Title: Maintenance and Performance Optimization of Reverse Osmosis Systems: Enhancing Membrane Lifetime and Winter Operation Management

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Abstract

Nowadays, the use of reverse osmosis systems is considered one of the most effective methods for water treatment in industries, drinking water supply, and pharmaceutical applications. Reverse osmosis membranes are semi-permeable membranes capable of removing a large portion of ions, mineral salts, suspended particles, microbiological contaminants, and organic pollutants, thereby producing high-purity water. However, achieving stable performance and an acceptable operational lifetime for these systems requires adherence to proper maintenance principles, continuous performance monitoring, and effective management of operating conditions, and is always associated with various challenges.

One of the most important challenges is membrane scaling and fouling phenomena. The deposition of mineral and organic compounds on the membrane surface can lead to a reduction in permeate water flux and system efficiency, while also affecting salt rejection performance. Therefore, to improve the durability and stability of membrane systems, appropriate pretreatment processes must be implemented, and water hardness should be reduced as much as possible. Chemical cleaning is one of the essential measures for restoring membrane performance after fouling-induced decline.

In addition, preventive maintenance practices, including daily monitoring of feed pressure, permeate flow rate, pressure drop across filters, inspection of pumps and mechanical components, control of temperature and PH, and evaluation of feed water quality, play a crucial role in maximizing membrane service life. Another major operational challenge in reverse osmosis systems is proper operation and membrane protection during winter conditions, as temperature reduction can lead to cracking and mechanical damage to membranes. The design and implementation of a comprehensive maintenance strategy and precise adjustment of operational parameters not only enhance membrane lifetime and produced water quality, but also reduce maintenance and replacement costs, while preventing unexpected shutdowns and disruptions in water treatment systems.

Keywords: Reverse Osmosis; Water Treatment; Membrane System; Preventive Maintenance; Scaling and Fouling

1. Introduction

Structurally, a reverse osmosis (RO) membrane is a multilayer polymeric composite membrane composed of a thin surface layer acting as the active layer and one or more porous layers serving as support layers [1]. In this type of membrane, separation is based on solubility and permeability, and the approximate pore size is less than 0.001 microns. The extremely small pore size enables RO systems to be widely used in seawater desalination and in the complete removal of ions and dissolved salts from water [2].

In the design of a reverse osmosis system with high efficiency and acceptable production capacity, in addition to the composite properties of the membrane, the module design and arrangement of membrane sheets play a significant role. Industrial-scale membrane modules are typically manufactured in the spiral-wound configuration (Figure 1). This type of module consists of multiple flat membrane sheets and spacers that are wrapped around a central tube, providing the final pathway for the collection and discharge of purified water, known as permeate [3]. In this configuration, two membrane sheets are assembled in the form of an envelope in which three sides are completely sealed and only one side remains open. A thin mesh-like layer is placed between the two membrane sheets inside the envelope. This layer, referred to as the permeate spacer, provides a channel for directing purified water toward the central tube. In the fabricated membrane envelope, the active layer faces the outside of the envelope, and the open side of the envelope is positioned on the central tube. In addition, another mesh spacer, known as the feed spacer, creates spacing between membrane envelopes and, in addition to generating uniform flow distribution for the feed stream, prevents membrane sheet compaction and fouling [2,4].

In reverse osmosis membrane systems, pressurized feed water enters the vessel containing the membrane module and flows parallel to the membrane surface through channels created by the feed spacer. Water molecules pass through the active membrane layer and enter the permeate spacer channel. The purified water is then directed toward the central tube, where it is collected. The concentrated stream, referred to as concentrate or rejection, which contains impurities and fails to pass through the membrane, exits the module from the opposite end [2,3]. Studies have shown that there is a linear relationship between membrane surface roughness and permeate flux in cross-linked polyamide networks. An increase in surface roughness enhances permeability and increases permeate water flux [5]. Highly cross-linked structures result in higher salt rejection but lower water flux, whereas lower cross-linking leads to higher permeate flux accompanied by reduced salt rejection. Factors affecting the performance of reverse osmosis membranes include feed water characteristics, operating conditions, pretreatment design and quality, maintenance and repair practices, and environmental conditions. Improving the performance of reverse osmosis systems after commissioning and extending the lifetime of membrane modules depend on providing suitable operating conditions and eliminating damaging factors [6]. Zhu and Elimelech [7] examined the effects of physicochemical interactions caused by silica colloids on the fouling behavior of composite reverse osmosis membranes made of cellulose acetate and aromatic polyamide. Their results showed that colloidal fouling increased with increasing ionic strength, colloid concentration in the feed, and permeate water flux. Elimelech et al. [8] investigated fouling behavior of thin-film composite cellulose acetate and aromatic polyamide membranes under identical initial permeate flux conditions.

The results indicated that polyamide membranes exhibit a higher tendency for surface fouling compared to cellulose acetate membranes, primarily due to their rougher and more uneven surface structure. In this review, the challenges associated with reverse osmosis membrane elements and the underlying causes are presented, followed by a discussion of maintenance principles for membrane modules and methods for controlling performance parameters under both daily operation and harsh conditions. Feed water characteristics are introduced, and the overall pretreatment process and its importance are described.
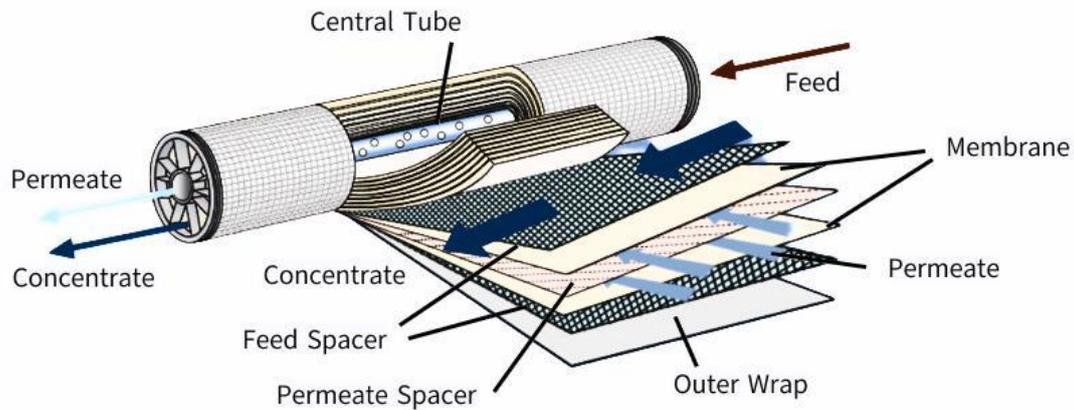

Figure 1. Spiral-wound RO membrane module schematic.

2. Methodology and Data Sources

In this study, relevant articles and scientific resources published between 1997 and 2025 were reviewed and analyzed. The primary criterion for selecting these articles was thematic relevance, with all selected sources addressing the principles of proper maintenance and operation of reverse osmosis systems.

The applied methodology consists of three main components: collection of literature based on the research topic, conceptual analysis and comparative synthesis of findings, and identification of challenges along with presentation of strategies to address them. Implementing a structured maintenance program not only enhances membrane life time and system reliability, but also significantly reduces operational cost and unexpected downtime in industrial water treatment facilities. In the following sections, challenges and operational issues encountered before and after system commissioning are discussed. Subsequently, proper maintenance practices under normal daily operation and during harsh seasonal conditions are examined.

3. Operational Challenges and Objectives

A critical challenge during the operation of reverse osmosis systems is the quality of the feed water, which directly affects membrane performance and service life.

Determining feed water quality and defining acceptable ranges for quality parameters such as microorganisms, total hardness (TH), biochemical oxygen demand (BOD), chemical oxygen demand (COD), turbidity, and total dissolved solids (TDS) are among the most critical factors in preserving membrane lifetime. Therefore, membrane fouling rate and intensity must be controlled primarily through feed water quality management [9].

The feed water entering RO membranes should, as much as possible, have low hardness and low suspended solids within predefined limits so that fouling effects occur over a longer period. Periodic physical cleaning can be applied to remove loosely bound deposits and delay the need for chemical cleaning. Physical cleaning removes deposits by increasing cross-flow velocity, reversing the flow direction, inducing turbulence, or flushing with treated water [10].

When fouling reaches a level that cannot be mitigated by physical methods, chemical cleaning becomes necessary. Timely and periodic cleaning, combined with appropriate pretreatment process design, can maintain membrane modules and improve performance. Operating conditions such as pressure, temperature, feed flow rate, pH, and recovery rate significantly impact membrane performance and service life. Recovery is defined as the percentage of feed water converted into permeate within the membrane module [11]. Low operating pressure results in lower water production with reduced energy consumption, whereas high pressure increases production but reduces membrane lifetime due to increased mechanical stress. Higher temperatures increase permeate flux but intensify fouling due to higher recovery rates and increased salt concentration near the active surface. High recovery rates lead to concentrate enrichment and increased fouling potential; insufficient flow exacerbates fouling and reduces production capacity [11,12].

Chemical cleaning can restore permeate flow, but it contributes to membrane wear; after each cleaning cycle, membrane performance declines and never fully returns to its initial state [14]. Therefore, fouling prevention through effective pretreatment is more important than temporary remediation through cleaning [11]. Figure 2 illustrates an RO membrane module before and after chemical cleaning. Environmental conditions, particularly winter temperatures, can cause freezing and mechanical damage to membrane structure [15]. Sudden pressure fluctuations, vibration, and mechanical shock can also severely affect RO systems. The objective of this review is to present optimized and systematic approaches for daily, seasonal, and annual maintenance to improve production performance while ensuring membrane integrity.

Figure 2. RO membrane module before and after chemical cleaning.

4. Analysis and Discussion

In this section, the principles of daily maintenance and performance enhancement of reverse osmosis systems, extension of membrane lifetime after operation, and performance management under winter conditions are described.

4.1 Daily Maintenance and Performance Enhancement of Reverse Osmosis Systems

Achieving reliable performance in reverse osmosis systems, along with high-quality and high-capacity water production and extended membrane service life, requires daily site inspection and continuous system performance monitoring [16]. Daily monitoring is the simplest and most cost-effective approach to membrane maintenance and prevention of major failures. The pressure differential (ΔP) between the inlet and outlet of the membrane is a key indicator of membrane integrity. An increase in inlet–outlet pressure drop usually indicates membrane fouling caused by organic or inorganic deposits [17]. Monitoring produced water quality via electrical conductivity (EC) and total dissolved solids (TDS) in both feed and permeate streams enables evaluation of system efficiency [11].

Data logging systems that automatically measure and record key parameters such as temperature, pressure, flow rate, and water quality support performance trend analysis and preventive maintenance [18]. Optimal recovery and concentrate flow must be balanced to maximize production while avoiding excessive salt concentration and fouling risk. Typical optimized recovery values for each element are around 8% for seawater and 15% for brackish water [22]. Daily rinsing before shutdown in intermittently operated systems can reduce fouling and CIP frequency [20]. Data-driven approaches can optimize cleaning schedules using long-term operational data and forecasting [21].

Figure 3. Daily monitoring and maintenance of RO systems.

Table 1. Important operational parameters to monitor during start-up and operation.

Daily monitoring parameter	Unit	Purpose of monitoring	Normal range
Feed pressure	bar	Check pump performance and applied pressure on the membrane surface	According to system design
Concentrate pressure	bar	Identify pressure drop	According to system design
ΔP (Pressure difference)	bar	Detect scaling/fouling or technical defect	Less than specified threshold
Permeate flow rate	m³/h	Evaluate production efficiency	Stable with allowable fluctuation
Concentrate flow rate	m³/h	Control hydraulic balance of the system	According to system design
Recovery	%	Prevent increase of salt concentration at the active surface	According to system design
EC Feed	µS/cm	Evaluate feed water quality	Feed water quality
EC Permeate	µS/cm	Evaluate produced water quality and membrane integrity	As low as possible
Feed TDS	mg/L	Monitor salt load in feed stream	Feed water quality
Permeate TDS	mg/L	Control produced water quality	According to standard
Feed temperature	°C	Performance correction and data review	20–25°C
PH of Feed	-	Prevent chemical damage to the membrane	6.5–8.5
Operating time	h/day	Performance analysis and scheduling for CIP	Stable, continuous (no shutdown)

4.2 Increasing Membrane Lifetime after Operation

Reverse osmosis membranes require continuous maintenance and performance monitoring to preserve service life and efficiency. Regular monitoring enables early detection of fouling indicators and timely cleaning. Effective pretreatment prior to feed water entry is essential.

For microbiological contamination, initial disinfection may be required. Chlorination oxidizes iron and enables removal by physical treatment; however, free chlorine can oxidatively degrade polyamide membranes. Hydrogen peroxide can be an alternative oxidant under certain conditions. Physical pretreatment with sand filters, carbon filters, and cartridge filters reduces turbidity and total suspended solids (TSS). Activated carbon also removes residual chlorine.

Before high-salinity and high-hardness feed enters RO, antiscalants are added to stabilize ions and prevent carbonate/sulfate scale formation. Indices such as LSI, SSI, and CCPP can be used to predict scaling tendency. Common antiscalants include SHMP, organophosphonates, and polyacrylates; organophosphonates and polyacrylates are generally recommended due to stability [11]. Membrane pretreatment methods such as MF/UF (and in some cases NF) can further reduce particles, bacteria, and colloids [19,28]. Ultimately, RO membranes remove approximately 95–99% of dissolved salts.

Table 2. Specified feed water quality limits for RO membrane elements.

Physical/General Parameter	Typical Maximum Limit	Purpose of Limit
Silt Density Index (SDI)	<5 or Ideal <3	Importance in fouling potential from suspended/colloidal particles
Turbidity	<1.0 NTU or Ideal <0.2 NTU	Low turbidity is essential for low SDI
Temperature	5°C–45°C (by membrane)	Affects membrane permeability, flux, and pressure requirement
PH Range	Typically, 2–11	Must be controlled to prevent hydrolysis of the polyamide layer
LSI / S&DSI	<0 for scaling ions	Must be negative to prevent $CaCO_3$ scaling with acid/antiscalant
Silica	<150 mg/L	Prevents hard and irreversible silica/silicate scale formation
Free Chlorine	<0.1 mg/L or Ideal: 0	Polyamide killer; must be removed by activated carbon
Total Organic Carbon (TOC)	<3–5 mg/L	High TOC leads to biofouling and organic fouling
Oil and grease	<0.1 mg/L	Fouls membrane
Dissolved Fe, Mn	<0.05–0.1 mg/L	Often removed by oxidation/filtration
Dissolved Al	<0.1 mg/L	A powerful foulant
Heavy metals (Cu, Zn, Cr)	Low level	Can catalyze oxidation or hydroxide formation

Chemical cleaning becomes mandatory when at least one of the following conditions occurs: a 10% decrease in normalized permeate flow, a 5-10% increase in normalized salt passage, or 10-15% increase in pressure differential across a stage [17]. The objective of chemical cleaning is restoration of normal membrane performance, including permeate flow, pressure drop and water quality. Cleaning flow direction should match normal operating direction to prevent telescoping of membrane element. For example, in the presence of calcium carbonate scaling, a 0.2% HCl solution at 25°C and PH 1-2 is recommended as cleaning solution [17,19]. When multiple modules exist in site, each module should ideally be cleaned separately using fresh chemical solution.

4.3 Performance Management under Winter Conditions

Proper operation of reverse osmosis systems during winter conditions is highly sensitive, as low temperatures can reduce performance and cause freezing of components, leading to serious damage to membranes and auxiliary equipment [16]. Within 15–35°C, for each 1°C decrease in temperature, permeate production decreases by approximately 3% [24].

Key recommendations include maintaining feed temperature in an ideal range (approximately 20–25°C) and avoiding temperatures below 5°C, insulating and protecting equipment, draining water from modules and pipelines during shutdowns, and using compatible preservation solutions for longer shutdown periods. According to standards, sodium bisulfite solutions (0.5–1%) or propylene glycol solutions (20–30% by weight) can be used as preservation agents for RO membranes, depending on membrane type and shutdown duration [1,2]. Preservation solutions should be checked periodically during long shutdowns and systems should be restarted gradually to avoid thermal shock [27]. Continuous monitoring of feed temperature, pump pressure, permeate and reject flow rate, electrical conductivity and pretreatment filter is essential during winter condition.

As a membrane manufacturer, understanding operational challenges and long-term performance is essential for developing durable and high-performance RO element. Continuous research and field data analysis enable the improvement of membrane structure, surface chemistry and resistance to fouling and harsh environmental conditions.

5. Conclusion

The most significant challenge in the operation of reverse osmosis (RO) systems is membrane scaling and fouling. Inadequate control of feed water quality intensifies this phenomenon, which can be significantly mitigated through appropriate pretreatment processes. Also, optimization of operating parameter such as pressure and recovery can delay fouling formation. Adherence to daily and long-term maintenance principles including operational parameter control, feed water quality monitoring, and proper pretreatment substantially extends system service life. Nevertheless, fouling is inevitable over time and periodic mechanical and chemical cleaning is essential to restore performance. A comprehensive maintenance program that includes effective pretreatment, continuous monitoring, timely cleaning, application of anti-fouling techniques, operation within design limits, systematic data recording, and adherence to manufacturer recommendations maintains performance and increases operational lifespan.

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