

SYSTEM AND METHOD FOR OPERATION OF REVERSE OSMOSIS UNITS

TECHNICAL FIELD

[0001] The invention relates generally to a method and system for operating reverse osmosis units and more specifically to the use of at least one objective constraint to arrive at
5 operating variables for the reverse osmosis units.

BACKGROUND

[0002] Energy recovery devices in the context of membrane process are gaining importance due to their ability to reduce the production cost of potable water by recovering and re-using the energy from one of the reject streams of membrane process. In addition, by
10 using energy recovery device (ERD), the size of the high pressure pump and its related equipment in the membrane process can also be reduced. This is because approximately half of the energy required to pressurize the feed water in a membrane process is supplied by ERD. Therefore, most of the new installations, particularly desalination plants are coming up with ERD along with the membrane process. There are different types of ERDs available in
15 the market such as pelton wheel, turbocharger, dual work exchange energy recovery (DWEER) and pressure exchanger. The pressure exchanger type ERD is stated to have higher efficiency followed by DWEER, turbocharger and pelton wheel types.

[0003] Though the production cost of water is reduced with energy recovery devices to a large extent by recovering waste energy from reject stream, there is still scope for
20 recovering wasted energy due to suboptimal operations by optimizing the associated operations. In general, the objective of optimization of membrane process with energy recovery device involves either (i) maximizing the permeate (or product water) throughput, or (ii) minimizing the specific energy consumption (i.e., energy consumed per m³ of permeate) or (iii) maximizing the profit by calculating the optimal set points for process
25 variables such as feed pressure, feed flow rate, reject pressure and reject flow rate. The first objective i.e. maximizing product permeate, is important where energy cost is not a major concern and plant capital expenditure is more concern, e.g. RO plant located in middle east countries. For second objective i.e. minimizing SEC is important when energy cost is major concern e.g. Europe, Asia and USA. When profit is major concern the third objective
30 becomes important. For all the three objectives, the constraints can be on product quality and

membrane life, etc. In many situations, these optimizers calculate the steady state optimal set points and they do not address optimal tracking of the set points which need to be adapted over time to reflect the system behaviour.

[0004] Since membrane processes are energy consuming, there is a need for the
5 implementation and optimal operation of RO train integrated with ERD in order to minimize the energy consumption and also to reduce the carbon foot print. In addition, there is a need for an optimization solution that considers the overall system (membrane model, pumps and ERDs) performance in membrane process.

BRIEF DESCRIPTION

10 [0005] In one aspect, the invention provides a system for operating an RO unit. The system comprises a water intake pump to provide a feed water; a pre-treatment section to pre-treat the feed water to provide a pre-treated water; a membrane section; an optimizer module to estimate a value for at least one operating variable associated with at least one decision variable, wherein the decision variable is associated with at least one objective constraint; and
15 a control module for operating the RO unit at the estimated value of the at least one operating variable. The membrane section comprises a high pressure pump for increasing an input pressure for the pre-treated water to yield a high pressure water, a membrane train to process the high pressure water to provide a product water and a reject stream having energy, a post-treatment section to process the product water, energy recovery device to exchange energy
20 from reject stream giving rise to waste stream, at least one valve to control the flow of waste stream, and a recirculation pump attached to energy recovery device to boost the pressure of feed water from the from energy recovery device.

[0006] In another aspect, the invention provides a method of operating a reverse osmosis (RO) unit. The method comprises identifying at least one objective constraint. The
25 method then involves calculating at least one optimal set point for at least one decision variable associated with the at least one objective constraint. The method then includes the step of estimating a value for at least one operating variable associated with the at least one decision variable. Subsequently, the RO unit is operated at the value of the at least one operating variable.

[0007] In another aspect, the invention provides a tool that uses the method of the invention.

DRAWINGS

[0008] These and other features, aspects, and advantages of the present invention will
5 become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

[0009] FIG. 1 shows a schematic of system of the invention; and

[0010] FIG. 2 is a flowchart representation of the exemplary steps of the method of
10 the invention.

DETAILED DESCRIPTION

[0011] As used herein and in the claims, the singular forms "a," "an," and "the" include the plural reference unless the context clearly indicates otherwise.

[0012] As used herein, the Reverse Osmosis (RO) means a filtration process that
15 involves forcing a liquid through one or more membranes at a pressure, wherein the membrane is designed to allow only the liquid to flow through while retaining the solutes. Other filtration techniques, such as nanofiltration or microfiltration or ultrafiltration methods, also involve similar principles and consequently the methods and systems described herein, while described with respect to reverse osmosis, are applicable in these situations as well.

[0013] As used herein, the phrase "RO plant" is also meant to encompass the phrase
20 "RO unit", and vice versa. RO plant comprises at least one RO membrane to effect the separation of solutes from the solvent, typically a set of membranes. The RO membranes are also referred to as membrane train or membrane section. A RO plant may comprise a plurality of membrane sections.

[0014] As noted herein, in one aspect the invention provides an RO system used to
25 purify a feed water. Fig. 1 shows a schematic of the RO system of the invention 20 configured in one kind of operation, wherein a plurality of membrane sections are comprised within the system of the invention. Other configurations may also be possible, and are

contemplated to be within the scope of the invention. Feed water from any source such as sea water, brackish water, ground water, spent water from a processing unit, and the like, is pumped into the system using a water intake pump 22. The feed water is then pre-treated at a pre-treatment section 24 to remove, for example, jelly fish, suspended particles and colloidal particles using travelling screens, sand filters, micron cartridge filters, and the like, and combinations thereof.

[0015] The pre-treated water is distributed among several membrane sections 26. The summation of flows over all membrane sections 26 equals to the flow obtained from sea water intake pump, and the amount of flow to each membrane section 26 depends on various factors, which will become obvious to one skilled in the art. Each membrane section 26 consists of a high pressure pump 28 to pump the pre-treated water at a high pressure into membrane train 30. The membrane train could be either 1 pass or 2 pass configuration. The membrane train separates the high pressure feed into two streams: (i) permeate water or product water consisting of low concentration of salts, and (ii) reject stream consisting of brine, which is highly concentrated with salts, and also consists of high pressure energy. The recovered product water or permeate will be sent to the post-treatment section 32 where it is disinfected for bacteria either with ultraviolet radiation or chlorination before further processing such as packaging or distribution. The pH value of permeate water may also be controlled. The membrane feed flow and membrane feed pressure are governed by the brine reject valve opening and also by the high pressure pump speed (if the pump has variable frequency drive to change the speed). The membrane feed concentration is governed by the feed water concentration coming from pre-treatment section.

[0016] The high pressure brine reject coming from the membrane elements is fed to an energy recovery device (ERD) 34 through high pressure inlet where the hydraulic energy of the brine is directly transmitted to the part of pre-treated water entering in to the energy recovery device 34. Portion of the feed water is also fed into the ERD. The pressurized feed water from both the high pressure and re-circulation pump is fed to the membranes in RO train. Once the energy is recovered, the low pressure brine reject passes through low pressure outlet of ERD through a reject valve 36 into reject stream 38. After gaining the hydraulic energy, the pressurized feed water passes through high pressure outlet of the energy recovery device to a re-circulation pump 40, where it provides the head to compensate the pressure losses across membrane, ERD and associated piping. The outlet streams coming from both

high pressure pump 28 and re-circulation pump 40 will get mixed before it passes through the membrane train 30. Thus part of the energy to the pre-treated water is supplied by the energy recovery device 34 while the rest is supplied by the high pressure feed pump 28 and re-circulation pump 40. During the process of energy recovery in ERD 34, very limited
5 amounts of high pressure brine reject will mix with the low pressure feed water which results in a change in the concentration of the high pressure feed water passing through high pressure outlet of ERD 34.

[0017] Typical ERD pressure exchangers include, for example, DWEER devices, pelton wheel and turbocharger type ERDs and the like. In one exemplary embodiment, the
10 ERD comprising pelton wheel typically comprise a (i) nozzle and (ii) Pelton wheel on a rotating shaft. The manner of operation of the pelton wheel ERD involves using the nozzle to convert the pressure energy of the brine into kinetic energy. The resulting high speed flow of brine is directed to the vanes of the pelton wheel which gets rotated. The pelton wheel is mounted on a high pressure pump shaft which together with motor drives the high pressure
15 pump 28 to pressurize the feed water. Similarly, in a turbocharger type ERDs, the turbocharger comprises a turbine and pump sections in a single housing. Both pump and turbine sections generally contain a single stage rotor. The high pressure brine from membrane train enters the turbine section of turbocharger, which converts the pressure energy of brine into kinetic energy of the turbine rotor. The pumping section re-converts the
20 kinetic energy of the rotor back to pressure energy supplied to the feed stream. Then, the feed water from the pre-treatment is partially pressurized by the high pressure pump 28, and is boosted by the turbocharger pumping section before sending it to the membrane train. Other forms of ERDs are known, and their manner of operation will be known to those skilled in the art, and is contemplated to be within the scope of the invention.

25 [0018] The product flow rate or recovery rate of the membrane train 30 will be affected by its feed flow rate and feed pressure. The feed flow and feed pressure to the membrane train 30 is governed by the flows and pressures in the outlet streams of high pressure pump 28 and re-circulation pump 40. In a similar fashion, as the flow and pressure in the low pressure brine reject stream 38 (i.e., low pressure outlet stream of ERD) changes,
30 the percentage mixing of brine and feed water in ERD changes which reflects in change in the concentration of membrane feed affecting the recovery rate.

[0019] The system of the invention 20 further comprises an optimizer module 42 to estimate a value for at least one operating variable associated with at least one decision variable, wherein the decision variable is associated with at least one objective constraint. The objective constraint could be at least one of (i) maximization of permeate flow rate or recovery rate, or (ii) minimization of specific energy consumption (SEC), or (iii) maximization of the profit, or combinations thereof. Specific energy consumption is the total energy consumption divided by permeate flow rate, wherein the total energy consumption generally includes the sum of energy consumed by the ((i) high pressure pump, (ii) re-circulation pump and (iii) sea water intake pump) / permeate flow rate. Similarly, profit is the total revenue from the sales of permeate water less the operating costs (which include energy costs associated with high pressure pump, re-circulation pump and sea water intake pump), pre-treatment costs and membrane maintenance cost.

[0020] The decision variables for the RO unit include at least one of (i) flow at high pressure (HP) pump, (ii) pressure at HP pump outlet, (iii) flow at re-circulation pump, (iv) pressure of low pressure brine reject stream, or combinations thereof. Though the decision variables described are related to the membrane section of the RO unit, the effects of other process variables in the pre-treatment section such as flows and pressures at gravity and other factors, such as, but not limited to, micron cartridge filters are also considered as bounds to the described decision variables. Therefore, the optimal set points thus calculated considers pre-treatment section as well as membrane section. Decision variables may also be identified as predicted variables (PVs) by one skilled in the art.

[0021] The mathematical formulation for calculating at least one optimal set point for at least one decision variable for a given membrane section is as follows:

Max. Permeate flow rate or Max. Recovery rate or Min. SEC or Max. Profit subject to

- (i) $C_p < \text{specified value}$ (constraint on product quality)
- (ii) $\Phi < \text{specified value}$ (constraint on concentration polarization or membrane life)
- (iii) $P_f < \text{specified value}$ (constraint on membrane feed pressure)
- (iv) $LB < Q_{f1} < UB$ (bounds on feed flow at HP pump)
- (v) $LB < P_{f1} < UB$ (bounds on outlet pressure of HP pump)
- (vi) $LB < Q_{f2} < UB$ (bounds on flow at re-circulation pump)
- (vii) $LB < P_{lpb} < UB$ (bounds on pressure of low pressure feed flow to ERD)

wherein C_p = permeate concentration, Φ = concentration polarization factor, P_f = pressure of feed to the membrane, Q_{f1} = flow at HP pump, P_{f1} = pressure at HP pump outlet, Q_{f2} = flow at re-circulation pump, P_{lpb} = Pressure of low pressure brine reject stream, LB = lower bound and UB = upper bound. The definitions for SEC and profit function are as already described
 5 herein. The mathematical formulation described herein may also be referred to as steady state model in the art.

[0022] The at least one operating variable is at least one of (i) HP pump speed, (ii) re-circulation pump speed, (iii) brine reject valve opening, or combinations thereof. These operating variables can easily be identified as manipulated variables (MVs) by one skilled in
 10 the art. The values of the MVs above are determined by minimizing the following model predictive control objective at each instant k :

$$J_k = \sum_{j=0}^{N_p-1} [Y_{SP,k+j} - \hat{Y}_{k+j}]^T W_E [Y_{SP,k+j} - \hat{Y}_{k+j}] + \sum_{j=0}^{N_c-1} [\Delta U_{k+j}]^T W_U [\Delta U_{k+j}]$$

subject to :

$$Y_L \leq \hat{Y}_{k+j} \leq Y_H$$

$$U_L \leq U_{k+j} \leq U_H$$

$$\Delta U_L \leq \Delta U_{k+j} \leq \Delta U_H$$

Model Equations

where,

$$Y_{SP,k} = [Q_{f1,sp} \quad P_{f1,sp} \quad Q_{f2,sp} \quad P_{lpb,sp}]^T : \text{vector of setpoints for the PVs at inst. } k$$

$$\hat{Y}_k = [\hat{Q}_{f1} \quad \hat{P}_{f1} \quad \hat{Q}_{f2} \quad \hat{P}_{lpb}]^T : \text{model predictions of PVs at inst. } k$$

$$\Delta U_{k+j} = U_{k+j+1} - U_{k+j}$$

$$U_k = [S_{HS} \quad S_R \quad V_B]^T : \text{vector of MVs at inst. } k$$

W_E and W_U are diagonal weighting matrices

N_p and N_c are prediction and control horizons respectively.

[0023] The model predictive control formulation described herein uses a dynamic model that relates the manipulated variables and predicted variables to obtain the predictions
 15 of the predicted variables at each instant. The model may be a data based linear model or a first principles nonlinear model. The data based model is obtained from data collected from the RO unit by conducting a step test or a perturbation test.

[0024] The optimizer module may advantageously comprise a two layered architecture for optimal operation of the process, wherein the top layer consists of a steady
 20 state optimizer 44 that uses the steady state model while the second layer consists of a

dynamic optimizer 46 that uses the dynamic model. The steady state optimizer 44 may be used to calculate the at least one optimal set points for the at least one decision variable as described herein based on the method of the invention. The dynamic optimizer 46 may then be used to estimate the values of the at least one operating variable, also as described herein the method of the invention. The dynamic optimizer 46 may then be configured to repeatedly estimate the values of the at least one operating variable based on various inputs, such as, for example, in the case of proportional-integral-derivative (PID) control process, or other closed loop control process.

[0025] Without being bound to any theory, the interaction between reject stream and membrane feed streams is effected by the presence of the ERD. The presence of ERD along with the associated re-circulation pump causes the brine reject stream to interact with membrane feed. For example, the flow and pressure of brine reject entering the ERD effects the pressure of the feed water leaving the ERD high pressure outlet, which in turn effects the membrane feed pressure. Similarly mixing between the high pressure brine reject and low pressure feed water in ERD effects the concentration of feed water leaving the ERD high pressure outlet, which in turn effects the membrane feed concentration. Since the product water flow rate or product recovery is effected by the flow, pressure and concentration of the membrane feed, the interaction between brine reject with membrane feed streams makes it challenging to identify which process variable (s) is to be manipulated in order to control the product water flow and also the specific energy consumption (energy consumed per m³ of product water). For example, as the flow rate at re-circulation pump (one of the indicators of interaction between membrane feed and brine reject) increases, the membrane feed pressure increases to a certain extent and then decreases. Similarly, the membrane feed concentration, product flow rate and SEC also changes with varying flow at re-circulation pump.

[0026] Having knowledge of the interaction between the brine reject and membrane feed streams, the manipulated variables are identified by understanding their effect as given in the following:

1. In general, the high pressure pump has the ability to deliver high pressures and flows which will impact the membrane feed conditions (flow and pressure) and hence the product flow rates or product recovery. Therefore, the flow rate or pressure at the outlet of high pressure pump becomes one of the manipulated variables, provided the

pump has variable frequency drive (VFD) in order to change the speed to deliver different flows and pressures.

2. Though the energy from brine reject is transferred to the feed water in ERD, the pressure of the feed water at ERD high pressure outlet will be still less than that of the feed stream coming from the high pressure pump due to pressure drop at membranes and ERD. Therefore, a re-circulation or booster pump is used in order to boost the pressure of the feed water coming from ERD, to compensate the pressure losses. In general, this pump cannot deliver high pressures except to the supply for the pressure losses, but can deliver different flows (using VFD) which affect the product recovery. Therefore, the flow at re-circulation pump can be considered as one of the manipulated variables.

3. The efficiency of the ERD is a function of flows and pressures of its inputs and outputs. Though the flow at high pressure outlet of ERD is controlled by the re-circulation pump, the flow or pressure at low pressure outlet of ERD can still be manipulated (by means of valve) and they can affect the SEC by influencing the efficiency of ERD. Therefore, the pressure of the stream (wherein the flow is calculated by material balance across ERD) at low pressure outlet of ERD is considered as one of the manipulated variables.

[0027] Overall, the above manipulated variables are identified by considering their effect on the overall RO section performance (in terms of product recovery and SEC) and the availability of degree of freedom (i.e., if the pump has VFD, then the choices may be one of either flow or pressure of the pump as a manipulated variable). The above described manipulated variables will change based on the type of configuration in membrane section i.e., if the ERD has a separate pump for the feed flow, then the flow associated with that pump also becomes one of the manipulated variables. Thus, once the manipulated variables are determined, the set points for them may be estimated, based on which the predicted variables are also estimated. Repetition of these described steps using the mathematical formulations using the steady state model and the dynamic model described, under the constraints, will give rise to optimized values for the variables. The RO unit may then be operated under optimum conditions that will ensure the at least one objective constraints are met.

[0028] It may be noted that the dynamic optimizer may be executed more frequently than the steady state optimizer. In one exemplary embodiment, for a given production demand for a particular day, the steady state optimizer is executed only once every 3 hrs while the model predictive control (MPC) is executed every 5 minutes in one embodiment, or less than 5 minutes in another embodiment.

[0029] The system of the invention 20 further comprises a control module 48 for operating the RO unit at the estimated value of the at least one operating variable. The control module 48 is in constant contact with the optimizer module 42 to become updated with the values of the at least one operating variable. The system of the invention also comprises appropriate communication modules (not shown herein) to allow seamless communication between all the modules comprises within the system.

[0030] The components of the system 20 are well-known to one of ordinary skill in the art, and may be made available from a variety of commercial sources. Further, other components associated with a RO system may become obvious to one skilled in the art, and is contemplated to be encompassed within the scope of the invention. Such additional components may include, for example, sensors for pressure, temperature, flow rates, and the like, that may be placed at strategic locations along the flow lines, to obtain real time information of various parameters in the RO system.

[0031] The optimizer module may be connected to any of the additional components, such as sensors, to obtain more real time inputs of the operation. One skilled in the art will understand that it need not be connected to all of the components, or in some situations, none of the components at all. In the latter case, the dynamic characteristics are manually input or estimated through other means, and then used in the model to obtain the individual product water flow rate. The optimizer module may be made available as a software on a hardware in the form of a distributed control system (DCS), programmable logic controller, standalone software that works with control system or other microprocessor based embedded systems. The optimizer module may further be made available as a dedicated hardware or may be installed as a software tool on an existing programmable system, such as a computer with sufficient computing capabilities. Thus, in yet another aspect, the invention provides a tool that uses the method of the invention.

[0032] In another aspect, the invention provides a method of operating a reverse osmosis (RO) unit, shown in flow chart representation in Fig. 2 and depicted by numeral 10. The method comprises identifying at least one objective constraint, by numeral 12 as already described herein. The method then involves calculating at least one optimal set point for at least one decision variable associated with the at least one objective constraint, by numeral 14 as described in the steady state model of the invention. The method then includes the step of estimating a value for at least one operating variable associated with the at least one decision variable, depicted by numeral 16 using the dynamic model shown herein. Subsequently, the RO unit is operated at the value of the at least one operating variable as shown by numeral 18. The method also includes (i) estimating optimal set point(s) for the decision variable(s) using steady state model, and (ii) estimating operating variable(s) for the corresponding optimal set point (s) using the dynamic model described herein. The estimated optimal set points are implemented via the corresponding estimated operating variables. This ensures more appropriate operation of the RO unit to achieve the at least one objective constraint set forth.

[0033] The method of invention can be used as an off-line application wherein the estimation is done independently using the necessary computing requirements, and subsequently, the solution applied to the operation of the RO unit. Alternately, the method of the invention may also be advantageously used as an on-line application, wherein the computing equipment required to solve the optimization problem is also connected to the RO unit. In the latter embodiment, the method of the invention also includes monitoring the predicted variables, and accordingly, if necessary, adjusting the at least one operating variables dynamically. One skilled in the art will recognize that operating an RO unit using the method of the invention will result in optimized energy consumption, thus resulting in considerable savings in costs while maintaining productivity and quality of product water.

[0034] While only certain features of the invention have been illustrated and described herein, many modifications and changes will occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

We Claim:

1. A reverse osmosis (RO) system comprising:

a water intake pump to provide a feed water;

5 a pre-treatment section to pre-treat the feed water to provide a pre-treated water;

a membrane section comprising:

a high pressure pump for increasing an input pressure for the pre-treated water to yield a high pressure water,

10 a membrane train to process the high pressure water to provide a product water and a reject stream having energy,

a post-treatment section to process the product water,

energy recovery device to recover energy from reject stream giving rise to waste stream,

at least one valve to control the flow of waste stream, and

15 a recirculation pump attached to energy recovery device;

an optimizer module to estimate a value for at least one operating variable associated with at least one decision variable, wherein the at least one decision variable is associated with at least one objective constraint; and

20 a control module for operating the RO unit at the estimated value of the at least one operating variable;

wherein the RO system is characterized by

a total energy consumed,

wherein the energy recovered by energy recovery device impacts the total energy consumed by the RO system, and

wherein the at least one decision variable is selected from a group consisting of flow rate at high pressure pump; pressure at high pressure pump outlet; flow rate at re-circulation pump; pressure of low pressure brine reject stream; or combinations thereof..

2. The RO system of claim 1 further comprising sensors to measure operation
5 parameters.

3. A method of operating a reverse osmosis (RO) unit, wherein the RO unit comprises at least one RO membrane train, at least one energy recovery device to recover energy from reject waste stream, at least one pump, at least one valve, wherein the method comprises:

10 identifying at least one objective constraint;

calculating at least one optimal set point for at least one decision variable associated with the at least one objective constraint;

estimating a value for at least one operating variable associated with the at least one decision variable; and

15 operating the RO unit at the estimated value of the at least one operating variable,

wherein the method is characterized by

the RO unit associated with a total energy consumed,

the energy recovered by energy recovery device impacts the total energy consumed by the RO system, and

20 the at least one decision variable is selected from a group consisting of flow rate at high pressure pump; pressure at high pressure pump outlet; flow rate at re-circulation pump; pressure of low pressure brine reject stream; or combinations thereof..

4. The method of claim 3 further comprising repeating the estimating a value for at least one operating variable at periodic intervals or on a real time basis.

25 5. The method of claim 3 wherein the at least one objective constraint is selected from a group consisting of maximization of permeate flow rate or recovery rate;

minimization of specific energy consumption; maximization of the profit; or combinations thereof.

6. The method of claim 3 wherein the at least one operating variable is selected from a group consisting of high pressure pump speed; re-circulation pump speed; brine reject
5 valve opening; or combinations thereof.

7. The method of claim 3 wherein the at least one operating variable is estimated by minimizing a model predictive control objective function.

8. The method of claim 3, wherein the method is made available in the form of a distributed control system (DCS), programmable logic controller, or any other
10 microprocessor based embedded systems.

9. A tool that uses the method of claim 3.

10. A reverse osmosis system that comprises the tool of claim 9.