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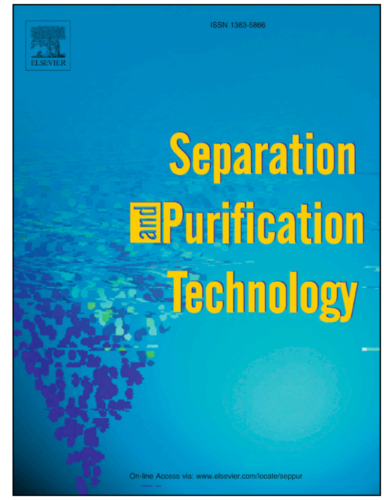

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PII: S1383-5866(17)33219-7
DOI: https://doi.org/10.1016/j.seppur.2018.06.023
Reference: SEPPUR 14677

To appear in: *Separation and Purification Technology*

Received Date: 4 October 2017
Revised Date: 2 June 2018
Accepted Date: 7 June 2018

Please cite this article as: C. Cruz, L.A. Cisternas, A. Kraslawski, Scaling problems and control technologies in industrial operations: Technology Assessment, *Separation and Purification Technology* (2018), doi: https://doi.org/10.1016/j.seppur.2018.06.023

Scaling problems and control technologies in industrial operations: Technology Assessment

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ABSTRACT

Calcium and magnesium ions are the major components of scaling in different water sources, especially seawater. Calcium and magnesium scale causes problems in various industrial operations such as reverse osmosis unit, heating unit of multi-stage flash distillation, concentration operation of copper-molybdenum mining industry, cooling water system of power generation industry, and water injection operation of oil and gas production. In general terms, scaling affects the operation performance that leads to increased production, as well as maintenance costs. The pH control, scale inhibitors, and nanofiltration membrane have been implemented by industrial operations to control scale. However, the drawbacks of these technologies may force to seek alternative technologies which could be potential alternatives for scale control.

This paper discusses the problems of calcium and magnesium scale affecting various industrial operations when seawater is used. It presents current technologies for scale control such as pH control, scale inhibitors, and nanofiltration. Moreover, the technology assessment (TA) was made to evaluate existing and emerging scale control approaches in the case of reverse osmosis (RO) process. The identification of the emerging technologies of scale control has been performed using bibliometric analysis. The comparison of the technologies was made using House of Quality (HOQ) matrix. The identified emerging technologies are: bioelectrochemical system, biomineralization, biosorbent, microbial desalination cells, step by step deposition and extraction technique, carbon dioxide as a precipitator, gas hydrate, ultrasonic crystallization, and capacitive deionization. The comparison of the technologies has shown that nanofiltration, as a common technology, could be an appropriate approach to ensure feasibility and efficiency of RO process, while emerging technology, microbial desalination cells, could become a potential alternative in the future.

Keywords: seawater; technology assessment; scale control technologies; scaling, hardness ions.

1. Introduction

Water is a key element for agriculture, urban, and industrial development sector. However, many places in the world are facing water shortages and lack fresh water. Some of the major causes are climate change, rapid population growth, limited natural resources, and unsustainable development (Mahmoud and Obada, 2014). As less than 3% of the world's water is fresh while the rest is seawater (Fry and Martin, 2005), the oceans and seas have become potential sources of water supply for industrial, urban, and agriculture sectors in semi-arid, arid, and hyperarid regions. For the industrial sector, quality of water is essential for its operations to achieve expected performance and desired specification of final products. Seawater quality is not suitable because it contains more dissolved ions of all types than fresh water. Nevertheless, it is used in several industrial operations, including reverse osmosis (RO) units, heating units in multi-stage flash distillation (MSF) (Khayet, 2016), cooling water systems in power generation industry (Pugh et al., 2005), water injection in oil and gas production industry (Bader, 2007), and concentration operation in copper-molybdenum mining industry (Jeldres et al., 2017).

Industrial operations, in which seawater is used face problems of corrosion, biofouling, and scaling (Demadis et al., 2007). The latter occurs when soluble minerals precipitate from seawater and deposit on surfaces that affect the performance of industrial operations. Scale deposition increases the costs of production linked with maintenance costs that cause losses billions of dollars (Gilron, 2013). Calcium and magnesium are the main ions that cause scaling problem and their scale deposits are calcium sulphate ($CaSO_4$,), calcium carbonate ($CaCO_3$), calcium fluoride (CaF_2), calcium phosphate ($Ca_3(PO_4)_2$), magnesium hydroxide ($Mg(OH)_2$), and magnesium carbonate ($MgCO_3$) (MacAdam and Jarvis, 2015).

The pH control, scale inhibitors and nanofiltration membranes are the most common technologies for scale control (Jwa et al., 2017; Mahmoud et al., 2016). However, these technologies present some disadvantages, e.g. risk of contamination of the marine environment, corrosion and high energy consumption. During the last decades, the technological advances have allowed developing new technologies, which can provide competitive advantages over current scale control technologies. Besides, it has provided many options for designing and improvement current scale control technologies. Technology development offers not only economic benefits, but also could reduce negative impacts on the environment contributing to the sustainable development (Ibáñez-Forés et al., 2014).

Technology assessment (TA) in an important field which has evolved over the past four decades (Tran and Daim, 2008). TA is essential for managers and decision makers to understand the circumstances in which a given technology is could be used. We see it being developed increasingly in the industrial sector to improve deficiencies in existing technologies or to introduce new technologies for minimizing the environmental impact of companies. TA can be relevant in determining new technology adoption, research and development direction, incremental improvement of existing technologies, level of technology friendliness, “make or buy” decision, identification market advantage, optimal expenditure of capital equipment fund and market diversification (Henriksen, 1997).

Information monitoring is an important stage of TA. It allows monitoring a technology in question, as well as providing exhausting information to decision makers. One of the methods of information monitoring is bibliometric analysis. It has been used to analyze information in various filed, e.g. medicine, social science, engineering, environmental science (Abejón and Garea, 2015). TA comprises also others stages ranging from the formulation of criteria to a final decision based on the technology comparison (Ibáñez-Forés et al., 2014). One of the methods for technologies comparison is House of Quality (HOQ). It is a tool that allows the translation of customer needs into technical characteristics of a technology or process under evaluation (Ramírez et al., 2017). HOQ is a conceptual matrix that has been used for the development and improvements of technologies or processes in various industries due to its simplicity and effectiveness (Yang et al., 2015).

This study seeks to achieve two objectives; first, to present the calcium and magnesium scale problems that affect different industrial operations when seawater is used. The second objective is to assess scale control technologies. Existing and emerging technologies of scale control are presented to conduct the technology assessment. The emerging technologies to control scales were identified through a bibliometric analysis in a subject-specific literature. Next, HOQ matrix is applied to compare scale control technologies for RO process.

1.1 Industrial operations affected by scale deposition

Scaling is described as precipitation or crystallization of inorganic salts, such as calcium, magnesium, carbonate, sulphate, phosphate, and silica that allow depositing minerals on the surface (Antony et al., 2011). Precipitation is a process which results in a rapid formation of solids that can produce small crystals at the beginning, which promotes scale formation and its deposit. Supersaturation is the main factor that leads to precipitation; it occurs when the activity of ions in the solution is above their saturation limit (MacAdam and Jarvis, 2015). This condition allows rapid nucleation of scale formation and growth of the crystal. However, temperature and pH of water environment, the presence of impurities, changes in pressure, hydrodynamics, and flow velocity are other factors to trigger precipitation of inorganic salts (El et al., 2011).

Scaling can be present in different types depending on operating conditions. In general terms, calcium and magnesium scales, such as $CaCO_3$, $CaSO_4$, $Ca_3(PO_4)_2$, MgOH, $MgCO_3$, calcium silicate (Ca_2SiO_4), and calcium hydroxide ($Ca(OH)_2$) have an inverse solubility, i.e. their solubility decreases with increasing temperature. While, other species are sensitive to pH, where scale formation increases with increasing pH; this is true of $CaCO_3$ and MgOH (MacAdam and Jarvis, 2015). So, scale deposition depends on the operating conditions of the industry.

As was mentioned above, scaling is a common problem in various industrial operation that uses seawater either directly or indirectly. Desalination industry uses seawater directly as feed water to obtain fresh water. In the RO process, concentration polarization takes place in the RO unit and is the main factor that promotes various scales formation on semipermeable membrane surfaces (Gilron, 2013). The phenomenon occurs when solute tends to accumulate on membrane surfaces while the solution passes through the membrane. This way, it increases retention of large molecules on membrane surfaces, while retention of small molecules decreases. Therefore, scale film blocks membrane pores, decreasing permeate flow and efficiency of water recovery as well (Arras et al., 2009). The scales of $CaCO_3$, $CaSO_4$, $Ca_3(PO_4)_2$, and CaF_2 are the main sources of scale deposits on semipermeable membrane surface (Antony et al., 2011; MacAdam and Jarvis, 2015). On the other hand, MSF is carried out at temperatures as high as 120 °C and scale are formed mainly due to thermal effects of the process because some scales have inverse solubility. Scaling affects mainly the heating unit in the MSF process, depositing on heat exchanger surfaces. Also, the release of carbon dioxide gas (CO_2 (g)) from evaporation brine in heating unit leads to the changes in pH of the solution, which influences the concentration of bicarbonate (HCO^-_3), carbonate (CO_3^{2-}), hydrogen (H^+) and hydroxide (OH^-) ions and induces carbonate scale deposition (Al-Anezi and Hilal, 2007). The scale of $Mg(OH)_2$, $CaCO_3$, and $CaSO_4$ blocks the flow of water on heat exchanger surface reducing heat transfer, as well as decreasing the operation performance (Al-Rawajfeh, 2005). Furthermore, scale deposits increase fuel consumption between 10 and 15% in comparison to free of scale situation (Knudsen, 1990). For both, RO and MSF desalination processes, scaling not only reduces water production rate and its quality but also increases the cost of water and shortens the life of components that are in contact with scale (Khayet, 2016).

Mining is another industry that uses seawater directly in its operations and its consumption in different metal and non-metallic mining industries have increased across the world (Dreisinger et al., 2008). Some mining industries are more affected than other when using seawater and depend on the type of mineral to be treated and the operating conditions. Concentration operation of copper-molybdenum sulfide ores is especially affected when seawater is used due to the presence of calcium and magnesium ions (Jeldres et al., 2017). Scale formation takes place when the operation is carried out in an alkaline environment to depress non-valuable minerals (Castro, 2012). Precipitation of calcium and magnesium species occurs leading to the formation of the scale of $Mg(OH)_2$, $CaCO_3$ and $CaSO_4$ on the surface of valuable ores, mainly on molybdenum ore, at pH >10 (Laskowski and Castro, 2012). Thus, operation performance decreases because scale disposition decreases the recovery of valuable minerals. Also, some concentration operations of copper-molybdenum sulfide ores are conducted in closed water circuits to recycle water into the operation. Recycling of seawater leads to the accumulation of calcium and sulphate ions, which can precipitate on molybdenum surface as $CaSO_4$, reducing their recovery by around 20% (Lucay et al., 2015).

The cooling water system is another operation that uses seawater as a coolant, either directly or indirectly, due to high heat capacity that it presents. The operation is used in various industries e.g. in chemical plants, steel mills, and oil refineries, however, power generation industries consume huge amounts of seawater (Pugh et al., 2005). Cooling water system involves seawater circulation through a network of heat exchangers to remove heat from the process. During the operation, changes in temperature and pressure drops are the main factors that cause scale formation of $CaCO_3$, $Mg(OH)_2$, $CaSO_4$ and $Ca_3(PO_4)_2$ on heat exchanger surfaces (MacAdam and Jarvis, 2015, 2015). Scale increases the resistance to heat transfer and decreases thermal efficiency of the equipment (Pugh et al., 2005).

On the other hand, seawater is used indirectly in processes for oil and gas production located offshore and near the coast. Seawater is the most common option for water injection operations to obtain oil and gas as in the case of Arabian Gulf (Bader, 2007). Changes in temperature and pressure in the operation promote the formation of $CaCO_3$ scale, while the mix of brine waters with a high content of sulphate and calcium ions promotes $CaSO_4$ scale formation (MacAdam and Jarvis, 2015). Therefore, scaling blocks the tubes and flow lines of water injection and deteriorates operating performance (Bader, 2007).

1.2 Common technologies for scale control

Seawater has a complex chemistry profile that inevitable contains some ions interfering with the performance of industrial operations. In particular, calcium and magnesium ions from seawater are the common ions that cause scaling problems. To control scale formation and its deposition, technologies have been implemented: pH control, scale inhibitors, and nanofiltration membrane (Jwa et al., 2017; Mahmoud et al., 2016). Table 1 shows the relationship between technologies used by the industrial operations commented above. Also, a description of these technologies are presented below.

Table 1

Technologies for scaling control used in industrial operations.

Operation affected	Technologies for scale control		
	pH control	Scale inhibitors	Nanofiltration membrane
RO unit	✓	✓	✓
Heating unit of MSF	✓	✓	✓
Concentration operation of copper-molybdenum mining	✓		
Cooling water system of power generation industry	✓		
Water injection operation of oil and gas production		✓	

1.2.1 Scale inhibitor

Scale inhibitor or antiscalant is a chemical reagent used to control the formation and/or deposition of scale. It does not eliminate the components of scale formation but prevents crystal nucleation and crystal growth (Hasson et al., 2011). To select a specific antiscalant and its doses, it is necessary to carry out tests to find out the composition of feed water and identify types and concentration of inorganic salts. Further, the type and efficiency of antiscalant will depend on the nature of the feed seawater and the conditions of the industrial operation to which they are applied (MacAdam and Jarvis, 2015). As shown in Table 1, RO unit, heating unit of MSF, and water injection operation of oil and gas production use scale inhibitor (Hasson et al., 2011). Regarding desalination processes, commercial scale inhibitors available to RO process are phosphates, phosphonate and polycarboxylates, and sodium hexametaphosphate ($(NaPO_3)_6$) as the first antiscalant available to the membrane industry (Antony et al., 2011). Thermal desalination processes use antiscalants of polycarboxylic acid species and phosphonate as well, being the low-molar-mass polymers or copolymers of acrylic or maleic acid the commercial antiscalants available (MacAdam and Jarvis, 2015). While, in water injection operation of oil and gas production, the two main categories of antiscalants used are polymers and non-polymers; polymers prevent scaling nucleation, while non-polymers prevent the crystal growth (MacAdam and Jarvis, 2015).

1.2.2 pH control

The pH control takes place through the dosing of acid to reduce pH of the feed seawater to 5-7. The acid reacts with carbonate and hydroxide ions present in seawater yielding H_2O and CO_2 and preventing the formation of $CaCO_3$ and $Mg(OH)_2$ mainly because ions remain soluble into the solution (Al-Hamzah and Fellows, 2015; MacAdam and Jarvis, 2015). As shown in Table 1, RO unit and MSF heating unit (Greenlee et al., 2009) and cooling water system (Müller-Steinhagen, 1999) use acid for scale control. Sulfuric acid (H_2SO_4) and hydrochloric acid (HCl) are common acids used in these industrial operations. Meanwhile, concentration operation of copper-molybdenum ores uses sodium metabisulfite reagent to avoid operating at pH >10 when scaling occurs on the surface of valuable minerals. The use of sodium metabisulfite allows operating at a slightly acidic pH, which keeps calcium and magnesium ions soluble in seawater (Cisternas et al., 2014). Thus, high recovery of valuable minerals can be obtained.

1.2.3 Nanofiltration membrane

Nanofiltration membrane (NF) is a pressure-driven, membrane-based separation process. Membranes are ion-selective and their retention rates are determined according to ions valence. Thus, monovalent ions such as chloride, sodium, and potassium can pass through membranes, while multivalent ions such as calcium, magnesium, carbonate, and sulfate are retained on the membrane (Koyuncu et al., 2015). NF is used as pretreatment for RO and MSF processes (see Table1). When it is introduced in RO process, the osmotic pressure of seawater fed to RO is reduced, which leads to the lower energy consumption of the system by about 25 - 30% and higher water recovery rate of more than 70% (Kaya et al., 2015; Llenas et al., 2013). Meanwhile, when NF is introduced to MSF process, it can operate at higher top brine temperature in the range between 120°C and 160°C, which increases plant production and improves water cost due to the reduction of sulfate, calcium and magnesium and carbonate ions from seawater (Hassan et al., 1998).

2. Methodology

2.1 Technology assessment

Technology assessment can help in reduction of the inherent risks of the competitive process of technologies by providing information in support of decision making (Henriksen, 1997). TA can be defined, according to Coates (2001) "as a policy study designed to better understand the consequences across society of the extension of the existing technology or the introduction of a new technology with emphasis on the effects that would normally be unplanned and unanticipated". To achieve this goal, several approaches and a wide range of methods and tools have been utilized e.g. impact analysis, scenario analysis, risk assessment, decision analysis, identification of emerging technologies, cost-benefit analysis methods, information monitoring, roadmapping (Tran and Daim., 2008).

Information monitoring is a critical step in TA before the comparison of technologies. It provides information about technologies in question, both existing and emerging, as well as supply valuable information to decision makers. It must be stressed that the final results obtained in TA will depend strongly on the selection criteria. The choice of criteria must be done by the decision maker based on their own opinion, and the rational method can be used to reinforce their selection (Ibáñez-Forés et al., 2014).

In this study, a bibliometric analysis is carried out to identify emerging technologies for scale control. Next, HOQ matrix is applied to compare emerging and existing scale control technologies. The selection of criteria used in HOQ matrix is based on the customer needs.

2.2 Bibliometric analysis

Bibliometric is a research method of information monitoring that facilitates the organization and analysis of the topic in question. It measures the data through a quantitative analysis that allows classifying information in given categories. Typical categories include a number of publications and productivity, type of documents published, publication year, collaboration between authors, keywords, citation network, research areas, and so on (Li et al., 2015; Abejon and Garea, 2015).

The analysis bibliometric in this study was conducted to find studies related to emerging technologies for calcium and magnesium scale control, mainly from seawater. To do it, the keywords related to seawater, treatment, technology, calcium, magnesium, hardness, and scaling were combined to search relevant papers using the

Web of Science database. The timeframe of the searched was between 2000-2017. This period was chosen as after 2000 new laws and regulations have been introduced aiming at the reduction of the environmental impact caused by various technologies. An example of such regulation is European Union through Council Directive 96/61 / EC on prevention and integrated control of pollution (Ibáñez-Forés et al., 2014).

2.3 House of quality

HOQ methodology is a key component of the quality function deployment (QFD) tool for decision making. QFD considers designing a product/service based on customer demands that involve the members of the producer or supplier organization. Basically, it allows that customers and industry think together to produce a quality technology or process that is manageable, attractive, useful, and profitable (Zare, 2010). The main purpose of QFD is to consider customer's needs during the design, construction and delivery process to obtain a higher quality product or process in the market (Akao and Mazur, 2003).

HOQ methodology is a conceptual matrix that provides the means for the planning and communications between customers and industry (Hauser and Clausing, 1988). The development of the HOQ matrix allows to establish priorities for the needs of the customer, identify deficiencies in compared technologies that lead to improving them, fluent communication among customers, engineers, and managers, and better manufacturing decision making (Ramírez et al., 2017; Yang et al., 2015). The HOQ matrix has a defined structure composed of different sections (see Figure 1) which are defined below:

I. Customer attributes: is the initial input to build HOQ, which is a list of the requirements of the product or service focuses on important needs of the customer in order to express “the voice of the customer”. It can be obtained through focus groups, interviews, existing data in the literature, customer complaints and so on (Ramirez et al., 2017; Zare, 2010).

II. Relative importance: is a weight established by the customer. It shows how important is every need with respect to the other ones.

III. Engineering characteristics: is a list of technical parameters about the product or service that can be measured and that should satisfy each customer attribute.

IV. Correlation matrix: is the roof of HOQ and shows the strength of interaction between engineering characteristics through symbols.

V. Competitive benchmarking: is customer perception that compares competitors, be it technology or service, against each attribute listed by the customer to identify opportunities for improvement. In other words, it helps to understand how customers rate the competition and it is expressed through a scale of points.

VI. Relationship matrix: is the body of HOQ and indicates the relationship between customer attributes and engineering characteristics. It is represented by symbols or numerical value.

VII. Objective measure: is a target value for each engineering characteristics and can then act as a baseline to compare.

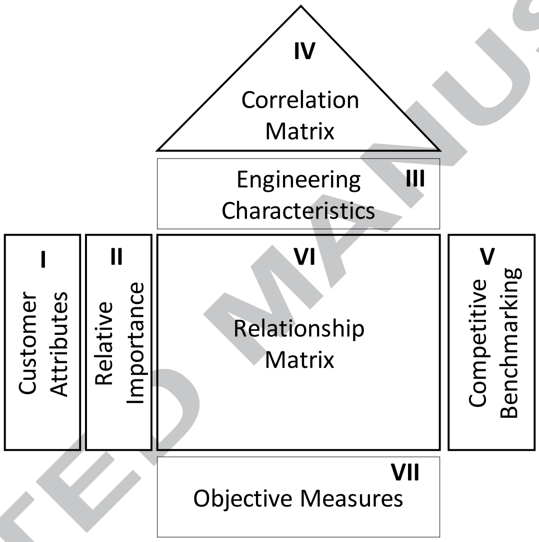

Fig. 1. Structure of HOQ. Adapted from Adiano and Roth, 1994.

3. Results and discussion

3.1 Potential future technologies for scale control

Biosorption (Mahmoud et al., 2013), biomineralization (Arias et al., 2017), bioelectrochemical system (Nam et al., 2015), microbial desalination cells (Brastad and He, 2013), gas hydrate (Park et al., 2011), carbon dioxide as a precipitator (Zhao et al., 2013), capacitive deionization (Seo et al., 2010), ultrasonic crystallization (Su et al., 2015; Chen et al., 2016) and layer by layer chemical deposition technique (Mahmoud and Obada, 2014) are emerging technologies as a potential alternatives to calcium and magnesium scale control identified from bibliometric analysis.

Biosorption is a physicochemical process that uses microorganisms as biosorbent. It involves the interaction of ionic species and functional groups present on the surface of the cell of a microorganism able to adsorb ionic species according to their size and specific charge. Meanwhile, biomineralization is a process by which living organisms produce minerals as a result of their cellular activity that promotes physicochemical conditions necessary for the formation and growth of minerals. In other words, bacteria have the ability to induce minerals formation (Achal, 2015). Bio-electrochemical system and microbial desalination cells (MDC) can generate electricity from chemical energy produced by microorganisms as biocatalysts and remove several ions from aqueous solutions (Subramani and Jacangelo, 2015). The difference between both technologies is their system design. MDC is composed of three chambers; anode, cathode and a desalination chamber in the middle separated with an anion-exchange membrane and a cation-exchange membrane. Bacteria growing on the electrode in the anode chamber oxidize organic substrate generating bioelectricity due to the potential difference across the electrode chambers. In addition, positively charged ionic species move to the cathode through a specific cationic membrane, where they combine with electrons and oxygen species to produce soft water (Saeed et al., 2015; Sophia et al., 2016). Meanwhile, the bio-electrochemical system is composed of two chambers (cathode and anode) separated with an anion-exchange membrane only. The microorganisms convert organic matter into electrical current in the anode chamber, while in the cathode chamber electrons and protons catalytically combine by reducing oxygen to water. Proton consumption at the cathode increases pH (at the cathode surface) inducing precipitation of metal ions (Nancharaiah et al., 2015; Chen et al., 2013).

Gas hydrate is a technology based on the crystallization of salts. It consists of a long column pressurized with saline solution and gas such as ethane, propane, and butane under specific conditions of temperature and pressure (Kang et al., 2014; Karamoddin and Varaminian, 2014). Gas is introduced into the column to react and form complex hydrates in the form of crystals, which float on the top of the column. These complex hydrates can store large amounts of crystallization water, so they are washed and dehydrated by adding heat to obtain water free of ions. The technology of carbon dioxide acting as precipitator is based on the dissolution of CO_2 (g) in seawater. It is done to provide a rich source of CO_3^{2-} and HCO_3^- ions which react with divalent ions to precipitate different species of calcium and magnesium (Al-Anezi and Hilal, 2007). This technology is attractive from an environmental perspective because it could mitigate greenhouse gas emissions related to CO_2 (g). Chemical absorption process with aqueous amine solvent is a widely technique used to separate CO_2 (g) from fuel gas (Nagy and Mizsey, 2015). Thus, it could support emerging technology by providing CO_2 (g) as a raw material.

On the other hand, capacitive deionization is an energy-effective and low-pressure technology. The ions are removed from saline solutions with the use of electrodes, which have a specific surface area and low electrical resistivity (Subramani et al., 2015). In this technology, positively charged electrode captures negatively charged anions from seawater while negatively charged electrode captures positively charged cations. Meanwhile, ultrasonic crystallization is a physical treatment in which acoustic waves are applied to the frequency higher than 20 kHz, i.e. within the range beyond human perception (Chen et al., 2016). The treatment is an effective way of achieving faster and uniform primary nucleation of crystal, and relatively easy nucleation of particles at lower supersaturation levels (Chen et al., 2012). Layer by layer chemical deposition is a simple and inexpensive technique, which has allowed developing new concepts, new materials, and applications through the fabrication of multilayer films (Ariga et al., 2014). For this technique, it is necessary to select appropriate species for interaction deposition, which can react and deposit a particular compound on the surface of solid substrates for the formation of deposited materials without the possibility of back-dissolution in the aqueous solution (Mahmoud and Haggag, 2011; Mahmoud and Obada, 2014).

Emerging technologies show superior performance over existing scale control technologies in terms of energy generation from microorganisms, biological waste generation, use of a limited number of reagents and creation of opportunities for use of CO_2 (g) as a raw material. However, most of those technologies are still under research or in the early development stage. Therefore, further studies and large-scale evaluations are needed to determine their commercialization potential.

3.2 House of quality

In this study, HOQ matrix is applied to RO process and assessing existing and emerging technologies of scale control technologies. The technologies under evaluation to RO process are the pH control, scale inhibitors and nanofiltration membrane as common technologies and microbial desalination cells as emerging technology. The reason for choosing the microbial desalination cells over the other emerging technologies is MDC offers a new cutting-edge solution that integrates scale removal and energy recovery in a single reactor. In addition, Sophia et al (2016) suggested that the introduction of MDC into RO process can reduce the overall load on RO membrane and to reduce water cost of desalination.

Edraw Max Software was used to build the HOQ matrix to evaluate scale control technologies for RO process. The HOQ was built considering customer attributes, relative importance, engineering characteristics, correlation matrix, competitive benchmarking, relationship matrix and objective measure as shown in Figure 2.

Customer attributes were identified from the literature using the Website Science Direct. A bibliographic research was performed to search the principal characteristics of the four scale control technologies. The analysis was performed considering the problems, advantage, drawbacks, and challenges of each technology.

Relative importance was obtained by counting the number of scientific publications on Science Direct website that mentions each customer attributes.

Engineering characteristics were identified from literature addressing technical information of scale control technologies that are under evaluation.

The relationship of the correlation matrix is denoted by positive (+) or negative (-) symbols. The negative symbol indicates that when an engineering characteristic increases it is accompanied by a decrease of another characteristic. In contrast, the positive symbol indicates that both characteristics decrease or increase simultaneously. However, there are engineering characteristics that do not interact with each other, so it is denoted by a blank space.

Competitive benchmarking was done using the results given by customer attributes. The customer perception is expressed by a 5-point scale; 1 is very poor, 2 is poor, 3 is neutral, 4 is good, and 5 is very good.

Relation matrix is represented by the symbols; ● denoted strong, ■ medium, and ▲ weak

The values of objective measure were obtained from the literature of “state of the art of RO desalination” (Fritzmann et al., 2007).

As mentioned before the customers attributes were obtained from bibliographic research to each scale control technology under evaluation. The customer attributes identified are presented below.

- Corrosion: The pH control leads to corrosion problems when pH value falls below 4.5 (Al-Hamzah and Fellows, 2015). Scale inhibitor causes minimal corrosion problems (Al-Hamzah and Fellows, 2015). In addition, there are scale inhibitors designed to prevent corrosion and scale formation at the same time (Hasson et al., 2011). The NF has a more dilute concentrated waste stream, and product water requiring less stabilization to minimize distribution system corrosion (Shahmansouri and Bellona, 2015). In MDC, one of the main problems is the short life of the electrode due to the highly corrosive electrolytes that are in the system as is the case of seawater (Bebelis et al., 2013).

- Biofouling: It is significant when the bacterial count is higher than 10^6 CFU/ml (Fritzmann et al., 2007). The pH control does not affect the growth of microorganisms, however, chlorine is the most effective disinfectant for the deactivation of microorganisms in pretreatment stage for RO process (Jiang et al., 2017). Antiscalants, mainly polyphosphonate-based, induce biofouling formation due to an additional source of phosphorous in seawater which enhances microbial population (Sweity et al., 2013). The biofouling is not a specific problem for NF as it can remove bacteria and turbidity from seawater (Llenas et al., 2013; Koyuncu et al., 2015). In addition, bacterias are too large and will remain as a biofilm on the surface and not inside the membrane pores (Van der Bruggen et al., 2008). The MDC has a separator which is a piece of glass fiber attached to the water-facing side of the cathode to prevent the occurrence of biofouling on the cathode (Saeed et al., 2015).

- Environmental impact: The acidity of pH control is consumed by naturally alkaline seawater, therefore the discharge pH to seawater is typically similar or slightly lower than that of seawater (Gude, 2016). Conventional polymeric antiscalants have a long lifespan and persist for several years after their disposal. However, polyphosphonate-based antiscalants are a concern as they can become nutrients leading to eutrophication problems in seawater (Hasson et al., 2011). NF technology discharges brine into seawater at ambient temperature and it has a salinity of 70 g/l (Pontié et al., 2013), being about double the normal salinity of seawater. Besides, the technology releases 2.1 kg/m^3 of CO_2 to the environment (Youssef et al., 2014). Instead, the MDC is considered as an environmentally friendly technology because it can generate electricity from microorganisms (Brastad and He, 2013; Sophia et al., 2016). So it could generate less impact on the environment

- Energy consumption: The acid for pH control and antiscalant are added by chemical dosing pumps, where energy consumption of H_2SO_4 dosing pump is 1.51E-05 kWh/m^3 of permeate, while antiscalant dosing pump uses 1.27E-06 kWh/m^3 of permeate (Al-Malek, 2005). For dual stage NF process with feed water of 35,000 and 39,000 mg/l of salinity, energy consumptions were 3.35 and 3.84 kWh/m^3, respectively, and the permeate stream were of 254 and 295 mg/l, respectively (AlTaee and Sharif, 2011). In contrast, the MDC can generate electricity from chemical energy produced by microorganisms. Although it is a growing technology yet, it can produce 180 to 231% energy in the form of hydrogen during the desalination of sodium chloride solution from 30g/l to 5g/l (Saeed et al., 2015). Also, osmotic MDC, which integrates forward osmosis into MDC, can produce 0.16 kWh/m^3 of the energy of treated saline water. (Zhang and He, 2013).

- Technical maturity: The pH control is an ancient technology that was widely used during the 1960s and the 1970s as the only practical technology for scale control (Al-Shammiri., 2000). Regarding a survey of 47 commercial RO plants in 2000, about 42.6% still use pH control whereas antiscalant alone represent 17% of surveyed plants (Al-Shammiri., 2000). Several studies have shown the evolution of NF as pretreatment technology in the desalination industry; moving from pilot to commercial/industrial scale (Llenas et al., 2013). In contrast, MDC is a new technology, in fact, it has been developed for less than a decade (Sophia et al., 2016). The technology is still used at laboratory scale and has high capital investment.

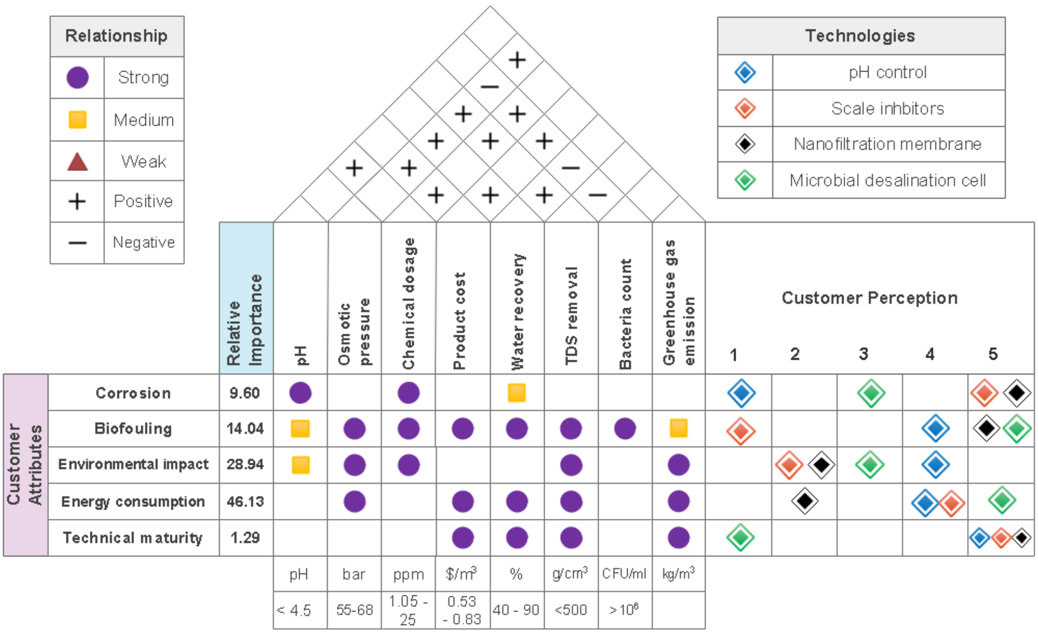

Fig. 2. House of Quality of the scale control technologies.

By analyzing the information provided by the HOQ matrix (see Figure 2), energy consumption is a big challenge in customer attributes because RO process is an energy-intensive process. Typically, the RO process requires about 4 - 7 kWh/m^3 of energy, including pre and post- treatment, however, the value depends on the size of plant and energy recovery system installed (Subramani and Jacangelo, 2015;

Lattemann and Höpner, 2008). When scale control technologies are not efficient in reducing the ions to prevent scale formation, the efficiency of RO process is reduced due to the increase in osmotic pressure, which leads to a higher total energy consumption. The MDC is the suitable technology to reduce energy consumption in comparison with its competitors. The MDC can generate electricity from chemical energy produced by microorganisms, being a competitive advantage over other technologies. Therefore, there is no need to improve MDC to address this customer need. In contrast, NF is not the suitable technology to reduce energy in the RO as it is a pressure-driven process that requires energy for ions separation.

The production of water through the RO process involves environmental impacts. This is the second concern for customers due to the discharges of brine or chemicals to the environment, which could affect marine life as well as air pollutant emissions attributed to the energy demand of the process. The pH control technology has a less environmental impact than other technologies because acidity is consumed by naturally alkaline seawater. Therefore, the discharge pH to seawater is typically similar or slightly lower than that of seawater (Gude, 2016). While scale inhibitors and NF have a greater impact on the marine environment: the polyphosphonate-based antiscalants lead to eutrophication problems in seawater, whereas NF discharge brine into the environment which could affect the marine environment. So, to mitigate these problems, green scale inhibitors that readily biodegrade and have a minimum environmental impact have been developed (Hasson et al., 2011). In addition, brine should be pre-diluted with seawater to minimize the effect of high salt concentration into the marine environment, as well as salts recovery and selection of outfall location for maximum mixing and dispersion have been conducted (Gude, 2016; Fritzmann et al., 2007).

Biofouling is the third concern to the customer. It is a dynamic process that involves the formation and growth of a bio-film attached to the RO membrane, which influences the performance of the process due to increased pressure loss along feed channel and reduction of the flux (Fritzmann et al., 2007). The MDC and NF technologies are the suitable alternatives to prevent biofouling in comparison to its competitors. The MDC has a separator in the cathode that prevents the growth of bacteria, while the NF can remove bacteria and turbidity from seawater. Therefore, both technologies meet the customer' demand and no improvements are needed. In contrast, scale inhibitors, mainly polyphosphonate-based, contribute to membrane biofouling reducing the performance of RO process. To struggle this problem efforts are being made to replace polyphosphonate-based antiscalants by polymeric compounds and green antiscalants (Fritzmann et al., 2007).

For the last customer attributes, corrosion and technical maturity are less worrying needs of the customer. Regarding corrosion, the pH control is the worst technology in comparison with its competitors as it can induce corrosion into RO process due to low pH values, so correct doses of acid are crucial. To avoid corrosion is needed a proper design with equipment made of corrosion resistant materials and anticorrosive additives (Fritzmann et al., 2007). Thus, this customer need should be better addressed. In contrast, NF and scale inhibitor are the suitable technologies to prevent corrosion. The concentrate waste stream from NF is more dilute. In consequence less effort to stabilization the corrosion in the distribution system is needed. In addition, scale inhibitors can solve scale and corrosion problems simultaneously. In relation to MDC technology, limited information on corrosion is available. So, further studies are needed in order to satisfy this need. Regarding technical maturity, the attribute with less relative importance, the pH control, antiscalants, and NF are mature technologies with commercial applications as pretreatment to RO process to prevent scale formation. Instead, the MDC is a young technology, still at the stage of research and development. However, many studies mention that this could be an environmental friendly technology of the future due to its characteristics: it can remove ions from aqueous solutions and can generate electricity (Subramani and Jacangelo, 2015).

In particular, NF technology could be the suitable current option to RO process because it does not cause corrosion problems, it can remove bacteria, turbidity and prevent biofouling on the membrane. Also, it is selective for the retention of ions according to their valence. The technology can remove 89.6% of calcium, 94.0% of magnesium, 97.8% of sulfate and 76.6% of bicarbonate, and 39.3% of total hardness from seawater, and also can remove more than 50% of TDS (Hassan et al., 1998). In fact, by the introduction of NF before RO process, the RO permeate increases because the osmotic pressure of seawater fed to the RO unit is reduced, which leads to higher water recovery rate of more than 70% (Kaya et al., 2015; Llenas et al., 2013). Also, nowadays NF is a mature technology with several commercial and industrial applications. However, it is necessary to improve the energy system to reduce energy consumption as this is a pressure- driven technology, as well as to reduce environmental impact produced by the discharge of brine into the marine environment. On the other hand, the MDC technology could become a potential alternative for scale control in the future due to its energy efficiency and environmental advantages. At laboratory scale for seawater desalination, the technology can remove 98% of salt from synthetic seawater (Sophia et al., 2016). However, to improve the efficiency of MDC more compact reactor design is necessary (Subramani et al., 2015). Also, future work is needed to scale-up the system for practical applications.

4. Conclusions

In this paper calcium and magnesium scale problems occurring in different industrial processes which use seawater were presented. The RO unit, heating unit of MSF, concentration operation of the copper-molybdenum mining industry, cooling water system of power generation industry, and water injection operation in oil and gas production are industrial operations affected by scale formation. The $CaSO_4$, $CaCO_3$, CaF_2, $Ca_3(PO_4)_2$, $Mg(OH)_2$ and $MgCO_3$ salts are the main components of scale present, with calcium and magnesium ions as the most common species in scaling problems when seawater is used. Independently of industrial operations affected, the scale is formed because operating conditions generate an environment that favours initiating scale formation and its growth.

Moreover, a technology assessment to evaluate existing and emerging scale control technologies was performed based on a bibliometric analysis and HOQ matrix for RO process. The pH control, scale inhibitors and nanofiltration membrane are the current technologies used to control calcium and magnesium scale. Whereas, the layer by layer chemical deposition technique, biosorption, carbon dioxide as a precipitator, bioelectrochemical system, microbial desalination cells, gas hydrate, biomineralization, ultrasonic crystallization, and capacitive deionization are emerging scale control technologies.

The pH control, scale inhibitors, nanofiltration membrane and microbial desalination cells were the technologies evaluated applied the HOQ matrix. The corrosion, biofouling, environmental impact, energy consumption and technical maturity were customer attributes evaluated for each technology, with energy consumption and environmental impact being the main challenges for RO process. NF technology could be the suitable current option to RO process because it meets with almost all customer needs such as corrosion, biofouling and technical maturity. However, it is necessary to implements solutions to reduce energy consumption and to mitigate the discharge of brine into the marine environment. Whereas, microbial desalination cells could become a potential alternative for scale control in the future due to its energy efficiency and environmental advantages. However, further studies are needed as well as full-scale to evaluate its performance into RO process.

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Acknowledgements

The authors thank CONICYT (PIA program) for financial support through the Project Anillo ACM 170005 and CICITEM for funding through the project R15A10002.

References

Abejón, R., Garea, A., 2015. A bibliometric analysis of research on arsenic in drinking water during the 1992–2012 period: an outlook to treatment alternatives for arsenic removal. Journal of Water Process Engineering 6, 105-119.

Achal, V.; Mukherjee, A.; Kumari, D. y Zhang, Q., 2015.Biomineralization for sustainable construction - A review of processes and applications, in Earth-Science Rev., vol. 148, pp. 1-17

Adiano, C., Roth, A. V., 1994. Beyond the house of quality: dynamic QFD. Benchmarking for Quality Management & Technology 1 (1), 25-37.

Akao, Y., Mazur, G. H., 2003. The leading edge in QFD: past, present and future. International Journal of Quality & Reliability Management 20 (1), 20-35.

Al-Anezi, K., Hilal, N., 2007. Scale formation in desalination plants: effect of carbon dioxide solubility. Desalination 204 (1-3), 385-402.

Al-Hamzah, A. A., Fellows, C. M., 2015. A comparative study of novel scale inhibitors with commercial scale inhibitors used in seawater desalination. Desalination 359, 22-25.

Al-Rawajfeh, A. E., Glade, H., Ulrich, J., 2005. Scaling in multiple-effect distillers: the role of CO_2 release. Desalination 182 (1-3), 209-219.

Al-Shammiri, M., Safar, M., Al-Dawas, M., 2000. Evaluation of two different antiscalants in real operation at the Doha research plant. Desalination, 128 (1), 1-16.

AlTaee, A., Sharif, A. O., 2011. Alternative design to dual stage NF seawater desalination using high rejection brackish water membranes. Desalination 273 (2), 391-397.

Al-Malek, S.P., 2005. Techno-economic Evaluation of Conventional and Membrane-based Pretreatment before Reverse Osmosis. MSc Thesis, United Arab Emirates University, Al Ain, United Arab Emirates.

Antony, A., Low, J. H., Gray, S., Childress, A. E., Le-Clech, P., Leslie, G. 2011. Scale formation and control in high pressure membrane water treatment systems: a review. Journal of membrane science 383 (1), 1-16.

Arias, D., Cisternas, L. A.,Rivas, M. 2016. Biomineralization of calcium and magnesium crystals from seawater by halotolerant bacteria isolated from Atacama Salar (Chile). Desalination 405, 1-9.

Ariga, K., Yamauchi, Y., Rydzek, G., Ji, Q., Yonamine, Y., Wu, K. C. W., Hill, J. P., 2014. Layer-by-layer nanoarchitectonics: invention, innovation, and evolution. Chemistry Letters 43 (1), 36-68.

Arras, W., Ghaffour, N., Hamou, A., 2009. Performance evaluation of BWRO desalination plant—a case study. Desalination 235 (1-3), 170-178.

Bader, M. S. H., 2007. Sulfate removal technologies for oil fields seawater injection operations. Journal of Petroleum Science and Engineering 55 (1), 93-110.

Brastad, K. S., He, Z., 2013. Water softening using microbial desalination cell technology.

Desalination 309, 32-37.

Bebelis, S., Bouzek, K., Cornell, A., Ferreira, M. G. S., Kelsall, G. H., Lapicque, F., Walsh, F. C., 2013. Highlights during the development of electrochemical engineering. Chemical Engineering Research and Design 91 (10), 1998-2020.

Castro, S., 2012. Challenges in flotation of Cu-Mo sulfide ores in seawater. The First International Symposium on Water in Mineral Processing. Society for Mining, Metallurgic, and Exploration, Seattle, USA.

Cisternas, L.A., Gálvez, E., Leyton, Y., Valderrana, J., 2017. Atacama seawater: Opportunities and advances for the sustainable use of sea water in mining (in Spanish). Master Ril, Santiago, Chile.

Chen, S., Luo, H., Liu, G., Zhang, R., Wang, H., Qin, B., Hou, Y., 2013. Integrated utilization of seawater using a five-chamber bioelectrochemical system. Journal of Membrane Science 444, 16-21.

Chen, Y., Sun, S., Lai, Y., Ma, C., 2016. Influence of ultrasound to convectional heat transfer with fouling of cooling water. Applied Thermal Engineering, 100, 340-347.

Chen, D.,Sharma, S.K ., Mudhoo, A., 2012. Handbook on Applications of Ultrasound: Sonochemistry for Sustainability. CRC Press, United State of America.

Coates, J. F., 2001. A 21st century agenda for technology assessment. Technological Forecasting and Social Change, 67(2-3), 303-308.

Demadis, K. D., Mavredaki, E., Stathoulopoulou, A., Neofotistou, E., Mantzaridis, C., 2007. Industrial water systems: problems, challenges and solutions for the process industries. Desalination 213 (1-3), 38-46.

Dreisinger D., Murray W., Norton E., Baxter K., Holmes M., Molnar R., 2008. The Boleo copper-cobalt-zinc-manganese project. Canadian Metallurgical Quarterly 47 (3), 357-368.

El, F. A. E. S. A., Aleem, I. S., Al-Arifi, A., El Salam, F. A., El Aleem, A., 2011. Corrosion and Scale Formation Problems in Water Systems. Water, Energy and Environment 148.

Fritzmann, C., Löwenberg, J., Wintgens, T., Melin, T., 2007. State-of-the-art of reverse osmosis desalination. Desalination 216(1-3), 1-76.

Fry, A., Martin, R., 2005. Water facts and trends. World Business Council for Sustainable Development 16.

Gilron, J., 2013. Scaling. Encyclopedia of Membrane Science and Technology. John Wiley & Sons, Ltd. http://dx.doi.org/10.1002/9781118522318.emst028

Greenlee, L. F., Lawler, D. F., Freeman, B. D., Marrot, B., Moulin, P., 2009. Reverse osmosis desalination: water sources, technology, and today's challenges. Water research 43 (9), 2317-2348.

Gude, V. G., 2016. Desalination and sustainability–an appraisal and current perspective. Water research 89, 87-106.

Hasson, D., Shemer, H., Sher, A. 2011. State of the art of friendly “green” scale control inhibitors: a review article. Industrial & Engineering Chemistry Research 50 (12), 7601-7607.

Hassan, A. M., Al-Sofi, M. A. K., Al-Amoudi, A. S., Jamaluddin, A. T. M., Farooque, A. M., Rowaili, A., Al-Tisan, I. A. R., 1998. A new approach to membrane and thermal seawater desalination processes using nanofiltration membranes (Part 1). Desalination 118(1), 35-51.

Hauser, J. R., Clausing, D., 1988. The house of quality. Harvad Business Review 66 (3).

Henriksen, A. D. P., 1997. A technology assessment primer for management of technology. International Journal of Technology Management, 13(5-6), 615-638.

Ibáñez-Forés, V., Bovea, M. D., Pérez-Belis, V., 2014. A holistic review of applied methodologies for assessing and selecting the optimal technological alternative from a sustainability perspective. Journal of Cleaner Production, 70, 259-281.

Jeldres, R. I., Arancibia-Bravo, M. P., Reyes, A., Aguirre, C. E., Cortes, L., Cisternas, L. A., 2017. The impact of seawater with calcium and magnesium removal for the flotation of copper-molybdenum sulphide ores. Minerals Engineering 109, 10-13.

Jiang, S., Li, Y., Ladewig, B. P., 2017. A review of reverse osmosis membrane fouling and control strategies. Science of The Total Environment 595, 567-583.

Jwa, E., Kim, H., Chon, K., Kim, C. S., Jeong, N., Park, S. C., Nam, J. Y., 2017. Bioelectrochemical precipitation system for removal of scale-forming ions from seawater using two different buffers. Desalination 418, 35-42.

Kaya, C., Sert, G., Kabay, N., Arda, M., Yüksel, M., Egemen, Ö., 2015. Pre-treatment with nanofiltration (NF) in seawater desalination—Preliminary integrated membrane tests in Urla, Turkey. Desalination 369, 10-17.

Kang, K. C., Linga, P., Park, K. N., Choi, S. J., Lee, J. D., 2014. Seawater desalination by gas hydrate process and removal characteristics of dissolved ions (Na^+, K^+, Mg^{2+}, Ca^{2+}, B^{3+}, Cl^-, SO_4^{2-}). Desalination 353, 84-90.

Karamoddin, M., Varaminian, F., 2014. Water desalination using R141b gas hydrate formation. Desalination and Water Treatment 52 (13-15), 2450-2456.

Khayet, M., 2016. Fouling and Scaling in Desalination. Desalination (393), 1.

Koyuncu, I., Sengur, R., Turken, T., Guclu, S., Pasaoglu, M. E., 2015. Advances in water treatment by microfiltration, ultrafiltration, and nanofiltration. Advance in Membrane Technologies for Water Treatment 83-128.

Knudsen, J. G., 1990. Fouling in heat exchangers. Hemisphere Handbook of Heat Exchanger Desig, Washington, D.C.

Laskowski, J. S., Castro, S., 2012. Hydrolyzing ions in flotation circuits: seawater flotation. 13th International Mineral Processing Symposium. Bodrum, Turkey.

Li, X., Zhou, Y., Xue, L., Huang, L., 2015. Integrating bibliometrics and roadmapping methods: A case of dye-sensitized solar cell technology-based industry in China. Technological Forecasting and Social Change 97, 205-222.

Llenas, L., Ribera, G., Martínez-Lladó, X., Rovira, M., de Pablo, J., 2013. Selection of nanofiltration membranes as pretreatment for scaling prevention in SWRO using real seawater. Desalination and Water Treatment 51 (4-6), 930-935.

Lucay, F., Cisternas, L. A., Gálvez, E. D., López-Valdivieso, A., 2015. Study of the natural floatability of molybdenite fines in saline solutions and effect of gypsum precipitation. Minerals and Metallurgical Processing Journal 32 (4), 203-208.

MacAdam, J., Jarvis, P., 2015. Water-Formed Scales and Deposits: Types, Characteristics, and Relevant Industries. In Mineral Scales and Deposits (pp. 3-23).

Mahmoud, B., Yosra, M., Nadia, A., 2016. Effects of magnetic treatment on scaling power of hard waters. Separation and Purification Technology, 171, 88-92.

Mahmoud, M. E., Obada, M. K., 2014. Improved sea water quality by removal of the total hardness using static step-by-step deposition and extraction technique as an efficient pretreatment method. Chemical Engineering Journal 252, 355-361

Mahmoud, M. E., Haggag, S.S., 2011. Implementation of layer-by-layer chemical deposition technique for static removal of magnesium from various matrices. Chemical Engineering Journal 171 (1), 181-189.

Mahmoud, M. E., Yakout, A. A., Abdel-Aal, H., Osman, M. M., 2013. Immobilization of Fusarium verticillioides fungus on nano-silica (NSi–Fus): A novel and efficient biosorbent for water treatment and solid phase extraction of Mg (II) and Ca (II). Bioresource technology 134, 324-330.

Müller-Steinhagen, H., 1999. Cooling-water fouling in heat exchangers. Advances in Heat Transfer 33, 415-496.

Nagy, T., Mizsey, P., 2015. Model verification and analysis of the CO2-MEA absorber–desorber system. International Journal of Greenhouse Gas Control, 39, 236-244.

Nam, J. Y., Jwa, E., Kim, D., Park, S. C., Jeong, N., 2015. Selective removal of multivalent ions from seawater by bioelectrochemical system. Desalination 359, 37-40.

Nancharaiah, Y. V., Mohan, S. V., Lens, P. N. L., 2015. Metals removal and recovery in bioelectrochemical systems: a review. Bioresource technology 195, 102-114.

Park, K. N., Hong, S. Y., Lee, J. W., Kang, K. C., Lee, Y. C., Ha, M. G., Lee, J. D., 2011. A new apparatus for seawater desalination by gas hydrate process and removal characteristics of dissolved minerals (Na+, Mg 2+, Ca 2+, K+, B 3+). Desalination 274(1), 91-96.

Pontié, M., Derauw, J. S., Plantier, S., Edouard, L., Bailly, L., 2013. Seawater desalination: nanofiltration—a substitute for reverse osmosis?. Desalination and Water Treatment 51(1-3), 485-494.

Pugh, S. J., Hewitt, G. F., Müller-Steinhagen, H., 2005. Fouling during the use of seawater as coolant—The development of a user guide. Heat transfer engineering 26 (1), 35-43

Ramírez, Y., Cisternas, L. A., Kraslawski, A., 2017. Application of House of Quality in assessment of seawater pretreatment technologies. Journal of Cleaner Production 148, 223-232.

Saeed, H. M., Husseini, G. A., Yousef, S., Saif, J., Al-Asheh, S., Fara, A. A., Aidan, A., 2015. Microbial desalination cell technology: a review and a case study. Desalination 359, 1-13.

Seo, S. J., Jeon, H., Lee, J. K., Kim, G. Y., Park, D., Nojima, H., Moon, S. H., 2010. Investigation on removal of hardness ions by capacitive deionization (CDI) for water softening applications. Water research 44 (7), 2267-2275.

Shahmansouri, A., Bellona, C., 2015. Nanofiltration technology in water treatment and reuse: applications and costs. Water Science and Technology 71 (3), 309-319.

Sophia, A. C., Bhalambaal, V. M., Lima, E. C., Thirunavoukkarasu, M., 2016. Microbial desalination cell technology: Contribution to sustainable waste water treatment process, current status and future applications. Journal of Environmental Chemical Engineering 4 (3), 3468-3478.

Su, M., Han, J., Li, Y., Chen, J., Zhao, Y., Chadwick, K., 2015. Ultrasonic Crystallization of Calcium Carbonate in Presence of Seawater Ions. Desalination 369, 85-90.

Subramani, A., Jacangelo, J. G., 2015. Emerging desalination technologies for water treatment: A critical review. Water research 75, 164-187.

Suss, M. E., Porada, S., Sun, X., Biesheuvel, P. M., Yoon, J., Presser, V., 2015. Water desalination via capacitive deionization: what is it and what can we expect from it?. Energy & Environmental Science 8 (8), 2296-2319.

Sweity, A., Oren, Y., Ronen, Z., Herzberg, M., 2013. The influence of antiscalants on biofouling of RO membranes in seawater desalination. Water research 47 (10), 3389-3398.

Tran, T. A., Daim, T., 2008. A taxonomic review of methods and tools applied in technology assessment. Technological Forecasting and Social Change 75 (9), 1396-1405.

Van der Bruggen, B., Mänttäri, M., Nyström, M., 2008. Drawbacks of applying nanofiltration and how to avoid them: a review. Separation and purification technology 63 (2), 251-263.

Yang, Q., Yang, S., Qian, Y., Kraslawski, A., 2015. Application of House of Quality in evaluation of low rank coal pyrolysis polygeneration technologies. Energy Conversion and Management 99, 231-241.

Youssef, P. G., Al-Dadah, R. K., Mahmoud, S. M., 2014. Comparative analysis of desalination technologies. Energy Procedia 61, 2604-2607.

Zare Mehrjerdi, Y., 2010. Quality function deployment and its extensions. International Journal of Quality & Reliability Management 27(6), 616-640.

Zhang, B., He, Z., 2013. Improving water desalination by hydraulically coupling an osmotic microbial fuel cell with a microbial desalination cell. Journal of membrane science 441, 18-24.

Zhao, Y., Yuan, J., Zhang, J., Xie, L., Ji, Z., Su, M., Chen, J., 2013. A different approach for seawater decalcification pretreatment using carbon dioxide as precipitator. Desalination 322, 151-158.

Zhao, Y., Cao, H., Xie, Y., Yuan, J., Ji, Z., & Yan, Z., 2016. Mechanism studies of a CO_2 participant softening pretreatment process for seawater desalination. Desalination 393, 166-173.

http://www.webofknowledge.com, (accessed 15/04/2017).

https://www.edrawsoft.com/, (accessed 23/06/2017).

Highlights

Current and emerging technologies to remove calcium and magnesium ions are discussed

 A technology assessment to compare scale control technologies was conducted

 The energy consumption is the main challenge in technologies of scale control