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Principles, operational challenges, and perspectives in boiler feedwater treatment process

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ABSTRACT

Because boilers are the throbbing heart of numerous industrial processes, optimization of their operating features, especially feedwater, is absolutely crucial from an environmental, economic, and efficiency standpoint. Inappropriate boiler feed water treatment results in significant operating failures, which can adversely affect the healthy operation of industrial boilers. Increasing equipment service life, preventing prolonged downtime, minimizing boiler failures (extensive corrosion and scale formation), maximizing the utilization of steam condensate, effective internal boiler water chemistry control to prevent entering pernicious impurities into the boiler and mitigating cost-prohibitive maintenance are the major positive consequences of a well-designed boiler feedwater treatment process. Despite the decisive roles of boiler water treatment methods in critical industries, scholarly literature suffers from the absence of an exhaustive review paper in this regard. Hence, this paper studies the main fundamentals of boiler feedwater treatment and various disconcerting challenges associated with the inadequate treatment of boiler feedwater. Also, performance enhancements, boiler maintenance, and cost analysis are thoroughly discussed. Based on the results, because almost all of the current operational boilers are powered by fossil fuels which emit significant quantities of greenhouse gasses into the atmosphere, advanced methods are required to decrease heat losses by recovery from flue gas and condensed water, and also alternative and eco-friendly fuel sources must be explored. In this regard, the authors propose the knowledge gaps and perspectives to delineate the future research direction concerning environmental-engineering-energy aspects. It concludes that despite some significant progress in the field of boiler water treatment, there is still a long way ahead to completely curb the pernicious feedwater-related challenges of the boiler. Therefore, intensive research efforts must be materialized to effectively mitigate or even remove these impediments.

1. Introduction

The critical roles of boilers in different industrial settings are undeniable, as they are essential for the generation of high-pressure steam for smooth operation. However, to maximize the performance of boilers, their feedwater must be properly treated, as untreated water poses several adverse effects on the operability of boilers. Increasing the lifetime of facilities, preventing shutdowns, keeping internal surfaces of the boiler clean and protected, increasing condensate to the highest amount, and avoiding corrosion and scale formation are major purposes for boiler feedwater treatment (Arachchige and Sandupama, 2019). To make the sure smooth operation of steam production systems in the steam boiler industry, feed water with high purity is absolutely essential. Moreover, blowdown with lower frequency greatly decreases fuel costs. Because of the lower dosages of impurities in the boiler feed water, it not only results in lower corrosion rates but also decreases scale generation. For instance, because of the high-purity steam produced by the boiler, turbine blade erosion is decreased (Kispotta Gayatri Choudhary et al., 2014). In order to avoid challenges like scale generation/deposition, corrosion, and carryover in the boiler systems, boiler water treatment in industrial plants is implemented. Accurate inspections, testing, and careful methods to take the water samples, environmental conservation practices, greater operating performance, and precise analysis of the utilized water, are crucial to the effective operation of boilers. Hence, the development of novel technologies and effective solutions with a high concentration on water treatment methods are critical to

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addressing challenges in the treatment of boiler feed water (Tsubakizaki. S, Ichihara.T, 2011). In this context, enhancing the reliability, performance, maintenance, and safety of boiler systems are considered the major results of the boiler feed water treatment process.

2. Novelty Statement and Research Gaps

Boiler feedwater treatment is of utmost importance in numerous industrial processing, which use a boiler for the main part of their operation. As was clearly mentioned, an inadequate treatment process in boiler feedwater can be highly problematic since it can cause countless operational challenges. Hence, it is glaringly obvious that all of the industrial plants which use boilers must gain solid knowledge concerning suitable boiler water treatment processes to minimize their serious operational failures. In this context, despite the decisive roles of boiler water treatment procedures in critical industries, there is not any review paper that comprehensively explores all its dimensions. Moreover, there are only a limited number of papers about the concept of boiler feedwater treatment (Arachchige and Sandupama, 2019; Kispotta Gayatri Choudhary et al., 2014; Pan and Xu, 2022; Panigrahi and Ganapathysubramanian, 2015; Siriwardena, 2020). Accordingly, the authors in this paper attempt to exhaustively discuss major principles of boiler water treatment and different stringent challenges due to the inappropriate treatment of boiler feedwater. Exactly this is the novelty point of this review paper. The authors believe that it not only can pave the way for the huge community of boiler users but also motivates different researchers in this field to further investigate novel methods to minimize the adverse effects of poor boiler water treatment processes in industrial processes.

The organization of this review paper is as follows: An overview of the necessity of boiler feedwater treatment and different impurities was presented in sections 1 and 2. Section 3 details the consequences of untreated feedwater in the boiler. Section 4 presents different external and internal treatment methods, section 5 briefly explores performance enhancements in boiler operation, and section 6 presents boiler maintenance methods and their advantages. Finally, in section 7 economics of the boiler water treatment process is briefly discussed. In the final part of the paper, future research perspectives and challenges were clearly included to bridge the knowledge gaps in a sustainable manner concerning the feedwater treatment of boilers.

3. Boiler Feed Water and Impurities

The boiler is used to generate steam, which includes the furnace to supply the required energy for fuel burning and the boiler proper to change water into steam. The generated stream is recirculated in the boiler to apply to different systems which need heating. Blowdown water (drained water to decrease impurities level), condensate water (reverted pure water after heat transformations), makeup water (demineralized, softened, or raw water), and feedwater (integration of makeup and condensate water) are major kinds of water stream which used during boiler operation. The makeup has been purified to certain rates, which is natural water or treated water. As a result, the quality of the makeup water and the quantity of condensate returned to the boiler will greatly determine the boiler feed water composition. The remaining water at the boiler bottom collects all of the external materials from the water that was converted to steam. The impurities have to be blown down by discharging some of the water from the boiler to the drains (McCrady, 1955). Feed water purity is a function of the amount and nature of impurities. In this context, compared with sodium salts, different impurities like silica, iron, and hardness are highly challenging. The required purity for any feed water relies on the amount of utilized feed water and the tolerance rate concerning boiler design parameters like heat transformation rate and pressure (Kispotta Gayatri Choudhary et al., 2014). Fig. 1 presents the schematic of the boiler feedwater treatment system.

Treatment of boiler feed water is completely essential because untreated water can cause numerous challenges, especially in extreme pressure and temperature, like high cleaning costs, overheating, damage, and lower performance in terms of heat transformation. Different additives during the synthesis of a chemical product or natural occurrence are two major origins of impurities. Fig. 2 presents different common impurities in boiler feedwater (Arachchige and Sandupama, 2019). Carbon dioxide, oil, iron, and calcium scale are common impurities in the boiler water. Carbonic acid is generated from the reaction of water and carbon dioxide, which lead to corrosion in the steam and

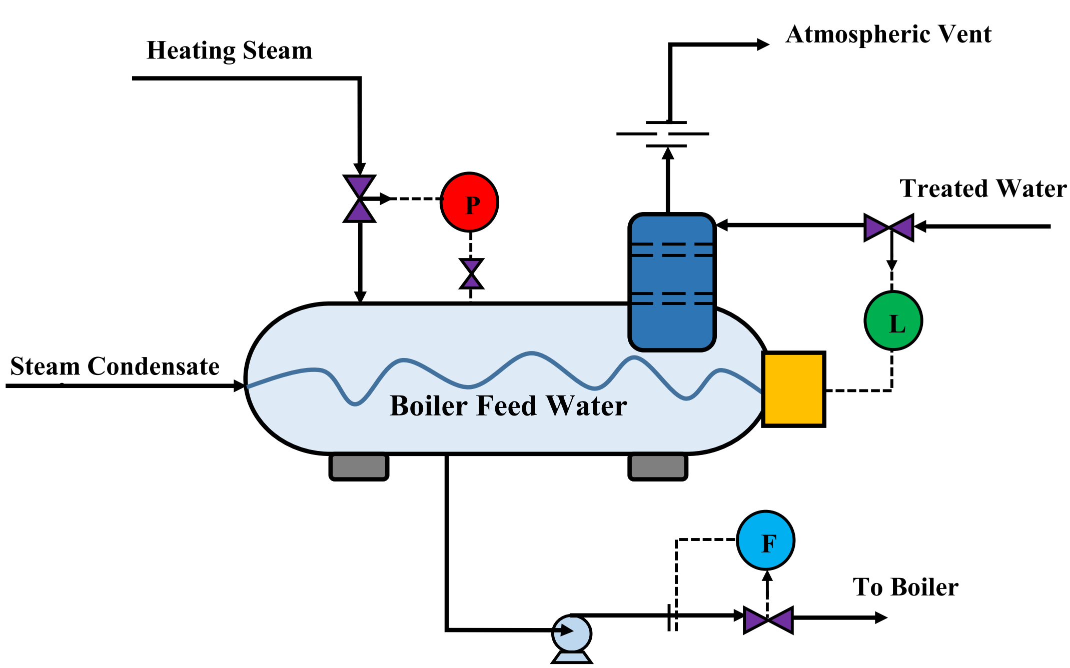

Fig. 1. The schematic of the boiler feedwater treatment system. Adapted from (Kispotta Gayatri Choudhary et al., 2014).

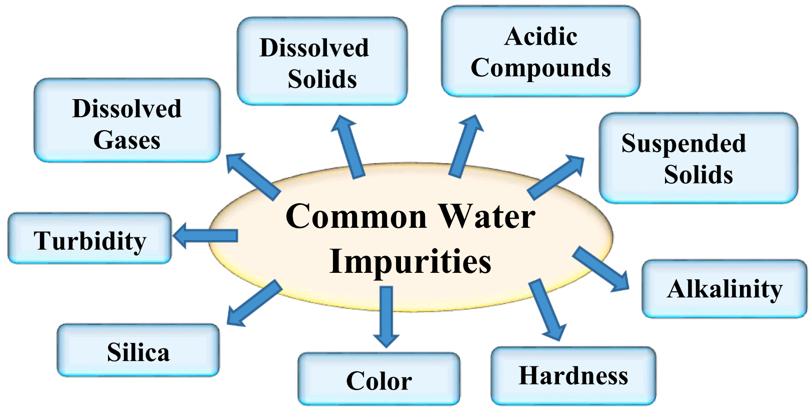

Fig. 2. Different common impurities in boiler feedwater. Based on (Arachchige and Sandupama, 2019).

return lines. From condenser air leakage or bicarbonate alkalinity in the feed water, carbon dioxide can be produced. Oil is a perfect heat insulator, and its adherence to tube surfaces exposed to high temperatures can lead to overheating and tube damage. Although high iron is not observed in raw water, high dosages can be generated from the exfoliation of boiler tubes and rusted piping. Because iron does not dissolve in water, it is detected in condensate return in a particle form. The dangerous aspect of iron is known as steam turbine solid particle erosion, which results in considerable erosion of steam turbine steam path components. Calcium nitrate, calcium chloride, calcium carbonate, calcium bicarbonate, and calcium sulfate are some of the common scaling compounds generated by the integration of calcium with sulfates and other compounds. During evaporation, adherence of different chemicals to tube walls causes scale formation. Scale generation increases directly with an increased evaporation rate. Hence deposits will be heavier where the gas temperatures are maximum. Scale is a heat nonconductor that reduces heat transformation of the boiler tubes because greater tube metal temperatures can cause tube failure (Kispotta Gayatri Choudhary et al., 2014). Pan and Xu (Pan and Xu, 2022) reported that equipment, environment, material, personnel, and methods are major determinants of deviation in feedwater quality. Based on their results, the precise explanations with the cause and effect approach are presented in Fig. 3.

With increasing boiler operating pressure, a pure and high-quality water source is required. Although the exact boiler feed water chemistry requires to be measured by a boiler feed water specialist and cross-referenced with the suggestions dictated by the boiler manufacturer, however, to obtain a big picture view, the American Society of Engineers (ASME) regulations for different pollutants at various pressures is highly beneficial and recommended (Table 1). As it is clear from the table, the tolerance for impurities reduces with increasing boiler pressure (Samco, 2020).

4. Challenges and Consequences Concerning Untreated Boiler Water

Deposition of scale and hardness, increased oxygen level, and striking a proper balance between water alkalinity and acidity are major typical operational challenges that occur because of the inadequate treatment of boiler water. Different types of water impurities like silica, Ca^{2+}, and Mg^{2+} ions at significant temperatures precipitate and generate a dense coating of materials known as scale on the boiler water side, which heavily influences the heat transformation mechanism by reducing the thermal conductivity rate. Due to the lower conductivity of scale compared with bare steel, this layer of scale performs as a strong insulator. In this condition, thermal cracking in boiler tubes will occur as a significant degree of heat is required for adequate steam generation (Tyusenkov and Cherepashkin, 2014). Low-quality feedwater not only

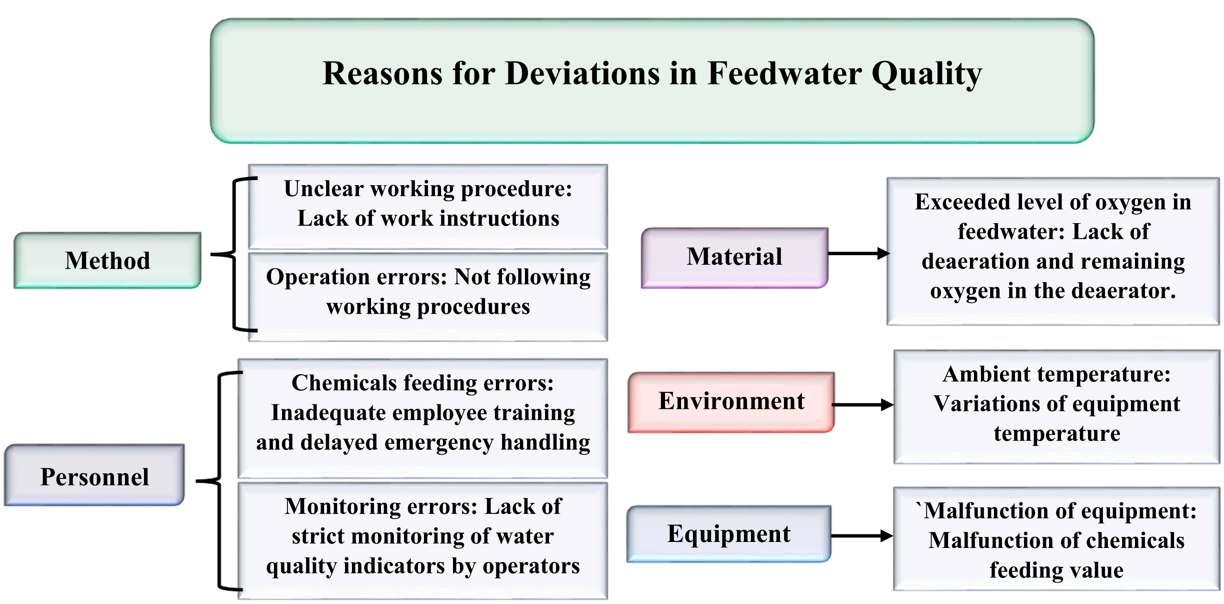

Fig. 3. Major reasons for deviation in feedwater quality. Based on (Pan and Xu, 2022).

Table 1
ASME Guidelines for water quality in modern industrial water tube boilers for safe and constant operation. Adapted from (Samco, 2020).

Boiler Feed Water				Boiler Water		
Drum pressure (psi)	Iron (ppm Fe)	Copper (ppm Cu)	Total hardness (ppm $CaCO_3$)	Silica (ppm SiO_2)	Total alkalinity (ppm $CaCO_3$)	Specific conductance (micro-ohms/cm) (unneutralized)
0-300	0.100	0.050	0.300	150	700	7000
301-450	0.050	0.025	0.300	90	600	6000
451-600	0.030	0.020	0.200	40	500	5000
601-750	0.025	0.020	0.200	30	400	4000
751-900	0.020	0.015	0.100	20	300	3000
901-1000	0.020	0.015	0.050	8	200	2000
1001-1500	0.010	0.010	0.0	2	0	150
1501-2000	0.010	0.010	0.0	1	0	100

causes scale formation in the boiler but also considerably reduces the metal strength and causes local deformation, bulging, and bursting. It is worth mentioning that a thick layer of scale will considerably increase fuel consumption. The vacuum inside the turbine condenser will be lower due to the presence of scale. As a result, turbine output and thermal performance will be significantly decreased, and even in extreme conditions, a shutdown will occur (Pan and Xu, 2022). Another deteriorating factor is that scale formation decreases the internal diameter of pipelines and greatly obstructs enough water flow rate. It is worth mentioning that boiler tube overheating, increased flue gas temperature, fuel loss, and associated financial burdens are severe consequences of scale formation on the efficiency of boiler operation (Arachchige and Sandupama, 2019). Because the pH value is definitely an indication of water acidity and an acidic environment initiates corrosion of boiler shell and tube, careful pH control is critical to avoid corrosion. Based on the standards, to ensure suitable chemical reactions between PO_4^{3-}, Ca^{2+}, and Mg^{2+} ions, the pH value of boiler water has to be sustained at almost 9.5 (Arachchige and Sandupama, 2019). It must be mentioned that with increasing pH levels higher than normal, the feasibility of scale deposition increases. In highly alkaline water, bicarbonate and carbonate ions can be integrated with Ca^{2+} and Mg^{2+} ions to generate stable salts, which act as scale deposition on the surface of boiler tubes. As a result, increasing resistance prevents adequate heat transformation. Because the significant concentrations of oxygen can accelerate the generation of red iron oxide or hematite (a major parameter of pitting corrosion), curbing oxygen content in boiler feedwater is crucial (Arachchige and Sandupama, 2019). If feed water does not undergo proper treatment, accumulation of salt in the superheater and turbine will be caused the metal tube wall to overheat and sometimes generate bursting, which greatly increases safety hazards. In such conditions, copper and iron content, conductivity, silicon content, CO_2, pH, hydrazine, dissolved oxygen (DO), oil content, and water hardness are monitoring factors (Pan and Xu, 2022). The turbine condenser, superheater, heater, feed pipelines, and the water-cooled wall of the coal generator will be greatly influenced and adversely corroded due to the low-quality feedwater of the boiler. Because of the serious corrosion, the lifetimes of facilities become shorter, which will be portrayed as substantial economic losses. This condition will deteriorate when some of

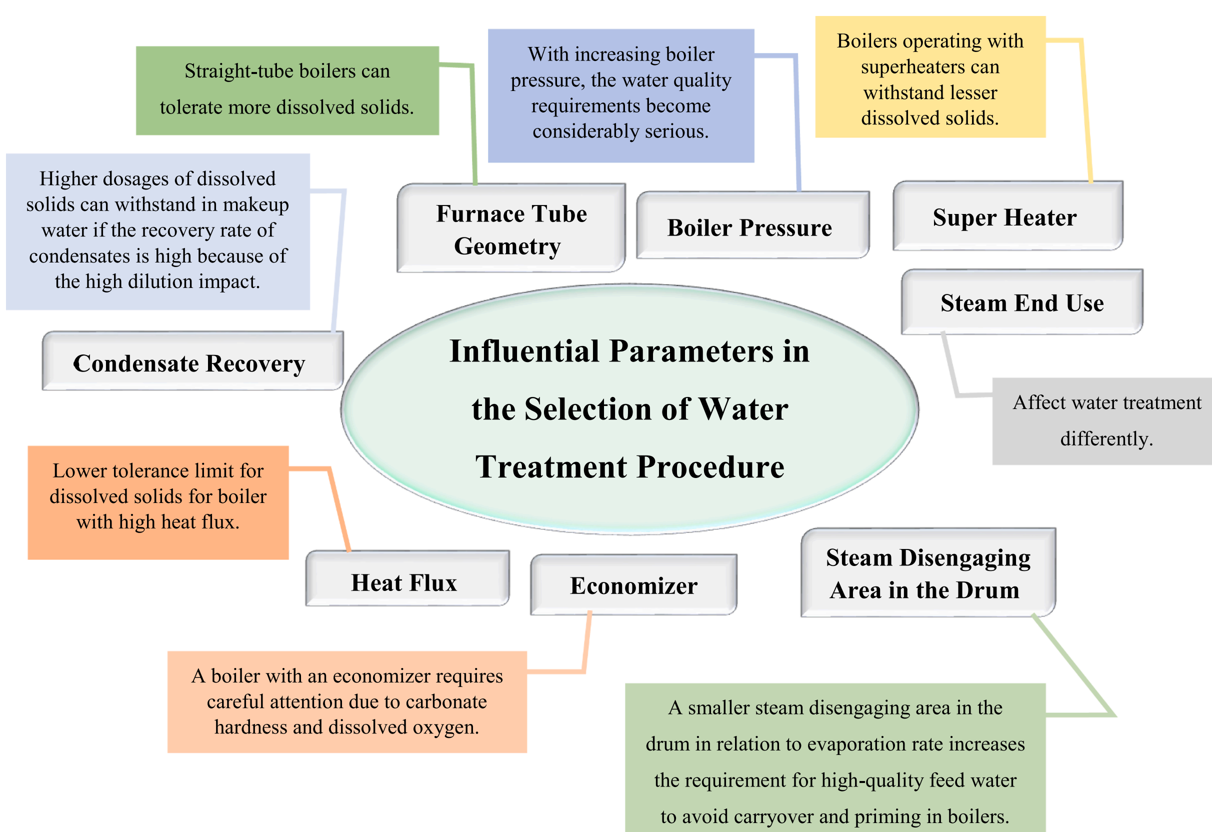

Fig. 4. Influential parameters in the selection of water treatment procedure. Based on (Dew Speciality Chemicals, 2020).

the corrosion-driven impurities putting back into the water and constantly contaminate water, and reinforce corrosion on the heated surface. In other words, a vicious circle of corrosion and scale formation constantly occurs (Pan and Xu, 2022).

5. Boiler Water Treatment

Elimination or chemical modification of potentially damaging materials to the boiler is the major purpose of boiler feed water treatment. To minimize foaming, corrosion, and scale, different forms of treatment are utilized at various locations (Kemmer and McCallion, 1979). Fig. 4 clearly demonstrates the major influential factors for the selection of the best feedwater treatment process in boilers. Also, boiler water treatment methods are mainly internal and external, which are discussed in the following sections (Arachchige and Sandupama, 2019).

5.1. External Treatment (Pretreatment)

External treatment of raw water is concentrated on impurities elimination before they reach the boiler. External treatment is typically performed by deaeration, demineralization, dealkalization, filtration, ionization, softening, and clarification (Arachchige and Sandupama, 2019). The major boiler feed water treatment methods are as follows filtration, floatation, sedimentation, coagulation, and flocculation. The main process in filtration is water passage through a bed of fine particles, typically sand (sand filtration). At significantly high water flow rates, sand filtration has low performance for the removal of fine suspended particles. Hence, before passing through the filter bed, feed water should usually undergo pre-treatment processes like flocculation or coagulation. In the flotation process, by making particles appear on the liquid surface, suspended particles are eliminated. The flotation chamber, pressurizing, and air supply are the main parts of flotation systems (Edzwald, 1995). By sedimentation, the solids are eliminated before the water passes to the filter and decreasing the amount of solids load on the filter, thus increasing the treatment performance. With the addition of aluminum sulfate to the raw water, settlement can be obtained in a significantly lower time which is the principle of flocculation and coagulation. In conventional water treatment, to eliminate impurities, special chemicals are added to raw water. In the coagulation process, a soluble chemical or integration of chemicals is added to the water to settle slow-speed particles or non-settling ones. However, in the sedimentation process, some particles will naturally settle out.

To decrease or eliminate magnesium and calcium salts from makeup water, the application of careful pre-treatment in a boiler cycle is highly recommended, which is directly determined by boiler design and operating pressure. Also, the pretreatment process must include effective deaeration to minimize the presence of DO to avoid corrosion. It is worth mentioning that DO and CO_2 in the condensate is the major reason for corrosion failure in condensate steam lines. As the carbonate content of the makeup water is the main source of CO_2 in steam, external treatment with the purpose of removing of bicarbonate content of the makeup water is highly advantageous in the reduction of corrosion failures in the return line system.

5.1.1. Clarification

Because natural settling will eliminate only coarse suspended solids, coagulation is the first stage in water processing used to remove suspended solids. During coagulation, by using chemical additives like ferrous sulfate and alum, suspended materials integrate together and generate larger particles that can rapidly be settled. Chlorination (to remove organic compounds) and aeration are the preliminary treatment processes. For the removal of manganese and iron (if oxidized and precipitated), volatile impurities and undesirable gases like CO_2 and H_2SO_4 aeration are utilized.

5.1.2. Filtration

After completion of the coagulation, settling, and chlorination process, water is undergone filtration to remove the remaining finely divided suspended solids. Also, to remove additional chlorine and final traces of organics, activated carbon filters are utilized.

5.1.3. Precipitation Softening Process

In the precipitation process, lime softening does not effective in the removal of non-carbonate hardness. Hence, soda ash is combined with the lime for its elimination from water. However, serious scaling challenges in pipelines, spoor solubility of both magnesium hydroxide and calcium carbonate decreased to a value below 25 ppm, and the slow reaction rate is the main limitation of the lime soda process.

5.1.4. Ion Exchange Process

The Ion exchange process involves impurities removal using a chemical reaction with lime. To adjust the hardness and alkalinity in the treated water, precise blending control is required. For the regeneration of sodium and hydrogen cation units, salt and acid are utilized. In the ion exchange process, magnesium and calcium in the water are eliminated and replaced by sodium.

5.1.5. Other Treatment Processes

In conditions with significant concentrations of dissolved impurities, like seawater or brackish estuaries, chemical treatment is not economical, and thus evaporation is frequently used, which presents water with almost free of all impurities. Another treatment process is reverse osmosis (RO) which is the pumping of high-pressure water through a special membrane to trap dissolved solids. Reverse osmosis is highly efficient and can be used before the ion exchange demineralization process. In this way, the regeneration price is considerably decreased by increasing the resin lifetime.

5.2. Internal Treatment

Internal treatment in the boiler is concentrated on restricting water's tendency to dissolve the boiler and keeping impurities in forms with the minimum possibility of generating problems like corrosion and scale deposition before they can be eliminated from the boiler in boiler blowdown (Barkdoll, 2000). In fact, during the internal treatment, different types of chemical additives are used to purify water inside the boiler. In this process, to eliminate carbonate like magnesium/calcium carbonate, phosphate-dependent chemicals and to eliminate oxygen, sulfite-dependent chemicals (as oxygen scavenging) are used. Hence, by controlling phosphates or carbonate dosages, scale deposition can be adequately curbed. Common oxygen scavengers are sodium bisulfite and sodium sulfate (Siriwardena, 2020). Also, as additive chemicals, alkalinity builders to increase pH value, sludge conditioners to maintain the dynamic condition, and neutralizing amines to avoid carbonic acid generation are utilized (Boiler, 2015). By this method, any potential failure during boiler operation will be decreased (Arachchige and Sandupama, 2019). By intermittent or constant blowdown, the possibility of carrying water to steam due to the increased TDS (total dissolved solids) can be adequately controlled. By deaeration, oxygen content can be decreased, which leads to the prevention of corrosion in tubes.

To prevent embrittlement, steam pollution, corrosion, and scale formation, internal treatment is used. Internal treatment is critical because even with the implementation of advanced external treatment, several impurities always remain in the boiler. The feedwater analysis and plant operating conditions determine the kind of utilized chemicals. Application of lignin and tannin to sludge conditioning and alkaline phosphate and soda ash for precipitation of magnesium and calcium are traditional internal treatment methods that effectively prevent boiler scale and reduce water hardness. However, trends for using tubes with smaller diameters and maximizing heat transformation rate decrease resistance against sludge which is due to the increasing possibility of impurities adherence to the heat transformation surface. Moreover, calcium hydroxyapatite generated in the PO_4 cycle is vulnerable to binding by oil. The rising quantity of copper, iron, and other metals in the feedwater increases the requirement for proper conditioning. The existence of iron and higher concentrations of phosphate can potentially increase the generation of iron phosphate, which aggregates sludge and increases its adherence to the tube surfaces. The generation of iron hydroxide deposits cannot be avoided even using a well-managed phosphate procedure. Systems with a high magnesium-to-calcium ratio, low alkalinity, and low silica are especially vulnerable to deposit challenges associated with magnesium phosphate (Dew Speciality Chemicals, 2020).

Arachchige and Sandupama (Arachchige and Sandupama, 2019) reported following major parameters must be regarded for smooth boiler operation: (1) suitable monitoring and guidelines in blow down, (2) keeping an appropriate level of DO and TDS in the boiler, (3) providing proper alkalinity level and water pH value and (4) silica, magnesium and calcium amount must be maintained in suitable concentration in feed water by using RO systems for pre-treatment, de-ionization and addition of water softener. RO systems are utilized for the removal of silica from water since it cannot be suitably removed using a water softener. However, because of the significant costs associated with RO systems, they are not usually used in industrial plants. Because deaeration individually is not adequate to control oxygen dosage in water (the main corroding factor), oxygen scavengers, especially sodium sulfide, must be utilized. In this process, sulfites remove free oxygen from water and convert it to sulfate. It is worth mentioning that for the protection of feed water lines, oxygen scavengers' reactions with oxygen must happen before oxygen arrives in the boiler; thus, oxygen scavengers must be injected into the storage of the boiler upstream (Arachchige and Sandupama, 2019). For efficient elimination of suspended solids available in the boiler and also to control and decrease carryover, corrosion, and scale formation, boiler blowdown is utilized (Lekshmi and Pillai, 2015). Lowering the utilization of chemicals for the treatment process, elevating boiler lifetime, decreasing maintenance downtime, lower utilization of makeup water, and reducing pre-treatment costs are some of the major advantages of boiler blowdowns (Jain, 2012).

5.2.1. Oxygen Scavengers

The oxygen molecule especially in the existence of water molecules can accelerate corrosion in industrial equipments (Shokri, 2019, 2020). Oxygen solubility in water is directly proportional to pressure and inversely proportional to temperature. That is, with increasing temperature, oxygen solubility reduces, while with increasing pressure, oxygen solubility increases in the water. The existence of DO in the water systems in different concentrations is the major reason for corrosion in different parts of the boiler. In hot water, oxygen is highly corrosive, even in small concentrations. Also, iron oxide produced by corrosion can generate iron deposits in the boiler. Hence, DO can be significantly challenging. Hence, it is crucial to be well aware of this threat in advance to conduct preventive measures to minimize it (Jafar and Fathi, 2015). Oxygen corrosion happens through an electrochemical reaction. In this reaction, the iron is oxidized (anodic reaction) and distributed into the water. The electrons from oxidation are released and absorbed by DO (cathodic reaction) (Shokri and Sanavi Fard, 2022a, 2022b).

$$\text{Cathodic reaction}: \ 2H_2O + 4e^- + O_2 \rightarrow 4OH^- \tag{1}$$

$$\text{Anodic reaction}: \ Fe \rightarrow Fe^{2+} + 2e^- \tag{2}$$

$$\text{Overall corrosion reaction}: 2H_2O + O_2 + 2Fe \rightarrow 2Fe(OH)_2 \rightarrow Fe_2O_3.xH_2O \ (\text{rust}) \tag{3}$$

In order to control oxygen-driven corrosion, oxygen must be removed from boiler water. In this way, to reduce corrosion, a DO deaerator is used. However, DO is not completely removed in this method, and the residual DO is usually around (0.007) ppm (Jafar and Fathi, 2015). Surprisingly this low quantity can affect corrosion. To remove this residual DO in the boiler water, chemical agents called oxygen scavengers, which are reducing agents, are used. In the boiler systems, oxygen scavengers like sodium sulfite, hydroquinone, hydrazine, carbohydrazide, hydrazine alternatives, methyl ethyl ketoxime, erythorbic acid, MEKO (methylethylketoxime), and DEHA (N, N-Diethylhydroxylamine) are utilized (Ketrick, 2014). Careful selection and appropriate use of the best oxygen scavengers according to any specific system are essential. Sodium sulfite reacts chemically with DO and generates sodium sulfate (optimum pH is 9-10), which is used constantly in the feed water system, like in the deaerator or in the storage section of the feedwater heater. In high-pressure systems, hydrazine is used as an oxygen scavenger and does not partake solids to the boiler. Hydroquinone is utilized as a catalyst for hydrazine, whereas DEHA and carbohydrazide can directly act as oxygen scavengers. Due to the highly quick reaction rate, even in rather cold water, it improves the efficiency of products which is utilized as a catalyst and makes it implemented in low-pressure systems. It is worth mentioning that hydroquinone is aqua toxic and must be used carefully. Carbohydrazide is an alternative to hydrazine which performs like hydrazine; however, without the similar dangers as hydrazine. Similar to hydrazine, it does not participate solids in the boiler. DEHA is a volatile oxygen scavenger, which has the capability to passivate the metal surfaces in the boiler, then pass out of the boiler with the steam, and perform as a metal passivating agent in the return line system. It can be catalyzed with hydroquinone or copper salt. The feed rate of the DEHA is 1.24 ppm of DEHA for one ppm of oxygen. Nevertheless, it has been observed that the best outcomes are with a feed rate of 3 ppm of DEHA for every one ppm of oxygen. DEHA reacts with oxygen and generates acetic acid, which then becomes an acetate salt in the boiler, leaving it with a blowdown (Eq. 4) (Ketrick, 2014).

$$4(CH_3CH_2)_2NOH + 9\ O_2 \rightarrow 8\ CH_3COOH + 2N_2 + 6H_2O \tag{4}$$

MEKO is a volatile oxygen scavenger, which, compares with DEHA, has a greater distribution rate. Hence this enables it to perform more efficiently in long-term condensate systems than DEHA. The distribution rate for MEKO is between DEAE and cyclohexylamine. MEKO has the most rapid reaction time of any sodium sulfite alternative (Ketrick, 2014).

5.2.1.1. Instant Oxygen Scavengers and Instant Volatile Oxygen Scavengers.

To improve the reaction rate of oxygen with sodium sulfite, instant oxygen scavengers like DEWTREAT-200 utilize a catalyst. In low-pressure boilers, oxygen-driven corrosion in the pre-boiler and boiler stages can be efficiently controlled by the application of a suitable concentration of DEWTREAT-200. However, because it is non-volatile, there is not any protection in the post-boiler stage. Hence, an additional 20-40 ppm sodium sulfite is usually presented in the boiler water when it is at the service, which will supply enough reserves of sulfite to control any variations in the boiler feedwater. Sodium sulfite reacts with oxygen to generate sodium sulfate, which shares with dissolved solids in the boiler water (Eq. 5).

$$Na_2SO_3 + \frac{1}{2}\ O_2 \rightarrow Na_2SO_4 \tag{5}$$

In contrast to sodium sulfite, oxygen-hydrazine reaction products do not generate solids in the boiler water and thus rendering it appropriate enough for high-pressure boilers. Hydrazine will react with DO to form nitrogen and water (Eq. 6).

$$O_2 + N_2H_4 \rightarrow 2H_2O + N_2 \tag{6}$$

However, because this hydrazine reaction with oxygen is very slow, DEWTREAT-201 is an instant volatile oxygen scavenger introduced to expedite the reaction. It also removes oxygen content in the feedwater and minimizes pre-boiler corrosion (Eq. 7).

$$6\ Fe_2O_3 + N_2H_4 \rightarrow 4Fe_3O_4 + 2H_2O + N_2 \quad (7)$$

Hydrazine reacts with iron oxide to generate passive magnetite and decreases cupric oxide to passive cuprous oxide. Magnetite performs as a protective layer against additional corrosion, and metal pick-up by the condensate is typically decreased. Aiming to be efficient, the concentration of oxygen scavenger in the feedwater should be such that it causes the suggested reserve of the chemical in the boiler water. Such reverse chemical offers enough safety against any accidental oxygen entrance into the boilers (Dew Speciality Chemicals, 2020).

5.2.2. Neutralizing Amines and Filming Amines

As discussed above, corrosion is induced by the presence of carbonic acid in the condensate. However, by addition of alkaline salts like caustic soda to feedwater cannot neutralize carbon dioxide in the condensate because salt does not volatilize and enter into the steam phase. Hence, by application of organic chemicals, and neutralizing amines, this challenge can be overcome. They can volatilize and enter into the steam phase and react with CO_2 instantly when condensate is produced. Moreover, through the generation of a thin, protective water repellent on the metal surfaces in the condensate system, filming amines provide enough protection against both CO_2 and O_2. However, for large-scale systems, utilizing a combination of filming and neutralizing amines is cost-effective. It is worth mentioning that they can be easily handled and provide outstanding protection against all condensate systems (Dew Speciality Chemicals, 2020).

5.3. Other Problems in the Boiler: Priming and Foaming

Either foaming or priming might cause the carryover of boiler water into the system, which decreases performance. This is because water has only sensible heat and thus will decrease system heat content. Moreover, post-boiler facilities, especially turbines, can be damaged. Priming is the ejection of boiler water into the steam take-off, which usually occurs because of the parameters related to boiler operation, like requiring steam higher than boiler capacity, operating the boiler below its design pressure, and operating the boiler at a high water level. Chemical compositions of water cause foaming. In contrast to pure water, in the existence of certain dissolved or suspended solids, steam bubbles remain small and do not burst. Boiler water pollution by foaming-induced materials like detergent, high concentrations of dissolved solids in the boiler water, and high alkalinity and suspended solids in the boiler water is major reasons for foaming. All of the mechanical parameters can be bypassed through modification of the operating conditions. Although the extent to which each facet of the water properties contributes to foaming is not completely realized, generally, the effect of suspended solids is higher than dissolved solids or alkalinity. With the addition of antifoaming (definite organic matter), the surface condition of steam bubbles is affected and makes them blend again. Also, blowdown can be considerably decreased by the application of antifoaming (Dew Speciality Chemicals, 2020).

6. Performance Enhancement in Boilers

Because the annual cost of fuel can simply be twofold or threefold higher than the installed cost of facilities, maximizing boiler performance is absolutely critical. Hence, considerable improvements in boiler performance and fuel cost can effectively compensate for high capital costs. Boiler performance is highly complicated when all of the influential parameters in boiler performance are regarded and a thorough thermodynamic study is conducted. Fuel-to-steam performance, combustion performance, thermal performance, and boiler performance itself are common terms of performance applied in the boiler context (Alazemi et al., 2019). Boiler performance has a considerable effect on heating-associated energy storage, and it needs minimization of heat losses in the boiler and the maximization of heat transformation to the water (Kuntal Bora and Nakkeeran, 2014). In boiler operations, thermal performance occasionally is the performance of heat exchangers (fuel-to-steam performance). This type of performance is crucial, although its calculation in real-world conditions is hard. Hence, combustion performance that can be readily calculated utilizing a combustion gas analyzer is commonly applied for efficiency comparison aims (Shah and Adhyaru, 2011). For testing boiler performance, two direct methods (a comparison between the energy content of boiler fuel and working fluid) and an indirect method (variations between input energy and losses) are used. Conduction of maintenance plans is also essential to increase boiler efficiency. Economizer tubes and air-preheater are essential parts. Based on the maintenance plan, wall thickness analysis, leak test, and tube cleaning must be performed. For components of the flue gas path, corrosion checks and wall thickness calculations should be performed (Jadeja and Zala, 2017).

Recycling flue gas heat by innovative approaches is one of the solutions to maximize industrial boiler performance. However, since boiler operations generate massive volumes of greenhouse gas emissions, exploring new renewable fuels to operate boilers is essential (Mgbemene, 2011). Airflow, burner performance, furnace pressures, and temperatures, the water level within the boiler, water flow, and boiler feedwater quality are some of the major parameters which greatly determine the appropriate operation of boilers. The full realization of boiler control systems is critical as they are major consumers in the energy portfolio. Hence, energy recovery to minimize energy loss would be a suitable approach to energy management. Generally, maximum heat recovery, application of alternative and renewable energy sources to decrease environmental footprints and cost reduction, and enhancements in boiler water treatment methods are among the main solutions for the optimization of industrial boilers (Siriwardena, 2020).

Between boiler performance and fuel and energy, cost there is a close connection as maintenance of ineffective boilers is cost-prohibitive. It is worth mentioning that not only older boilers have low performance, but they also are great emitters of greenhouse gases (Einstein et al., 2001). Economizer capacity, fuel combustion, and fuel-air ratio are some of the parameters that determine boiler performance and energy saving. As a result, maximizing heat transformation to water and minimizing heat loss in the boiler is crucial (Al-ghandoor et al., 2009).

Ambient temperature, boiler blowdown and maintenance, combustion, and rate of heat transformation are the main parameters that heavily affect overall boiler operating efficiency (Siriwardena, 2020). Effective and regular boiler maintenance to extend equipment lifetime is essential (D. Elettronica, 2019). Low heat transformation is another serious challenge in boiler performance. Corrosion and dust particle deposition across heating facilities are the main factors that considerably decrease heat conductivity hence resulting in significant flue gas temperature at the outlet and finally reducing boiler performance (Mallikarjuna et al., 2014). Hence, maintaining the surface of facilities clean enough is important. With decreasing component height, hot end baskets must be changed with the middle ones, and to increase heat transformation rate, dual rolled baskets can be utilized. Because the operability of boilers heavily relies on combustion performance, their optimization is crucial for maximizing boiler efficiency as well (Siriwardena, 2020). Theoretically, although the increasing ratio of fuel/air will increase the combustion rate, however, excessive amounts of air will result in incomplete burning of combustion. Installation of an oxygen sensor or transmitter will suitably optimize this ratio (Chu et al., 2003). Installation of automatic blowdown systems in boilers can save considerable amounts of energy (Gupta et al., 2011). The ambient temperature generated by the operation of the boiler has a fair influence on both the boiler and chimney performance (Gupta et al., 2011). For example, a 40 °C change in temperature can affect boiler performance by up to 1% (Djayanti, 2019). Fig. 5 demonstrates major sources of energy loss in the boiler (Siriwardena, 2020).

Boiler heat recovery can be used to minimize adverse environmental emissions, increase process performance, minimize fuel consumption,

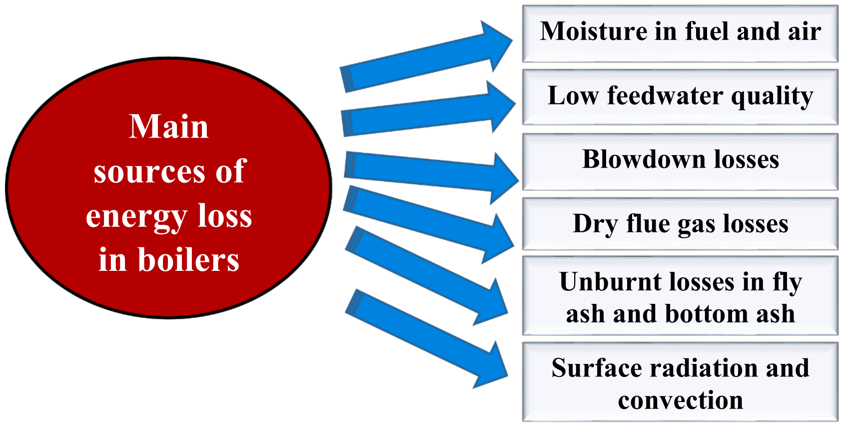

Fig. 5. Major sources of energy loss in the boiler. Based on (Siriwardena, 2020).

and cost reduction. Following are some practical recommendations for maximizing boiler energy performance (Siriwardena, 2020):

(1) Blowdown heat recovery by application of heat recovery exchanger or flash vessel.
(2) Fuel preheating by electric heating coil or boiler steam to make boiler combustion effective.
(3) Air preheating by flue gas of the boiler system to increase combustion performance.
(4) Maximizing application of hot condensate water as proper boiler feedwater.
(5) Application of economizer to use remaining heat energy of flue gas to heat boiler feedwater.
(6) Suitable boiler insulation to minimize radiation-driven heat losses.
(7) Feedwater pre-treatment to minimize scale, sludge, and corrosion.
(8) Comparing flue gas temperature variations with oxygen content, ambient temperature, and steam load to monitor boiler performance.
(9) Management of boiler combustion to minimize additional air.

7. Boiler Maintenance Methods and Benefits

Procedures for suitable use of the assets like machines and equipment, precise historical operating data, and technical skills are prerequisites of suitable maintenance. Ensuring safety, service life, and smooth system function with minimum costs are the major purposes of maintenance (Alsyouf, 2007). Three inextricable but various decision dimensions, namely the resources dimension, risk dimension, and output dimension, are thought to regard at the same time. These will be optimized for maintenance comprehensively (Alazemi et al., 2019). Fixing any failure in the boiler operation only after its occurrence is known as reactive maintenance. This type of maintenance is simple as it does not need any monitoring or planning in advance, and exactly due to this reason, it is not the most efficient maintenance. Thus, reactive maintenance in the boiler can be totally expensive, considering serious consequences like a significant decrease in the boiler service life and labor costs due to the fixing boiler to prevent any further boiler downtime (Alazemi et al., 2019). Also, it is quite clear that failure under reactive maintenance is highly likely and frequent (Daley, 2005). In this way, preventive or proactive maintenance (precise monitoring of boiler facilities to predict and avoid failures like plant shutdown) of the boiler is strongly recommended because it includes procedures that greatly enhance system condition by efficiency optimization and avoiding unintentional boiler operation failure. Careful inspection, servicing, fixing, or replacing physical parts of machinery and equipment according to the provided timetable are some of the main processes during preventive boiler maintenance. Preventive maintenance implies that there would be enormous returns for plants with higher value in terms of equipment and asset. It is unanimously concerted that preventive maintenance is greatly efficient in terms of minimizing boiler maintenance costs and maximizing equipment reliability (Oyedepo and Olayiwola, 2011). The historical operating data of the boiler is considered the backbone of an efficient preventive boiler maintenance plan. Fuel consumption, flue gas temperature, condensate temperature, oil pressure, and temperature, feedwater pressure and temperature, operating pressure and temperature, and water level are critical sectors based on boiler operators gathering daily data (Alazemi et al., 2019).

In contrast to reactive maintenance, boiler failure is obviously less likely in the preventive maintenance of the boiler (Daley, 2005). Through careful data monitoring based on the recorded schedule, like monthly or weekly, it is quite easy to detect changes and trends that indicate any service. It is worth mentioning that regardless of routine boiler maintenance performed by operators, periodical professional inspections (yearly) are recommended. Ultrasonic testing, magnetic particle testing, and liquid penetrant testing are the traditional professional methods for the non-destructive inspection of boiler equipment (Shimomura et al., 2002). In addition, strict monitoring of boiler operating logs is crucial. All records of critical parameters, water chemistry activities, and safety device tests must be written systematically. In conclusion, the following are the main benefits of the preventive boiler maintenance method: Enhanced safety and quality conditions, recognition of boiler facilities with significant maintenance prices, identifying areas that require proper operator training, decreased fixing costs due to decreasing secondary failures, decreasing overtime costs and cost-effective use of maintenance workers, preventing premature replacement of boiler machinery and equipment by increasing service life and effective assets conservation and reducing downtime (Schoonahd et al., 2012).

8. Cost Analysis of the Boiler Water Treatment Process

The cost of boiler water treatment is one of the complicated and critical parameters which must be determined in advance. Despite the complexity of determining precise boiler water treatment costs, they can be decreased based on different parameters like makeup water chemistry, manufacturer recommendations, and different boiler pressures. The major parameters that will ascertain the cost of boiler water treatment will be discussed here as presented in Fig. 6. Regarding boiler water treatment, understanding the required water quality and makeup quantity is crucial because poor water remediation can cause fouling, corrosion, and scaling of the boiler and downstream facilities (Samco, 2020).

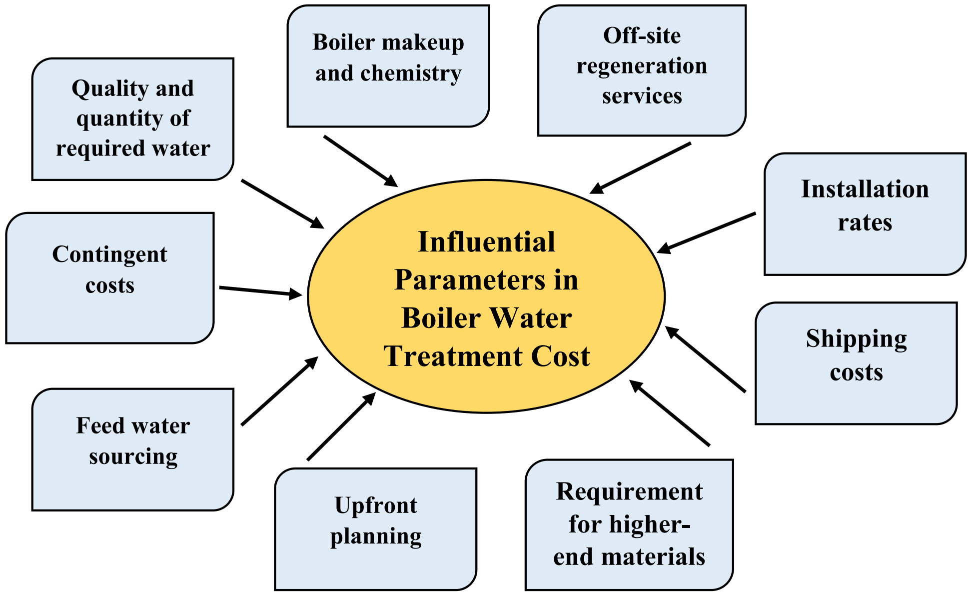

Fig. 6. Influential parameters in boiler water treatment cost. Based on (Samco, 2020).

(1) **Installation rates.** Typically installation rates for a boiler feed water remediation system will be 15-25% of the project. Generally, they have a lower footprint and do not need as much civil or construction work. It must be kept in mind that the installation rates are case-specific. Because the boiler feed water remediation systems are typically prepackaged, their footprint is usually lower (almost 100×100 feet is the average size).

(2) **Feed water sourcing.** The selection of a feed water source is an essential factor in minimizing capital and operating costs. These sources might be well water, in-plant recycled wastewater (cooling tower or blowdown recycling), city-treated effluent, city water, and the like.

(3) **Quality and quantity of required water.** The quality of boiler feed water relies on the operating pressure of the boiler in relation to the required volume of water to process per day (gallons per minute, GPM). For a given pressure, there is the highest level of pollutants that can be fed into the boiler, and with increasing boiler pressure, providing high-quality water is essential. Generally, the cost for a lower pressure boiler (600 PSI and lower) feed water remediation system utilizing adequately pretreated water can be approximately between 50,000 to 100,000 $ at 100 GPM, and with the requirement to softener and dealkalizer, it would be between 100,000 to 250,000 $. For the high pressures boilers, based on the quality of pretreated water, the cost would be almost 500,000 to 1,000,000 $ for 100 GPM, and for 200 GPM, it would be between 1,000,000-1,500,000 $.

(4) **Off-site regeneration services.** Many companies which require a polishing component in their boiler feed water remediation system outsource resin regeneration. This approach not only reduces the quantity of needed labor and maintains the capital cost of the system low but also removes the requirement to maintain specific chemicals on hand, like acid and caustic. Thus, to a great extent, mitigate concerns regarding discharge regulations.

(5) **Boiler makeup and chemistry.** Although boiler chemistry, which is dependent on boiler makeup, is complicated to predict, a reasonable evaluation will assist in the choice of the required method for the treatment of boiler feed water.

(6) **Shipping costs.** Typically shipping cost is almost 5-10% of the whole cost of the equipment. However, it may significantly fluctuate based on the time of purchasing and plant location.

(7) **Requirement for higher-end materials.** A basic boiler feed water system might have plastic vessels, plastic piping, and multiport valves. Industrial equipment like refineries and power plants need a highly effective treatment system like stainless steel piping with industrial valve nests and rubber-lined vessels. Hence these industrial criteria raise the cost of the system by 50-100%.

(8) **Upfront planning.** There are several costs related to developing the concepts, designs, and regulatory requisites for boiler feed system projects. Usually, the cost of engineering for a boiler water treatment will be almost 10-15% of the entire project cost.

(9) **Contingent costs.** When purchasing a boiler feed water remediation system, it must be considered that there might be other contingent costs. Like, as environmental regulatory costs or permits, possible utility costs associated with installation location, related costs to remediating the secondary waste generated by the system, and system taxes or further purchasing costs. For instance, with severe environmental guidelines, the waste for discharge should be treated or solidified and transported to a third-party disposal firm.

9. Conclusion and Research Perspectives

Because of various adverse effects like scale deposition, corrosion, and equipment damage, various boiler feed water treatment methods have been explored. Different impurities in the water can pose significant challenges. Hence, detrimental issues can be avoided through precise data monitoring and implementing suitable countermeasures. In this context, exploring economic and highly efficient boiler water treatment methods is of prime concern. Nowadays, a great share of industries utilize fuels that present serious negative repercussions like environmental contamination, climatic variations, and massive quantity of greenhouse gases. Hence, intensive research efforts are required to explore green fuels which are environmentally benign. Also, due to the expensive costs of fuels and associated operating costs, maximizing heat recovery and suitable energy management methods are extremely urgent. Condensate water and blowdown recovery, insulations, preheating, and application of economizer are some of them. All in all, the authors conclude that regardless of several considerable progress in the field of boiler water treatment, in order to completely curb pernicious feedwater-related challenges of the boiler, there is still much research work to do.

In this context, the following are the recommendations to demarcate future research pathways:

(1) Recycling flue gas heat using innovative methods, installing automatic blowdown systems and blowdown heat recovery, optimization of economizer capacity, rate of heat transformation, fuel combustion, and fuel-air ratio to maximize boiler performance.
(2) Exploring new renewable fuels and conducting life cycle assessments to explore and mitigate any adverse environmental footprints.
(3) Fully realization of governing parameters in the operation of the boiler to minimize factors associated with the energy portfolio.
(4) Investigating innovative corrosion resistance materials to prevent corrosion and dust particle deposition across heating facilities
(5) Identification, management, and mitigation of main sources of energy loss in boilers to save considerable amounts of energy.
(6) Fuel preheating by electric heating coil or air preheating by flue gas of the boiler to make boiler combustion effective.
(7) Maximizing application of hot condensate water as proper boiler feedwater.
(8) Suitable boiler insulation to minimize radiation-driven heat losses.
(9) Feedwater pre-treatment to minimize scale, sludge, and corrosion.
(10) Careful monitoring, identifying areas that require proper operator training, decreased fixing costs due to decreasing secondary failures, servicing, fixing, or replacing physical parts of machinery and equipment based on the provided timetable to prevent additional maintenance.
(11) Conduction of non-destructive inspection of boiler equipment via ultrasonic testing, magnetic particle testing, liquid penetrant testing, and other advanced methods.
(12) Optimization of major influential factors in the selection of the best feedwater treatment process, including furnace tube geometry, boiler pressure, superheater, steam end use, the steam disengaging area in the drum, economizer, heat flux, and condensate recovery.

CRediT authorship contribution statement

Aref Shokri: Data curation, Methodology, Visualization, Investigation, Supervision, Validation, Software, Resources. **Mahdi Sanavi Fard:** Supervision, Writing – original draft, Writing – review & editing, Methodology, Formal analysis, Project administration, Validation, Investigation, Software, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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