



Article

Analysis of the Effect of Inlet Pressure and Feed pH on Permeate Conductivity Stability in a Reverse Osmosis Unit at a Coal-Fired Power Plant

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ABSTRACT

The Reverse Osmosis (RO) unit in the Water Treatment Plant (WTP) of a coal-fired power plant plays a vital role in producing low-conductivity demineralized water for boiler feed. Permeate quality stability is strongly influenced by operating conditions, particularly inlet pressure and feed pH. This study evaluates the effects of inlet pressure and feed pH, both partially and simultaneously, on permeate conductivity as an indicator of RO performance stability. A quantitative approach was applied using industrial operational data obtained from the SCADA system and log sheets from 8 November 2025 to 30 January 2026. Twenty data points under normal operating conditions without cleaning in place (CIP) were analyzed over an inlet-pressure range of 0.57-0.65 MPa and a pH range of 8.32-8.83. Multiple linear regression and coefficient of variation (CV) analysis were used. The results show that inlet pressure significantly affects permeate conductivity (p -value < 0.05) with a positive regression coefficient. Feed pH also has a significant effect (p -value < 0.05), with a negative regression coefficient (-0.5456). Simultaneously, both variables have a significant effect, with a coefficient of determination (R^2) of 82.24%. These findings confirm that inlet pressure and feed pH are dominant parameters and should be jointly controlled to maintain stable permeate quality in industrial RO operation.

1. Introduction

High-quality water availability is a critical factor in the operation of coal-fired power plants. Boiler feedwater must meet specific quality standards, particularly for total dissolved solids (TDS), conductivity, and ions that can promote corrosion or scaling [1]. Poor water quality may reduce heat-transfer efficiency, cause scale formation and corrosion in piping and equipment, and increase maintenance costs [2]. Therefore, the Water Treatment Plant (WTP) plays a strategic role in ensuring continuity and reliability of power-plant operation [3].

One of the main units in a modern WTP is Reverse Osmosis (RO) [4]. RO operates on the principle of reverse osmosis, in which external pressure is applied to overcome natural osmotic pressure so that water molecules pass through a semipermeable membrane while ions and other dissolved substances are retained [5]. RO separation performance is influenced by operating parameters such as inlet pressure, temperature, membrane characteristics, feed-water chemistry, and solution pH [6]. Among these parameters, inlet pressure and feed pH directly affect membrane separation performance and operational stability [7].

Inlet pressure acts as the driving force in reverse osmosis [8]. Theoretically, increasing pressure increases permeate flux and product-water flow rate [9]. However, uncontrolled pressure increases can accelerate fouling, cause membrane compaction, and change salt-rejection characteristics [10]. Pressure variations within the operating range may also affect the stability of permeate conductivity, which is a key indicator of product-water quality [11].



Feed pH influences the chemical speciation of dissolved ions and the potential for scaling on the membrane surface [12]. Changes in pH can affect membrane surface charge and electrostatic interactions between the membrane and dissolved ions [13]. At certain pH levels, ion rejection may improve, whereas at other conditions the risk of precipitation of inorganic compounds such as calcium carbonate or magnesium hydroxide may increase [14]. Therefore, pH control is important for maintaining long-term RO stability [15].

In industrial operation, fluctuations in permeate conductivity are often used as an early indicator of changes in membrane performance or imbalanced operating conditions [16], [17]. Increased conductivity indicates a higher concentration of dissolved ions in the permeate and can directly affect boiler feedwater quality [18]. Nevertheless, quantitative studies that simultaneously evaluate the effects of inlet pressure and feed pH on permeate-conductivity stability under actual coal-fired power-plant operating conditions remain limited [19].

Most previous studies have focused on laboratory-scale experiments or single-parameter optimization [20]. Statistical approaches using multiple linear regression to analyze the partial and simultaneous effects of operating variables on permeate quality in actual industrial systems have been less frequently reported [21]. This indicates the need for operational-data-based evaluation to provide a more accurate and applicable basis for process control [22].

Based on this background, this study evaluates the effects of inlet pressure and feed pH on the performance stability of the Reverse Osmosis unit in the WTP of a Harita Group coal-fired power plant in North Maluku, using permeate conductivity as the evaluation parameter. Partial and simultaneous analyses were performed using multiple linear regression to determine the significance of each variable and their combined contribution to conductivity variation. The results are expected to provide a technical basis for operating-parameter control to improve RO stability and reliability.

2. Research and Methodology

2.1. Research Location and Period

The study was conducted at the Water Treatment Plant of a coal-fired power plant operated by one of the Harita Group companies in North Maluku, specifically at the RO unit. Daily operational data from 8 November 2025 to 30 January 2026 were used because they were available and representative of normal RO operating conditions.

2.2. Equipment and Data

The equipment used in the study comprised the existing Reverse Osmosis (RO) system at the WTP, the DCS/SCADA system or operating log sheets, and Microsoft Excel for data processing. The study used RO operating data consisting of inlet pressure, feed pH, Silt Density Index (SDI), temperature, Oxidation-Reduction Potential (ORP), and permeate conductivity.

2.3. Research Procedure

The study was carried out through integrated stages covering treatment selection, data collection, and data analysis. The initial stage selected data from RO operating periods that had reached steady state, defined as at least 20 minutes after a change in inlet pressure and feed pH. Four pressure-pH combinations (P-pH) were evaluated: P-pH 1 (8 December 2025), P-pH 2 (12 December 2025), P-pH 3 (16 December 2025), and P-pH 4 (23 December 2025). Five data points were collected for each treatment combination at 120-minute intervals, resulting in 20 analyzed data points. Data were included only when the RO unit was operating normally, without cleaning in place (CIP), without process disturbances, and with all control variables within their normal operating ranges.

Data were collected from historical SCADA records and RO operating log sheets and were filtered according to the inlet-pressure and feed-pH ranges of each treatment combination. Each data point was verified as being obtained under steady-state, non-CIP conditions. Recorded parameters included inlet pressure, feed pH, permeate conductivity, ORP, SDI, and temperature, which were then compiled according to treatment combination and replicate. Data analysis was carried out in stages using descriptive statistics (mean, standard deviation, and coefficient of variation), partial-effect analysis, simultaneous-effect analysis, evaluation of RO performance stability, and comparison with control variables.

3. Results and Discussion

3.1. Effect of Inlet Pressure on RO Permeate Conductivity

As shown in Figure 1, the relationship between inlet pressure and permeate conductivity tends to be positive, with higher pressure followed by higher permeate conductivity [10]. This pattern is consistent with the regression results, which show statistical significance (p -value < 0.05), as summarized in Figure 1.

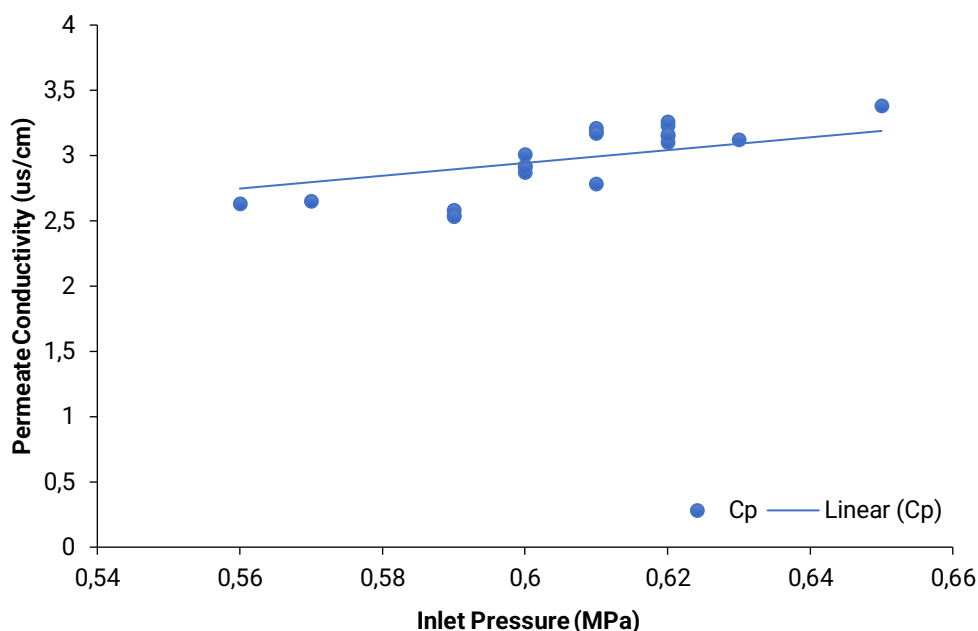


Figure 1. Effect of inlet pressure on permeate conductivity.

Figure 1 indicates that pressure significantly affects conductivity. Although the observed inlet pressure operated within a narrow range of 0.57-0.65 MPa and remained within the normal operating range, the regression coefficient was positive. This suggests that the RO system was highly sensitive to changes in driving force [11].

Theoretically, a clean membrane would be expected to show a negative relationship in which an increase in pressure is followed by a decrease in conductivity. In this study, however, the regression was positive, meaning that higher pressure was followed by higher conductivity. This behavior is associated with salt forcing under high-recovery conditions. Because the data were collected without CIP, the membrane surface was likely covered by a fouling layer. When pressure increased, the driving force pushed not only water but also salt ions trapped within the fouling layer through the membrane. If salt penetration increased faster than water flow because of fouling resistance, the dissolved-solute concentration on the permeate side increased [12].

According to basic membrane theory, a fouling layer may induce cake-enhanced concentration polarization, causing solute accumulation at the membrane surface and inhibiting salt back-diffusion. This reduces salt rejection and increases salt passage [13].

3.2. Effect of Feed pH on RO Permeate Conductivity

Table 1. Permeate-conductivity stability for each treatment.

Treatment	Mean Permeate Conductivity (μS/cm)	Standard Deviation (σ)	Coefficient of Variation (%)
P-pH 1	3.21	0.04	1.14
P-pH 2	2.90	0.08	2.88
P-pH 3	3.18	0.11	3.56
P-pH 4	2.59	0.05	2.06

As shown in Table 1, RO operating stability, represented by the coefficient of variation (CV) of permeate conductivity, differed among treatments. The best stability was obtained for P-pH 1 with a CV of 1.14%, whereas the lowest stability occurred for P-pH 3 with a CV of 3.56%. The increase in CV indicates that higher feed pH tended to increase fluctuations in permeate conductivity and reduce RO operating stability.

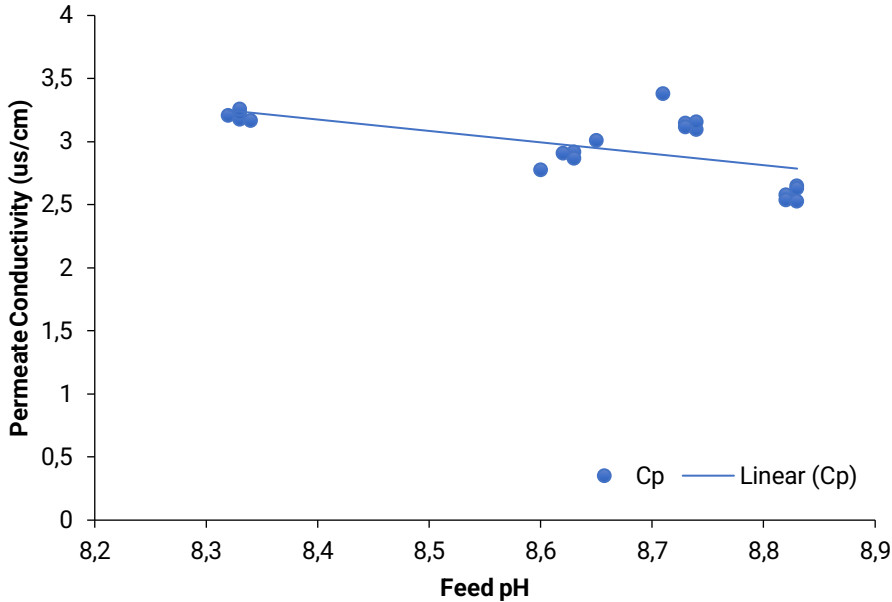


Figure 2. Effect of feed pH on permeate conductivity.

The partial-effect analysis in Figure 2 shows a tendency for average permeate conductivity to decrease at higher pH values, consistent with the negative regression coefficient -0,54564 at p-value 0,00259. The negative coefficient indicates that increasing feed pH tends to reduce average permeate conductivity. From a permeate-quality perspective, a higher pH therefore produced water with lower conductivity and indicated improved ion rejection by the RO membrane.

Although higher feed pH can lower average permeate conductivity, it does not necessarily improve performance stability. At higher pH, the risk of inorganic scaling, particularly calcium carbonate (CaCO₃), tends to increase. Scaling may change flow resistance and membrane-surface characteristics nonuniformly, making membrane separation performance more variable [23], [24], [25].

Consequently, even when average permeate quality improves, temporal variation in membrane performance may become larger, as reflected by an increase in the CV of permeate conductivity. This

explains why treatments at higher pH produced lower average permeate conductivity but poorer operating stability [14].

The implication is that feed-pH control in an RO unit should not focus solely on achieving the lowest permeate conductivity. Operating stability must also be considered. Excessively high feed pH can increase scaling risk, reduce membrane-performance stability, and increase the required CIP frequency even when average permeate conductivity improves.

3.3. Simultaneous Effect of Inlet Pressure and Feed pH

Based on the multiple linear regression results, the Significance F value was $4,17 \times 10^{-7}$, which is far below the significance level of $\alpha = 0.05$. This result demonstrates that inlet pressure and feed pH simultaneously have a significant effect on permeate-conductivity fluctuations in the investigated RO unit.

Furthermore, the coefficient of determination (R^2) of 0.82243 indicates that the regression model explains 82.24% of the variation in permeate conductivity under the observed operating conditions. This value reflects the strong explanatory power of the model for RO operational data within the limited ranges of pressure and pH considered.

Thus, the high R^2 value indicates that within the analyzed normal operating range, inlet pressure and feed pH are dominant operating parameters affecting permeate-conductivity variation. Approximately 17.76% of the variation remains attributable to factors outside the model, such as membrane-fouling condition, local scaling distribution, and variations in control variables that were not included as independent variables.

Physically, the observed permeate-conductivity fluctuations result from the interaction between the mechanical driving force of inlet pressure and ion-rejection mechanisms affected by feed-water chemistry, particularly pH. Increasing inlet pressure increases the driving force for ion transport through the membrane, whereas pH control affects membrane surface charge and dissolved-ion speciation. If higher pressure is not balanced by optimal pH control, salt penetration tends to increase, especially when fouling or scaling layers add resistance and destabilize separation performance [15].

Therefore, the simultaneous analysis confirms that inlet pressure and feed pH should be controlled in an integrated manner to maintain stable permeate conductivity under actual RO operating conditions.

This study was conducted using actual operational data obtained from an industrial Reverse Osmosis unit operating under normal plant conditions. Consequently, the analyzed inlet-pressure range (0.57-0.65 MPa) and feed-pH range (8.32-8.83) were relatively narrow and reflected only the routine operating window of the system. In addition, the dataset was limited to periods without Cleaning in Place (CIP) and major process disturbances to ensure operational consistency. Therefore, the statistical relationships identified in this study should be interpreted within the investigated operating conditions and may not fully represent RO performance under wider pressure and pH ranges, different membrane-fouling conditions, or other industrial settings. Nevertheless, the results provide valuable insights into the dominant operating factors affecting permeate conductivity stability under actual coal-fired power plant operating conditions.

3.4. Operational Implications for WTP Operators

The results indicate that inlet pressure should be carefully controlled during RO operation. Increasing pressure under fouled membrane conditions does not necessarily improve permeate quality and may even increase ion passage through the membrane. Therefore, operators should maintain pressure within the recommended operating range and avoid excessive pressure increases as a corrective measure for declining membrane performance.

Feed pH is another critical operational parameter. Although higher pH values were associated with lower average permeate conductivity, excessive pH may increase the risk of inorganic scaling, particularly calcium carbonate precipitation. Previous studies have reported that scaling can reduce membrane performance stability and increase cleaning frequency [15].

Furthermore, monitoring the coefficient of variation (CV) of permeate conductivity may provide an effective early warning indicator of membrane fouling and scaling. Continuous monitoring through SCADA systems can support proactive maintenance strategies before significant deterioration of water quality occurs. Overall, the findings suggest that inlet pressure and feed pH should be controlled simultaneously rather than independently. An integrated operating strategy can improve permeate-quality stability and support long-term RO performance under industrial operating conditions.

4. Conclusion

Based on the analysis and discussion, the following conclusions can be drawn: (1) inlet-pressure variation significantly affected permeate conductivity (p -value < 0.05) with a positive relationship; under fouled-membrane conditions, higher inlet pressure may be followed by higher permeate conductivity because of increased ion penetration; (2) feed pH significantly affected permeate conductivity (p -value < 0.05) with a negative regression coefficient of -0.5456 , higher pH tended to lower average permeate conductivity but may affect membrane operating stability; and (3) inlet pressure and feed pH simultaneously had a significant effect on permeate-conductivity fluctuations, with $R^2 = 82.24\%$, indicating that most of the conductivity variation under the observed operating conditions was explained by the combination of these two parameters. Future studies should evaluate inlet pressure and feed pH over wider operating ranges and more specifically consider the degree and type of membrane fouling. Additional water-quality parameters, such as TDS and specific ions, should be included to clarify ion-rejection mechanisms and scaling potential. Long-term operational-data-based predictive models are also recommended to support more optimal and sustainable pressure and pH control.

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