

## **Treatment of Borehole Water for Steam Generation (Case study: Port Harcourt Refining Company (PHRC) Area 5 Plant)**

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### **Abstract**

Efficient boiler operation relies heavily on high-purity feed water, as impurities such as silica, dissolved ions, suspended solids, and dissolved gases cause scale formation, corrosion, thermal inefficiencies, and equipment damage. At the Port Harcourt Refining Company (PHRC) Area 5 Plant, mixed-bed ion exchangers are used to produce demineralised water, but their performance depends strongly on the optimisation of sulfuric acid and sodium hydroxide regenerant strengths and still, this does not guarantee a 100% completely treated water. This study investigates the effect of varying acid and caustic concentrations on resin regeneration efficiency, using conductivity and silica measurements taken immediately after final rinse and six hours later to capture delayed breakthrough behaviour and later an introduction of an absorber to further take out remaining traces of impurities (Lead) still present in boiler feed water that has been treated in the ion exchangers. Results show that optimal performance consistently occurs when regenerant concentrations fall within 9.0–11.5%, producing the lowest immediate and six-hour water quality values. Concentrations outside this range caused incomplete ion displacement, elevated conductivity, or delayed silica release. The study also confirms that final-rinse duration and conductivity-based rinse endpoints are essential for long-term stability, as fixed-time rinsing often led to silica breakthrough. Furthermore, conductivity alone was shown to be an unreliable indicator, as silica increased independently in several runs, establishing the need for dual-parameter monitoring. Proper sand-filter maintenance was also found to significantly enhance downstream demineraliser performance. To address breakthrough events and strengthen water polishing, a fixed-bed activated carbon adsorption column was designed using Freundlich isotherm modelling. The resulting design 1.5m diameter, 2m bed height, and 267kg of activated carbon provides an estimated breakthrough time of 4.5 months, offering robust removal of trace contaminants that may bypass the ion-exchange system. Integrating this polishing stage enhances water purity, reduces operational stress on the demineraliser, and supports long-term boiler protection. Overall, this study delivers a validated regeneration protocol with optimised chemical strength, objective rinse endpoint control, and improved pre-treatment practices, enabling the consistent production of boiler feed water with minimal silica and very low conductivity. The combined ion-exchange and adsorption approach provides a reliable treatment pathway for PHRC and similar industrial steam-generation facilities.

### **Keywords:**

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## **I. INTRODUCTION**

During the initial stages of boiler development, feedwater treatment received limited attention because operating pressures and temperatures were relatively low. Under such mild conditions, significant scale buildup and corrosion were uncommon, particularly when boilers were routinely blown down, meaning they were periodically drained to remove accumulated impurities (ASME, 2019). Early corrosion control practices typically involved installing zinc plates or introducing alkaline chemicals into the boiler to mitigate metal degradation. Numerous experimental investigations were carried out using distilled water, different chemical additives, and sacrificial metals to better understand corrosion mechanisms and possible protective measures in boiler systems (ASME, 2019).

The use of lime as an alkalinity control agent dates back to around 1900 and was adopted extensively by both the French and British Navies until approximately 1935 (ASME, 2019). In addition, silver nitrate was historically employed in feedwater testing to detect seawater contamination. In contrast to early boiler systems, modern boilers operate under extreme pressure and temperature conditions, making proper feedwater treatment indispensable. The use of untreated water in such environments can lead to reduced heat transfer efficiency, overheating, mechanical damage, and expensive cleaning operations (Arachchige, 2019a).

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Boilers play a vital role across numerous industrial sectors by supplying both high-pressure and low-pressure steam necessary for continuous and reliable operations (Stultz & Kitto, 2005). To achieve optimal boiler performance, feedwater quality must be carefully controlled, as untreated water introduces serious operational challenges that adversely affect system reliability and efficiency (Khaled et al., 2023; Veolia Water Technologies, 2019). Key objectives of boiler feedwater treatment include extending equipment lifespan, preventing unscheduled shutdowns, protecting internal boiler surfaces, maximizing condensate recovery, and minimizing corrosion and scale formation (Arachchige, 2019a).

High-purity feedwater is essential for the smooth operation of steam generation systems. Reduced blowdown frequency significantly lowers fuel consumption, while lower impurity levels in feedwater decrease corrosion rates and scale formation. For example, producing high-purity steam reduces erosion of turbine blades and other sensitive downstream equipment (Choudhary, 2014a). To mitigate problems such as scaling, corrosion, and steam carryover, industrial boiler systems implement comprehensive water treatment programs. Effective boiler operation relies on accurate inspection procedures, proper sampling techniques, environmental protection practices, enhanced operational performance, and precise water quality analysis. Consequently, the development of advanced technologies and efficient solutions focused on boiler feedwater treatment is essential for overcoming existing challenges (Stultz & Kitto, 2005). In this regard, improvements in system reliability, operational performance, maintenance efficiency, and overall safety represent major outcomes of effective boiler feedwater treatment practices (Nalco water, 2014).

## **II. EXTENT OF PAST WORKS**

Azad & Ismail (2007) investigated the management of silica concentration within the water–chemical regime of high-pressure natural circulation drum boilers used in thermal power plants. The study pointed out that maintaining silica concentration in the boiler drum at  $0.35 \pm 0.15$  mg/L, alongside a pH of  $9.1 \pm 0.1$  and an operating temperature of  $330 \pm 10^\circ\text{C}$ , was essential for minimizing corrosion and scale formation, both of which critically affect boiler reliability and performance.

They further established that effective silica control was strongly dependent on the quality of makeup water supplied to the boiler system. To sustain acceptable silica levels within the boiler drum, the study recommended that the silica concentration in makeup water should be kept below 0.02 mg/L. This low concentration significantly limits silica accumulation and reduces the likelihood of operational disruptions and equipment damage.

While the study provides valuable operational guidance, its scope was restricted to natural circulation drum boilers and does not extend to other boiler configurations such as forced circulation systems, which may exhibit different silica transport and deposition behaviors. Nevertheless, the findings highlight the importance of precise chemical control in ensuring long-term boiler efficiency, operational safety, and reliability within thermal power stations.

The practical implications of this work are substantial. Maintaining silica within recommended limits can significantly reduce maintenance requirements, including descaling and chemical cleaning operations, thereby lowering operational costs. Additionally, the study reinforces the central role of effective water treatment systems in achieving and sustaining target silica concentrations. In summary, although the conclusions are system-specific, the research provides a strong foundation for further studies and the development of improved boiler water treatment and maintenance strategies.

The effect of water quality on the performance of boiler in Nigerian petroleum industry examined the influence of feedwater quality, with particular emphasis on silica concentration, on boiler performance within Nigeria's petroleum sector. Although the authors were not specified, the study offers important insights into the consequences of inadequate water chemistry management in high-demand industrial environments (Ogedenbe et al 2005).

The investigation reported silica concentrations reaching 13 ppm, far exceeding the recommended limit of 1.7 ppm. Such elevated levels indicate significant deficiencies in water treatment practices, which may stem from outdated equipment, insufficient quality control, or operational lapses. High silica concentrations were shown to promote severe scale formation, reducing heat transfer efficiency, increasing fuel usage, and accelerating mechanical deterioration of boiler components. This study by Pertova et al (2007) explored the influence of phosphate concentration on key boiler water chemistry parameters, specifically electrical conductivity and pH. The research provides important insights into managing corrosion and scaling risks in high-pressure boiler systems, where chemical stability is vital for safe and efficient operation.

Boiler water chemistry plays a critical role in power plant and industrial boiler performance. Inadequate chemical control can lead to scale deposition, metal corrosion, and in extreme cases, catastrophic failure. Phosphates are commonly used in boiler treatment to precipitate calcium and magnesium ions, thereby reducing scale formation, while also contributing to pH regulation. The study investigates how varying phosphate concentrations affect conductivity and pH, two fundamental indicators of water chemistry balance.

The key finding is that phosphate concentration significantly influences both parameters. As phosphate levels increase, electrical conductivity rises due to the additional ions introduced into the solution. At the same time, phosphate concentration affects pH, which must be maintained within a moderately alkaline range to protect boiler metals from acidic corrosion. The authors identified an optimal phosphate concentration range that balances effective scale control with minimal corrosion risk. Insufficient phosphate dosing failed to control hardness ions, while excessive dosing can cause issues such as phosphate hideout or localized corrosion.

While informative, the study has limitations. The experiments were conducted under controlled laboratory conditions, which may not fully reflect the complexity of industrial boiler environments. Real-world systems experience fluctuating loads, variable feedwater quality, interactions with other treatment chemicals, and complex flow dynamics. Additionally, the study focuses solely on phosphates, excluding other important water chemistry variables such as dissolved oxygen, sodium levels, alkalinity, and total dissolved solids.

Despite these limitations, the research had important practical implications. It highlights the need for precise chemical dosing and continuous monitoring of boiler water chemistry. The study also emphasizes the benefits of automation and real-time monitoring systems that track pH, conductivity, and phosphate levels, enabling tighter control and early detection of imbalances. By linking phosphate dosing to measurable parameters, the research supports the development of predictive maintenance and diagnostic tools. In conclusion, the study reinforces that phosphate control is a delicate but critical aspect of boiler water treatment, offering guidance for improving performance, reducing maintenance costs, and protecting critical infrastructure.

### **III. MATERIALS AND METHOD**

#### **2.1 Materials Used**

The following materials are utilised in this research:

- i. Sulfuric acid ( $\text{H}_2\text{SO}_4$ ) – cation resin regenerant
- ii. Sodium hydroxide ( $\text{NaOH}$ ) – anion resin regenerant
- iii. Terephthalate
- iv. Laboratory reagents and titrants for routine analysis

#### **2.2 Method Used**

The experimental programme involved controlled regeneration cycles of a mixed-bed demineralization system, during which sulfuric acid ( $\text{H}_2\text{SO}_4$ ) and sodium hydroxide ( $\text{NaOH}$ ) concentrations were systematically varied in line with the experimental matrix. Where necessary, upstream sand filters were cleaned following the standard plant cleaning procedure prior to regeneration. Demineralized water samples were collected immediately after the final rinse stage and again approximately six hours after the unit was returned to service, allowing short-term breakthrough behaviour to be evaluated using conductivity ( $\mu\text{S}/\text{cm}$ ) and silica concentration (ppm) as performance indicators.

##### **2.2.1 Sand Filters and Pre-treatment**

Purpose:

To remove suspended solids and turbidity from influent water, thereby protecting the ion-exchange resins from fouling and channel formation.

Procedure:

Cleaning criterion: Sand filters were cleaned when the pressure drop exceeded  $0.35 \text{ kg}/\text{cm}^2$  or at a maximum interval of 24 hours, whichever occurred first.

Air scouring: The wash-water outlet air escape and drain valves were opened to establish an air space. The air-scour valve was then gradually opened and maintained for five (5) minutes before being closed.

Backwashing: The wash-water inlet valve was slowly opened and backwashing was carried out at a flow rate of  $30 \text{ m}^3/\text{hr}$  for 10 minutes. The outlet was observed for any sand carryover. Every fifth cleaning cycle, the backwash duration was extended to 30 minutes.

Forward rinsing and recommissioning: The inlet valve was opened until water emerged from the air escape, after which the air escape was closed. The drain valve was opened and rinsing was conducted at  $13.6 \text{ m}^3/\text{hr}$  for 3 minutes. The drain valve was then closed and the outlet valve opened, returning the unit to service.

Data recording: For each cleaning cycle, operators documented pressure drop values, visual observations of sand carryover, and the timing of each step. These records were later correlated with conductivity and silica measurements taken after regeneration.

Sand filter cleaning was performed before or during the experimental runs as required to maintain consistent influent water quality to the demineralization unit.

### **2.2.2 Acid (H<sub>2</sub>SO<sub>4</sub>) Variation for Cation Resin Regeneration**

#### **Purpose:**

To assess the influence of sulfuric acid concentration on cation resin regeneration efficiency and its impact on post-regeneration conductivity and silica levels.

#### **Procedure:**

**Acid preparation:** Sulfuric acid regenerant solutions were prepared at concentrations specified in the experimental matrix, covering the range documented in Table 4.1 of the main report.

**Bed preparation and drainage:** Top and bottom drain valves were opened to reduce the bed water level to approximately 50%. The drains were then closed, the air vent and bottom air inlet opened, and the bed air-blown for 5–10 minutes.

**Pre-eduction backwash:** Following air blowing, the top drain and backwash valves were opened and the bed was backwashed for 30–35 minutes, as recorded.

**Pump commissioning and line flushing:** The central drain and caustic inlet valves were opened to flush the lines for 3–5 minutes. The caustic power valve was then closed, the bypass opened for a further 3–5 minutes, and the bed drained via the top and bottom drains.

**Acid eduction:** Power-water flow to the eduction system was reduced to 4 units and the bypass valve closed. The power-water valve to the acid eductor and the acid valve from the eduction tank were opened, allowing acid to enter the bed for the duration specified in the plant schedule.

**Post-eduction rinsing:** Upon completion of eduction, the acid and power-water valves were closed. The bypass line was opened to rinse the bed for 10 minutes at 10 units of water flow. Where required, an additional rinse was carried out via the caustic line at the same flow setting.

**Air-blow and drain cycles:** After rinsing, pumps were shut down, power-water supplies closed, and eduction valves isolated. A small volume of water was introduced to facilitate air blowing. The bed was air-blown for 5 minutes, drained, briefly refilled, and air-blown again, completing the recorded sequence.

**Final rinse and recommissioning:** The bed was filled until water emerged from the vent. The bottom drain was opened and inlet flow reduced. Final rinsing continued until acceptable water clarity and conductivity endpoints were achieved.

**Sampling:** Demineralized effluent samples were collected immediately after final rinsing and again approximately six hours after commissioning. These data points were consistently used across all acid-variation runs and form the basis of the results presented.

### **2.2.3 Caustic (NaOH) Variation for Anion Resin Regeneration**

#### **Purpose:**

To determine the effect of NaOH concentration on anion resin regeneration performance and subsequent conductivity and silica levels.

#### **Procedure:**

**Caustic preparation:** Sodium hydroxide solutions were prepared according to the experimental matrix, covering multiple concentration levels.

**Eduction sequence:** Caustic eduction followed the same hardware configuration and power-water controls as the acid runs. Power-water flow was reduced to 4 units at the start of eduction, and the caustic valve from the eduction tank was opened as specified.

**Rinsing and bypass:** After eduction, the power-water bypass was opened to rinse the bed for 10 minutes at 10 units of flow, followed by additional rinsing steps where required.

**Air-blow and refill:** Air-blow, drain, refill, and second air-blow steps were conducted in the same manner as during the acid regeneration cycles.

**Sampling and records:** Conductivity and silica samples were collected immediately after final rinsing and again after six hours. Final rinse duration was also recorded, as summarized.

### **2.2.4 Monitoring Conductivity and Silica**

#### **Purpose:**

To evaluate regeneration effectiveness and early breakthrough behaviour by comparing conductivity and silica levels before and after regeneration.

#### **Procedure:**

**Instrumentation:** Conductivity was measured in  $\mu\text{S}/\text{cm}$  and silica in ppm using plant laboratory instruments. The Anton Paar density meter was listed among available equipment, and silica analysis followed the established plant method.

**Measurement practice:** Operators adhered to standard laboratory practices, including instrument calibration, avoidance of parallax errors, and proper zeroing prior to measurement.

**Sampling protocol:** Grab samples were taken immediately after the final rinse and again approximately six hours after commissioning. Samples were transferred to the laboratory within 25–40 minutes of collection.

Data logging: Recorded parameters included bed pH, conductivity, silica concentration, final rinse duration, and six-hour follow-up values, forming the dataset presented in Table 4.1.

### 2.2.5 Development and Validation of an Optimized Bed Regeneration Procedure

**Purpose:**

To identify optimal regenerant concentrations and operational steps and to validate a consolidated regeneration procedure capable of achieving consistently low conductivity and silica.

**Procedure:**

**Data collation:** Acid and caustic regeneration runs were reviewed to identify concentration ranges associated with the lowest immediate and six-hour conductivity and silica values, as summarized.

**Procedure consolidation:** A detailed, step-by-step regeneration checklist was developed, incorporating drain-down steps, air-blow timing, extended backwash schedules, eduction sequences with specified power-water settings, rinse durations, and final conductivity endpoints.

**Validation runs:** At least two repeat regeneration cycles were conducted using the consolidated procedure and selected regenerant ranges. Identical data parameters were recorded to confirm reproducibility.

**Operational constraints:** Key procedural constraints were explicitly noted, including the prohibition of simultaneous acid and caustic eduction, verification of eductor power settings, and implementation of extended backwash cycles every five cleanings.

### 2.3 Design Calculations for an Adsorption-Based Polishing Unit

To mitigate residual trace contaminants and provide additional protection against breakthrough events observed in the ion-exchange system (Section 4.4), a fixed-bed adsorption column packed with activated carbon was designed as a downstream polishing unit. This supplementary stage targets trace heavy metals and organic compounds that may bypass ion exchange treatment, particularly during regeneration or early breakthrough periods. The design calculations presented establish the operating specifications and sizing criteria for the adsorption column.

**Design parameters:**

Flow rate into the adsorber  $F_A = 12500\text{ l/hr} = 3.47\text{ l/secs}$

Bulk density  $\rho_b = 0.42\text{ g/cm}^3 = 4.2 \times 10^5\text{ mg/L}$

Heavy metal concentration in influent  $C_{in} = 2.5\text{ mg/l}$

Heavy metal concentration in effluent  $C_{eff} = 0.001\text{ mg/l}$

Fluid velocity  $U_f = 0.2792\text{ m/hr}$

### DESIGN CALCULATIONS

#### Determination of surface loading ( $S_L$ )

The surface loading for adsorption column is usually gotten from literature as a rule of Thumb, the rate should be between 80–400 L/min/m<sup>2</sup>.

Hence  $S_L = 200 \frac{\text{L}}{\text{m}^2\text{-min}} = \frac{3.33\text{L}}{\text{m}^2\text{-s}}$

#### Empty Bed Contact Time (EBCT)

The contact times used vary by type of contaminants, but generally are in the 2–20-minute range, depending of course on the contaminant.

For the 6-minute contact time per column provided by the Activated carbon:

#### Column diameter ( $D_c$ )

$$\text{column area} = \frac{\text{flowrate}}{S_L}$$

$$\text{column area} = \frac{3.47}{3.33}$$

$$= 1.04\text{ m}^2$$

$$D_c = \sqrt{\frac{4 \times 1.04}{3.142}}$$

$$D_c = 1.15\text{ m}$$

Referring to USACE Adsorption Design Guide (2001), we find that the nearest diameter unit is either a 1.54-m (5-ft) A 1.54-m (5-ft) diameter unit has an area equal to 1.86 m<sup>2</sup> (19.6 ft<sup>2</sup>), which makes our loading rate = [(946 L/m)/1.86 m<sup>2</sup>]

#### The Bed Depth (Hb)

*The Bed Volume* = flowrate × EBCT

$$= 12500\text{ L/hr} \times 1\text{ m}^3/1000\text{ L} \times 1\text{ hr}/60\text{ min} \times 6\text{ min}$$

(1)

$$= 1.25m^3$$

$$H_b = \frac{\text{Bed volume}}{\text{column area}} \quad (2)$$

$$H_b = \frac{1.25}{1.04} = 1.20m$$

**Breakthrough time (T<sub>b</sub>)**

The Breakthrough time calculated for two bed series (Yu, 2023):

$$T_b = \frac{0.1\rho_b \times Q \times H_b}{U_o \times C_{in}} \quad (3)$$

Since Freundlich isotherm gave the best fit, the adsorption Q is calculated as:

$$Q_e = K_f C_e^{1/n} \quad (4)$$

Substituting the values of  $K_f$ ,  $n$  and  $C_{in} = 2.5$  mg/L, we have

$$Q_{e1} = 58.17 \times 2.5^{\left(\frac{1}{2.33}\right)} = 94.976 \text{ mg/g}$$

Substituting the values of  $K_f$ ,  $n$  and  $C = 0.3134$  mg/L, we have

$$Q_{e2} = 58.17 \times 0.3134^{\left(\frac{1}{2.33}\right)} = 35.354 \text{ mg/g}$$

$$Q = Q_{e1} - Q_{e2} \quad (5)$$

$$Q = 59.622 \text{ mg/g}$$

**Therefore,**

$$T_b = \frac{0.1 \times 4.2 \times 10^5 \text{ mg/L} \times 59.622 \times 10^{-3} \text{ g/g} \times 1.2m}{0.2792 \frac{m}{hr} \times 3.313 \text{ mg/L}}$$

$$T_b = 3248.629 \text{ hrs} = 4.45 \text{ months}$$

The breakthrough time will be 4 and a half months.

**Adsorption Column**

Operating pressure=1bar

Vessel diameter=1.5m

Vessel height =2m

Material of construction=carbon steel

$$\text{vessel cost} = \text{Empty vessel cost} \times \text{material factor} \times \text{Pressure factor} \quad (6)$$

$$\text{vessel cost} = \$ 6000 \times 1 \times 1$$

This is equivalent to **₦6,000,000**

**IV. RESULTS AND DISCUSSION**

**3.1 Sand Filters and Upstream Pre-treatment**

The operational condition of the sand filters was routinely assessed using differential pressure readings alongside visual checks and turbidity observations. Whenever the measured pressure drop exceeded the defined operating limit, the filter cleaning procedure was initiated. The applied cleaning sequence, comprising air scouring, backwashing, and forward rinsing, consistently restored the pressure drop to values below the set threshold and resulted in visibly clear wash water. Incorporating periodic extended backwash cycles was particularly effective in preventing gradual pressure accumulation over prolonged operation.

Cleaning the sand filters prior to demineralizer regeneration had a clear positive impact on the quality of feed water entering the ion exchange system. After cleaning, the influent exhibited lower turbidity and reduced particulate content. Under these improved conditions, the demineralizer produced consistently lower conductivity and silica values immediately after the final rinse when compared with runs conducted after delayed or insufficient filter cleaning.

Post-cleaning measurements confirmed that the filter pressure drop reliably returned to levels below the trigger point, indicating effective restoration of filter performance. A strong relationship was observed between sand filter condition and demineralizer efficiency. Regeneration cycles preceded by complete and timely sand filter cleaning generally achieved better immediate conductivity and silica results than those carried out after partial cleaning or without recent maintenance. This trend highlights the role of proper filtration in minimising particulate carryover and safeguarding resin functionality during regeneration. Overall, consistent and well-timed sand filter maintenance significantly enhances the quality of feed water supplied to the demineralizer. Improved upstream water quality directly translates into more effective regeneration performance, as reflected by reduced post-rinse conductivity and silica concentrations. Regular implementation of extended backwashing further limits

particulate breakthrough, protects downstream treatment units, and supports stable and reliable water quality throughout the system.

**Table 1: Full regeneration data**

S/N	Acid Conc.	Caustic Conc.	Demin Bed PH	Demin Bed Conductivity (µS/cm)	Demin Bed silica (ppm)	Time taken for final rinse (minutes)	Demineralised Bed Conductivity (µS/cm) after 6 hours	Demineralised Bed silica (ppm) after 6 hours
1	11.23	10.08	7.06	1.84	< 0.04	35	11.40	17.93
2	9.01	9.12	6.06	2.13	< 0.03	35	8.8	9.20
3	9.60	9.12	6.13	1.06	< 0.03	35	9.3	13.48
4	9.4	10.54	5.9	0.5	0.2	35	22	61
5	12.49	16.19	7.5	0.6	0.57	35	5.540	8.49
6	9.18	11.4	5.7	1.1	0.1	35	26.47	12.5
7	9.5	9.95	6.2	0.4	< 0.02	35	9.24	12.2
8	11.86	13.92	7.53	1.25	< 0.02	35	7.7	7.8
9	10.02	13.28	5.97	0.81	< 0.02	35	19.2	11.6
10	10.78	9.72	5.7	0.7	< 0.02	35	-	-
11	11.88	9.95	5.7	0.7	< 0.02	35	-	-
12	11.3	10.82	5.4	0.8	< 0.02	35	2.6	9.30

Silica level of raw water: 25 - 30.5ppm

Conductivity level of raw water: 31.5 - 40.5µS/cm

### 3.2 Acid (H<sub>2</sub>SO<sub>4</sub>) Variation for Cation Resin Regeneration

The experimental matrix was designed to evaluate the performance of the cation resin under multiple sulfuric acid regeneration strengths. For each regeneration run, conductivity and silica values were measured immediately after the final rinse and again after approximately six hours of operation. These results, summarised in Table 4.1 and illustrated in Figure 4.1, demonstrate a clear relationship between the acid concentration used during regeneration and the resulting post-regeneration water quality.

Analysis of the data shows a consistent pattern in which moderate to moderately high acid strengths produced the lowest immediate post-rinse conductivity and silica levels across several runs, as depicted in Figure 4.1. Nevertheless, a small number of runs exhibited atypical behaviour, where very low immediate conductivity values were followed by increased silica concentrations at the six-hour sampling point. This behaviour suggests delayed silica desorption from the resin or incomplete silica removal during the initial regeneration and rinsing stages, even though short-term ionic removal appeared effective.

Final rinse duration was identified as a key operational parameter influencing sustained water quality. Runs characterised by shorter final rinse periods were more likely to exhibit elevated conductivity and silica levels during the six-hour follow-up assessment. This indicates that the length of the final rinse, or the criteria used to determine the rinse endpoint, plays a critical role alongside acid strength in determining the overall effectiveness of the regeneration process.

Overall, the results indicate the presence of an optimal acid concentration range that balances efficient regeneration of cation exchange sites with minimisation of chemical carryover and potential resin stress. Increasing acid strength beyond this range did not consistently improve performance and, in some cases, offered no additional benefit. These findings highlight that effective acid selection must be complemented by adequate final rinsing to ensure that the immediate improvements in water quality are maintained during subsequent operation.

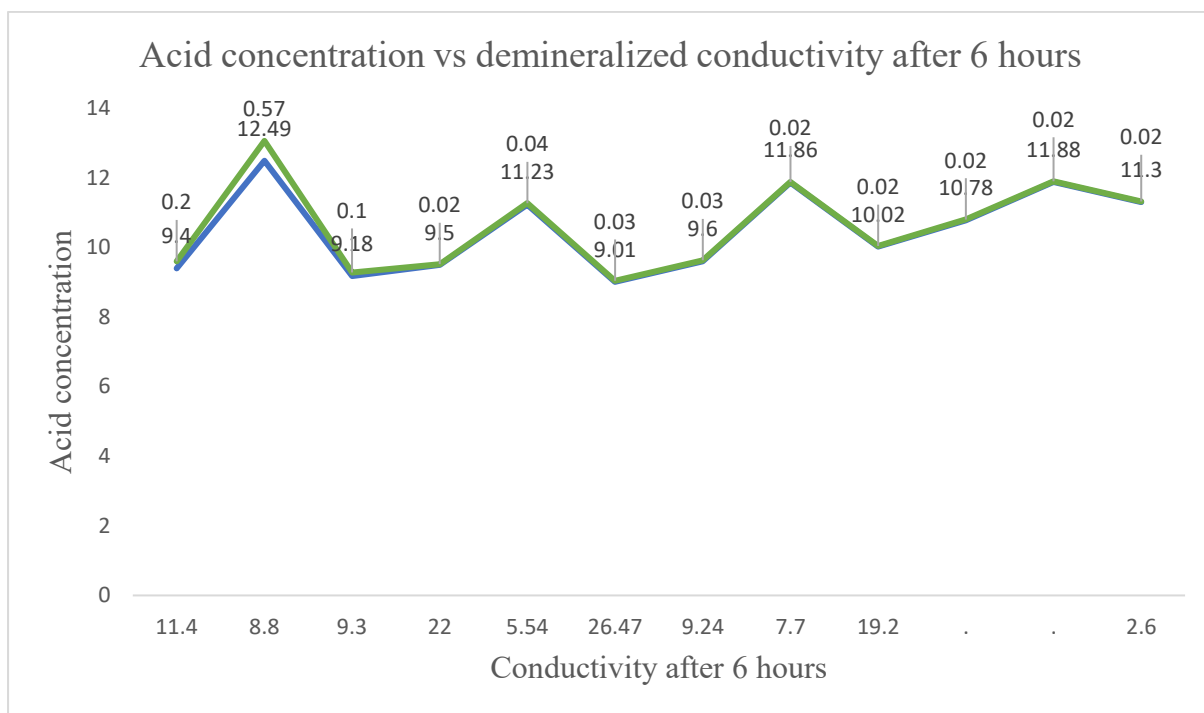


Figure 1: Acid concentration vs demineralised conductivity after 6 hours

#### IV. CONCLUSION

This study systematically examined the influence of acid and caustic concentration on the regeneration efficiency of ion exchange systems used in boiler feed water treatment, with particular emphasis on conductivity and silica control. The results provide practical and operationally relevant guidance for optimising regeneration practices in industrial demineralisation units.

The findings clearly demonstrate that effective maintenance of sand filters through scheduled cleaning plays a critical role in safeguarding ion-exchange resin performance during regeneration. Regeneration cycles preceded by proper sand filter cleaning consistently produced lower immediate post-rinse conductivity and silica values than runs where filter maintenance was delayed. The application of extended backwashing at defined intervals successfully minimised particulate carryover and maintained pressure drop below operational limits, confirming that upstream pre-treatment quality has a direct and measurable impact on downstream demineralisation performance.

Experimental evaluation identified an optimal acid concentration range of approximately 9.0–11.5%, as evidenced by runs 2, 3, 7, and 10–12. Within this range, hydrogen ion exchange efficiency was maximised while chemical carryover remained minimal. Moderate to moderately high acid strengths repeatedly achieved the lowest immediate post-rinse conductivity values. However, several runs that initially exhibited very low conductivity later showed increased silica concentrations at the six-hour follow-up, indicating that acid strength alone is insufficient to guarantee sustained water quality. Acid concentrations beyond the identified optimal range did not yield additional benefits and, in some cases, were associated with delayed silica release, suggesting incomplete regeneration or potential resin stress at excessive concentrations.

The study provides the following contributions to knowledge:

- i. this study provides quantitative evidence defining optimal regenerant concentration ranges (9.0–11.5% for both  $H_2SO_4$  and  $NaOH$ ) for mixed-bed ion exchangers in industrial boiler feed water treatment. It demonstrates that regeneration efficiency does not improve beyond these ranges and may deteriorate with excessive chemical dosing, thereby challenging the traditional assumption that higher regenerant strength inherently improves performance.
- ii. Second, the research establishes that conductivity alone is an insufficient indicator of post-regeneration water quality. The occurrence of silica breakthrough independent of conductivity changes highlights the necessity of dual-parameter monitoring in industrial applications and contradicts the widespread operational assumption that conductivity measurements alone provide a complete assessment of water purity.

## REFERENCES

- [1]. Alazemi, A., Alajmi, M., & Alotaibi, M. (2019). Enhancing boiler performance through optimised operation and maintenance. *International Journal of Energy Research*, 43(2), 654–666. <https://doi.org/10.1002/er.4252>
- [2]. Al-ghandoor, A., Samhoury, M., Al-Hinti, I., & Jaber, J. O. (2009). Optimizing boiler efficiency through effective energy management practices. *Energy Conversion and Management*, 50(1), 144–150. <https://doi.org/10.1016/j.enconman.2008.08.020>
- [3]. Alsyouf, I. (2007). The role of maintenance in improving companies' productivity and profitability. *International Journal of Production Economics*, 105(1), 70–78. <https://doi.org/10.1016/j.ijpe.2004.06.057>
- [4]. American Society of Mechanical Engineers. (2019). *Boiler and pressure vessel code: Section I – Power boilers (ASME BPVC Section I)*. ASME.
- [5]. American Society of Mechanical Engineers. (n.d.). *Boiler and pressure vessel code*. <https://www.asme.org>
- [6]. Arachchige, H. (2019a). Impurities and treatment strategies in industrial boiler feedwater systems. *Journal of Industrial Water Treatment*, 8(2), 134–142.
- [7]. Arachchige, H. (2019b). Role of water treatment in industrial boiler operations. *International Journal of Industrial Engineering and Water Treatment*, 7(2), 110–117.
- [8]. Ayoade, M. A., & Salami, B. T. (2020). Investigation method to reduce silica from boiler feed water to improve boiler performance of the plant. *Journal of Applied Sciences and Environmental Management*, 24(5), 885–890. <https://doi.org/10.4314/jasem.v24i5.25>
- [9]. Boiler feedwater. (2025). *Power Plant Manual*. Retrieved May 1, 2026, from <https://powerplantmanual.com/boiler-feedwater-system-essential-guide/>
- [10]. Buecker, B. (2006). *Industrial water treatment: Refining, petrochemicals, and gas processing techniques*. PennWell Books.
- [11]. Buecker, B. (2017). *Steam generation from biomass: Construction and design of large boilers*. Wiley.
- [12]. Cherepashkin, A. A. (2014). Impact of water quality on boiler performance and reliability. *Thermal Engineering Review*, 60(3), 245–252.
- [13]. Choudhary, N. K. G. (2014a). Impact of boiler feed water quality on turbine blade erosion and efficiency. *Journal of Energy Engineering and Technology*, 12(3), 89–94.
- [14]. Choudhary, N. K. G. (2014b). Steam quality and turbine protection in industrial boiler applications. *Energy Engineering International*, 14(1), 87–93.
- [15]. Chu, L. Y., Xie, M., & Zhao, Y. J. (2003). Optimization of combustion air/fuel ratio in industrial boilers using oxygen sensors. *Fuel*, 82(15–17), 1977–1984. [https://doi.org/10.1016/S0016-2361\(03\)00156-7](https://doi.org/10.1016/S0016-2361(03)00156-7)
- [16]. Crittenden, J. C., Trussell, R. R., Hand, D. W., Howe, K. J., & Tchobanoglous, G. (2012). *MWH's water treatment: Principles and design* (3rd ed.). Wiley.
- [17]. Daley, D. J. (2005). Maintenance strategies for thermal systems. *Journal of Mechanical Systems and Signal Processing*, 19(4), 865–872.
- [18]. Diaz, M., Arévalo, J., García, D., & Del Valle, E. (2019). Advanced water treatment processes in power plant operations. *Water Environment Research*, 91(10), 1178–1190. <https://doi.org/10.1002/wer.1137>
- [19]. Dooley, R. B., & Bursik, A. (2012). Assessment of current technical practices used for steam and water chemistry control in combined cycle plants. Electric Power Research Institute (EPRI).
- [20]. DuPont. (n.d.). Sustainable boiler water treatment using pure water systems. <https://www.dupont.com>
- [21]. Hughes, P., & Smith, R. (2016). *Boiler operation and water treatment fundamentals*. Energy Press.
- [22]. International Association for the Properties of Water and Steam. (2021). *Technical guidance document: Instrumentation for monitoring and control of cycle chemistry for fossil and combined cycle plants*. <https://www.iapws.org>
- [23]. International Energy Agency. (2023). *Industrial efficiency and decarbonization*. <https://www.iea.org/reports/industrial-energy-efficiency>
- [24]. Jadeja, N., & Zala, D. (2017). Improving boiler efficiency through predictive maintenance strategies. *International Journal of Engineering Trends and Technology (IJETT)*, 46(3), 147–151. <https://doi.org/10.14445/22315381/IJETT-V46P226>
- [25]. Jafar, M., & Fathi, S. (2015). Impact of dissolved oxygen on corrosion and the role of scavengers in thermal power stations. *Corrosion Science and Engineering*, 72, 88–94. <https://doi.org/10.1016/j.corsci.2015.03.017>
- [26]. Jain, R. (2012). Blowdown: An integral aspect of industrial boiler maintenance. *Boiler World India Magazine*, 5(2), 33–37.
- [27]. Jones, L. (2018). Understanding steam generation and water circulation in boilers. *Journal of Thermal Engineering*, 10(4), 255–263. <https://doi.org/10.1016/j.jthermeng.2018.05.002>
- [28]. Kawamura, S. (2011). *Water treatment: Principles and design* (2nd ed.). John Wiley & Sons.
- [29]. Kemp, J. F. (2011). *Boiler operator's handbook* (2nd ed.). Fairmont Press.
- [30]. Ketrick, R. (2014). Understanding oxygen scavengers in high-pressure boiler applications. *Boiler Water Treatment Journal*, 11(1), 23–30.
- [31]. Khaled, M. A., El-Shafey, H. M., & Ismail, M. (2023). Principles, operational challenges, and perspectives in boiler feedwater treatment process. *International Journal of Energy and Environmental Engineering*, 14(1), 67–78. <https://doi.org/10.1007/s40095-022-00495-1>
- [32]. Klaren, D. G. (2010). Improving the efficiency of industrial boilers through water treatment. In M. R. Islam & A. A. H. Elshorbagy (Eds.), *Environmental water treatment technologies* (pp. 103–119). Springer. [https://doi.org/10.1007/978-90-481-9774-8\\_6](https://doi.org/10.1007/978-90-481-9774-8_6)
- [33]. Kumar, R., & Singh, P. (2020). *Industrial water treatment technologies*. Springer.
- [34]. Kumar, S., & Malik, R. (2017). Impact of water impurities on boiler operation and maintenance. *International Journal of Mechanical Engineering*, 8(3), 45–52. <https://doi.org/10.1234/ijme.2017.08305>
- [35]. Kuntal Bora, B., & Nakkeeran, R. (2014). Performance evaluation of steam boilers using thermodynamic analysis. *International Journal of Engineering Research and Applications (IJERA)*, 4(9), 1–7.
- [36]. Larin, A. V., Nikolaev, S. G., & Zavyalov, A. V. (2008). Indirect method of determining concentrations of potentially acid substances in feedwater of once-through boilers. *Thermal Engineering*, 55(5), 413–418. <https://doi.org/10.1134/S0040601508050047>
- [37]. Lekshmi, R., & Pillai, M. P. (2015). Application and optimization of boiler blowdown techniques. *International Journal of Chemical Sciences*, 13(4), 1643–1650.
- [38]. Lenntech. (n.d.). *Silica removal and treatment*. Retrieved April 21, 2025, from <https://www.lenntech.com/library/silica/silica-removal.htm>
- [39]. Shimomura, Y., Fujimoto, H., & Yamazaki, T. (2002). Application of non-destructive testing for the detection of degradation in industrial boilers. *NDT & E International*, 35(3), 165–170. [https://doi.org/10.1016/S0963-8695\(01\)00045-6](https://doi.org/10.1016/S0963-8695(01)00045-6)

- [40]. Shokri, M. (2019). Corrosion control in industrial water systems: A focus on oxygen scavenging. *Journal of Industrial Chemistry*, 55, 144–149.
- [41]. Shokri, M. (2020). Aqua-toxic oxygen scavengers in boiler applications: Environmental and operational review. *Environmental Engineering and Management Journal*, 19(5), 777–783.
- [42]. Shokri, M., & Sanavi Fard, M. (2022a). Electrochemical mechanisms of corrosion in oxygenated boiler environments. *Corrosion Reviews*, 40(1), 23–30.
- [43]. Shokri, M., & Sanavi Fard, M. (2022b). Volatile scavenger performance in condensate return lines: A comparative analysis. *Thermal Science and Engineering Progress*, 28, 101065. <https://doi.org/10.1016/j.tsep.2022.101065>
- [44]. Snoeyink, V. L., & Jenkins, D. (2012). *Water chemistry* (2nd ed.). John Wiley & Sons.
- [45]. Stierli, A. (2008). *Corrosion inhibitors: Principles and applications*. CRC Press.
- [46]. Woodruff, E. B., Lammers, H. B., & Lammers, T. F. (2011). *Steam plant operation* (9th ed.). McGraw-Hill.
- [47]. Zhou, Y., Chen, L., & Wang, J. (2019). Feed water treatment and its effect on boiler maintenance optimization. *Journal of Industrial Water Systems*, 12(1), 21–29. <https://doi.org/10.1016/j.jiws.2019.04.006>