓ *No marine impact expected*	○ *Expensive option* ○ *Risk of underlying soil and groundwater pollution* ○ *Needs dry climates with high evaporation rates* ○ *Requires large areas of land with a level terrain* ○ *Needs regular monitoring*

	✓ *Low technological and managing efforts*	
Brine concentrators/Zero liquid Discharge	✓ *Can produce zero liquid discharge* ✓ *Can commercially exploit concentrate* ✓ *Recovery of salt and minerals* ✓ *No marine impact expected*	○ *Expensive* ○ *High energy consumption* ○ *Production of dry solid waste – precipitates*
Mixing with the cooling water discharge	✓ *Achieve dilution of both effluents prior to discharge* ✓ *Combined outfall reduces the cost and environmental impacts of building two outfalls* ✓ *Necessary to reduce salinity if disposing in fresh water bodies*	○ *Dependent on the presence of a nearby thermal power plant*
Mixing with the sewage treatment effluent	✓ *Achieve dilution of brine effluent prior to discharge* ✓ *Does not overload the operational capacity of sewage treatment plant* ✓ *Use of existing infrastructure* ✓ *Necessary to reduce salinity if disposing in fresh water bodies*	○ *The brine could enhance the aggregation and sedimentation of sewage particulates that can impact benthic organisms and interfere with the passage of light in the receiving water body*

Source: *Adapted from "Report on the evaluation of existing methods on brine treatment and disposal practices" in Development of an advanced, innovative, energy autonomous system for the treatment of brine from seawater desalination plants by SOL-BRINE on June, 2012*

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3. Conclusion

Production and disposal of reject brine are an integral part of an overall desalination process. Several disposal techniques of the brine concentrate are practiced worldwide. These include direct surface water discharge, discharge to a sewage treatment plant, deep well disposal, land application, evaporation ponds, brine concentrators, and mixing with the cooling water or sewage treatment effluents before surface discharge. Several available options may deem infeasible due to the following reasons: Discharge to surface water method was deemed infeasible because of the lack of perennial stream flow with sufficient carrying capacity to assimilate the contaminants present in the concentrate. Deep well injection may be deemed feasible, yet one has to consider the geological conditions of the area. Similarly, land application/irrigation was deemed infeasible due to the discharge limitations in surface water bodies. Discharge limitations set by the Tamilnadu Pollution Control Board/Central Pollution Control Board (TNPCB/CPCB) preclude direct application of RO concentrate onto the surface water bodies. Irrigation of RO concentrate requires considerable treatment and blending with low chloride/TDS water, and a source of low chloride/TDS water is not available. At this juncture, the following technologies were identified as feasible for application to concentrate disposal or reduction of concentrate were *Solar evaporation, Constructed wetlands and EDR;* Nontraditional RO, including *VSEP membrane treatment, EMS, Blending with wastewater effluent and Mechanical evaporation and crystallizer.*

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