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Desalination process and perspectives in Morocco

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ABSTRACT

Water scarcity is a great challenge that has always stimulated research interests to find efficient ways for the production of pure water. In this context, reverse osmosis is considered as the most important and optimized membrane desalination process that currently dominates the desalination market to help meet the growing water needs, specifically in water-stressed countries. This paper reviews the evolution of desalination in Morocco and presents three case studies of desalination plants: Laayoune, Boujdour (seawater desalination) and Khénifra (the first experience of demineralization of brackish surface water in Morocco). Also, the challenges encountered during the operation of the desalination plant.

Keywords: Water; Desalination; Reverse osmosis; Pretreatment; Membrane fouling

1. Introduction

Water scarcity is one of the major challenges in the world and may increase conflicts between governments concerning shared water resources, as in the 1950s–1960s [1]. Although water is plentiful on Earth 97.5% of it is seawater with an average salinity of 35,000 ppm or milligrams per liter [2,3]. 80% of the remaining fresh water of which is contained in glaciers, leaving 20% (or 0.5% of total water) available in rivers, lakes and aquifers [4]. The world is thirsty due to growth and rapid urbanization of the world population, climate change, rising living standards and changing water habits [5,6]. In many regions of the world, fresh water resources are limited, so new techniques for the production of drinking water are needed to sustain the populations and will perhaps lead to a standardization in water management [4]. This is the desalination of seawater and brackish water easily accessible for countries with a coastline and for those who have salt water reserves [7]. Currently, more than 20 different technologies are used for seawater desalination [8]. Nonetheless, only a handful of these dominate global water production. Commercial desalination processes are grouped into three broad categories: thermal processes, membrane separations, and emerging technologies. Within thermal processes, multi-effect distillation (MED) and multi-stage flash distillation (MSF) stand out. Reverse osmosis (RO) is the dominant technology [9], currently, 70% of desalination plants use membrane systems thanks to their high effectiveness and lower energy consumption and costs compared to thermal phase change technologies, being the main supply of drinking water for millions of people [10]. RO is the fastest growing technology in the world, and its market is estimated to reach 9,227 million USD by 2022 [11]. Table 1 shows the characteristics of the different membrane desalination technology.

Environmental impacts vary depending on the type of used technology and characteristics of feedwater, especially its salinity and temperature. Forward osmosis (FO) has the lowest environmental impacts, followed by electrodialysis and reverse electrodialysis (ED/RED), and operations by

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membrane distillation (MD) in the third place. While RO showed greater environmental impacts among the studied technologies [16], brine discharges can also impact marine environments, and ground, surface, and underground water sources. The energy water nexus has become increasingly evident, as competition for these resources impacts the reliability indicators, and therefore a balance is required between the two factors to achieve sustainable economic development [17].

RO systems are the most common desalination systems (62%) followed by the MED (14%), MSF (10%) and ED (5%). The cumulative global, installed online capacity is 95.37 million m^3/d in 2018.

This article presents a review of the evolution of desalination in Morocco, the description of the treatment plant of Laayoune and Boujdour as a case study of seawater desalination and the description of the plant of Khénifra which carries the first experiment of desalination of surface water in Morocco. The challenges encountered during the operation of desalination plants are also discussed.

2. Factors affecting reverse osmosis desalination

2.1. Energy use, efficiency, and water recovery

Two of the most significant factors in RO desalination are the substantial electricity requirements and capital investment costs [18]. For example, large-scale RO plants can consume 3.5–4.2 kW h of energy per m^3 of water, of which 2.9–3.5 kWh is used by the RO system directly and the remainder is used for the intake of feed water, pre-treatment, and other auxiliary systems [19]. In addition, the energy required to remove salts from the feed water, transport treated water, and manage waste is typically obtained from fossil-fuel combustion [18], which is costly and unsustainable. For instance, it is estimated that approximately 50% of the oil produced domestically in Saudi Arabia is used to fuel its desalination plants, and in Kuwait, 70% of the fossil-fuel produced electricity is used to desalinate water [4,15]. Many countries are looking to reduce costs by powering their desalination plants with renewable energy resources such as solar and wind power [6]. For instance, the RO Adelaide Desalination Plant in Australia and the desalination plant in Agadir, Morocco, are powered entirely by wind, solar and hydro energy [3,18].

2.2. Membrane fouling

Another factor affecting RO desalination is membrane fouling [20], which reduces membrane efficiency and consequently increases costs because more pressure needs to be applied by the pumps to maintain a constant water production [19]. The level of fouling depends on a variety of factors, including feed water characteristics and membrane materials and surface properties such as surface charge [20]. Proper pretreatment of the feed water is important

Table 1
Comparison of different membrane desalination technologies

Technology	Energy consumption (kWh/m^3)	Advantages	Disadvantages	References
Reverse osmosis (RO)	2–6	Technological maturity. Does not use phase changes. Does not extensively use chemical inputs. Easy to scale and operate. Does not require elements for energy recovery. Low space requirements.	Membrane fouling and durability. Water recovery reduction with increasing scale.	[12]
Forward osmosis (FO)	21	Generation of concentrated brine. Lower environmental impacts.	High energy consumption due to the extraction solution recovery process.	[13]
Electrodialysis (ED)	1–12	Less susceptibility to scale formation. High salt removal.	High capital costs. Obstruction and loss of energy.	[12,13]
Membrane distillation (MD)	22–67	Ability to handle elevated levels of salinity. Low fouling. Use of low-grade heat.	High energy consumption. Low water recovery.	[13,14]
Nanofiltration (NF)	2.54–4.2	Low operating pressures. High rejection of divalent ions especially sulfates. Ability to remove microorganisms and turbidity from water and a fraction of dissolved salts. Wide integration capacity as pretreatment for other desalination technologies, achieving cost reduction.	Low ability to reject boron. High levels of membrane fouling.	[15]

because it can remove fouling agents such as dissolved organic compounds, salts, colloids, and bacteria. Effective removal of bacteria can be especially challenging because unless 100% of these microorganisms can be removed, they will continue to adhere and reproduce on the membrane, causing biofouling and thus making the membrane harder to clean and less efficient [20]. Besides pretreatment, there are other ways to control membrane fouling [20]. For instance, it is important to clean membranes periodically and to monitor the RO performance (e.g., monitoring for a flux drop over time) as an indicator of fouling levels. In addition, acids, disinfectants, and scale inhibitors are added to the water to reduce scaling and fouling [20]. Also, modification of membrane surface characteristics or materials can be beneficial [17]. For instance, membranes with greater surface hydrophilicity and smoothness tend to have a lower fouling tendency [17]. Furthermore, researchers have found a variety of materials with excellent antifouling properties that can enhance conventional thin-film composite membranes, including carbon nanotubes (which can increase surface hydrophilicity), nanoporous graphene, and metal oxide nanoparticles [17]. Researchers have also been investigating materials that could substitute the polyamide in thin-film composite membranes. For instance, a study by Mahmoud and Ibrik et al. [17] found that a polyvinyl alcohol (PVA) and Gum Arabic membrane showed superior permeation, salt rejection, and biofouling resistance. However, more research is needed before these new materials can become widely available commercially.

Another problem concerning the operation of a reverse osmosis plant is to the residual free chlorine in the pretreated water. The free chlorine is an oxidant and can damage the RO membrane. To monitor the presence of free chlorine, the plant is equipped with on continuous measurement device of redox potential. In case of higher values of the redox potential, the Sodium Bisulfate is added to neutralize the chlorine [22].

2.3. Overview of desalination industry in Morocco

Morocco, is a country that has used desalination for a long time. In 1975, the first demineralization unit was developed in Tarfaya. This unit was designed for demineralization by electrodialysis of brackish water containing 5 g L^{-1} of dissolved salt with a production capacity of 75 m^3 d^{-1} was planned to meet the needs of drinking water [23,24]. In 1977, a mechanical steam compression for the desalination of seawater was installed in the city of Boujdour for a production capacity of 250 m^3 d^{-1} [25]. In 1983, ONEP received a new demineralization plant based on the reverse osmosis process to reinforce the electrodialysis demineralization unit in Tarfaya [26]. In 1986, a second reverse osmosis plant was installed in Smara with a production of 330 m^3 d^{-1} using DuPont B-9 membranes for demineralization of brackish water of 10 g L^{-1} [27,28]. In 1995, two reverse osmosis desalination plants using DuPont B-10 hollow fiber membranes with a production capacity of 7,000 and 800 m^3 d^{-1}, respectively, were built in Laayoune and Boujdour.

Fig. 1 shows a location of desalination plants in Morocco [21].

Since 2000, all desalination plants in Morocco operate with reverse osmosis systems between medium, large and very large plants [29]. Several stations have already been completed or are in progress, for example: Al Hoceima station (2020), Khénifra station (2015), Tadla-Khouribga and region station (2018), Sidi Ifni station and Agadir (under construction).

2.4. Description of the treatment process of the Laayoune and Boujdour stations

The seawater desalination plants of Laayoune and Boujdour [30] are fed from the Atlantic Ocean by coastal wells, with an average depth of 40 m. The material used in the water transport channel is 316 L stainless steel.

The Laayoune and Boujdour plants are designed for a production capacity of 26,000 and 9,500 m^3 d^{-1} respectively, and include the following structures:

- Pre-treatment unit which includes the following treatment steps:
  - Pre-chlorination;
  - A battery which ensures a pressure filtration on sand;
  - Acidification (H_2SO_4) to bring the pH to 6.9 in order to prevent precipitation of calcium carbonate;
  - Injection of a sequestering agent upstream of the microfilters to mitigate the precipitation of sulfates on the membranes;
  - A battery of microfilters composed by cartridge filters that allows the removal of particles larger than 5 μm and allows a final protection for the membranes;
  - Injection of sodium bisulfite to dechlorinate the water.
  - Compound reverse osmosis unit, with energy recovery.
- A final treatment unit including:
  - Storage of the osmosis water;
  - Correction of pH and aggressiveness by injection of lime water;
  - Chlorine injection for final disinfection.

2.5. Challenges of Laayoune and Boujdour station

Since the commissioning of the first units of the seawater desalination plants, and although the turbidities and silt density index (SDI) remain within the limits recommended by the manufacturers of the membranes, the Laayoune and Boujdour plants have experienced several malfunctions including the deterioration of the reverse osmosis membranes and frequent clogging of the membranes due to biological activity [31].

This phenomenon has been solved by stopping the continuous pre-chlorination and introducing shock chlorination periodically. The problem related to the corrosion of pipes and special parts was initially due to a bad correction of the aggressiveness of the osmosis water, this problem was solved by the method of preparation of the lime water which allows to respect the required conditions for the correction of the aggressiveness and pH [32].

The clogging of coastal boreholes by algae for the desalination plant of Laâyoune has been solved by cleaning and setting up a preventive maintenance of the boreholes. The

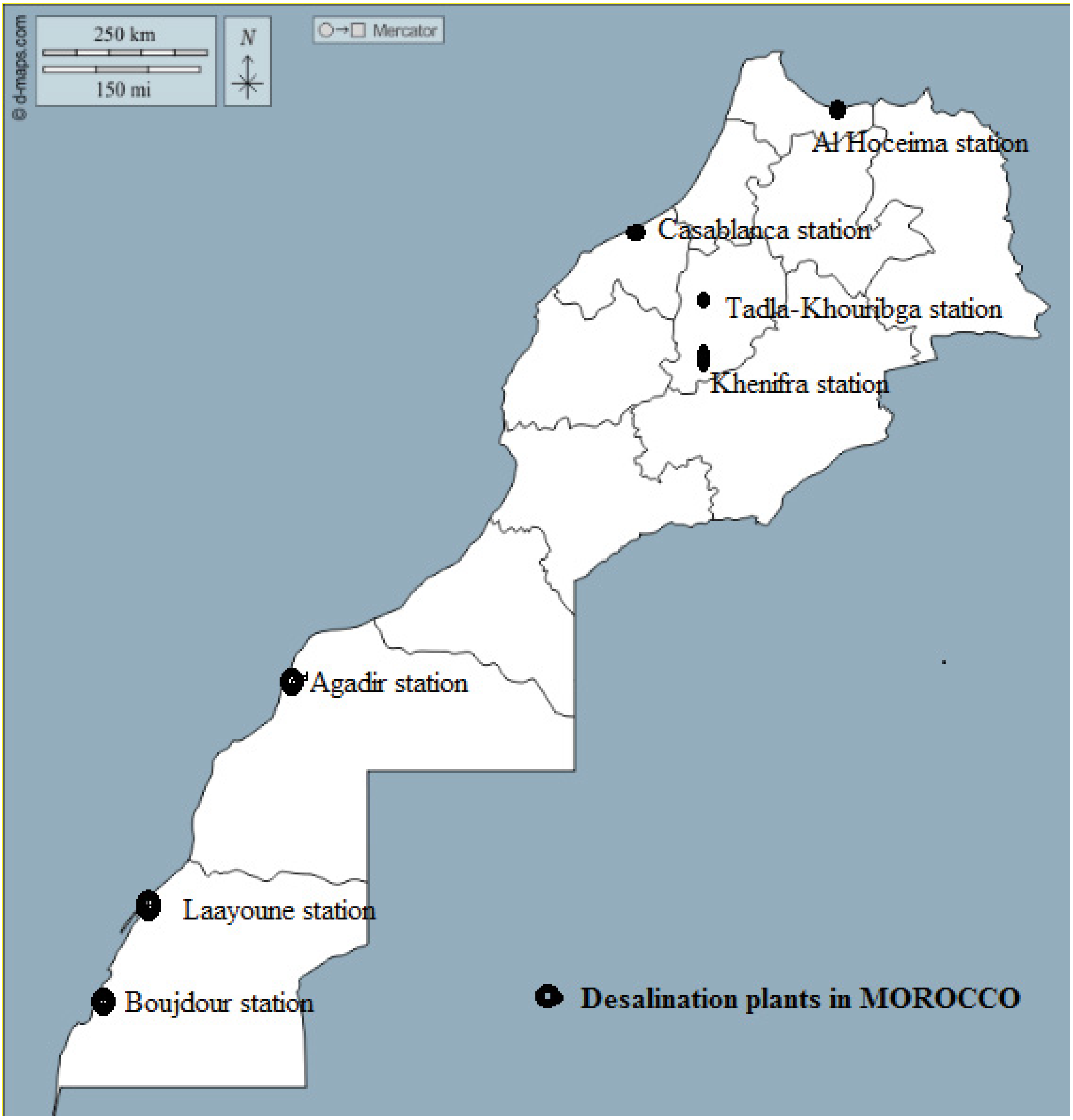

Fig. 1. Location of desalination plants in Morocco.

latter due to the rise of very fine sand for the desalination plant of Boujdour and which was able to infiltrate at the level of sand filters and microfilters and caused the complete stoppage of the desalination plant has been solved by:

- Auscultation, maintenance and cleaning of coastal drillings;
- Construction of a raw water tank of sufficient capacity allowing the deposit of sand at the bottom for its evacuation;
- Changing the filtering media by proposing sand filters with layers of granulometry descending from the bottom to the top [33].

It should be noted that the desalination plant of Laayoune has allowed to gain experience in membrane types. Furthermore, it helped with trying out three different systems of energy recovery. To strengthen the production of drinking water in the city of Laayoune which is undergoing considerable development, a new desalination plant with a production capacity of 26,000 m^3 d^{-1} with direct sea intake is under construction [20].

2.6. Description of the treatment process of the Khénifra plant

The first surface water treatment plant in Morocco (Fig. 2), which combines a conventional treatment with a reverse osmosis process was set up in Khénifra in 2013 [22]. It will cover drinking water needs until 2030 with a production of 36,290 m^3 d^{-1} of water. The plant was supplied from the Oum Rbiâa River [11]. This surface water is

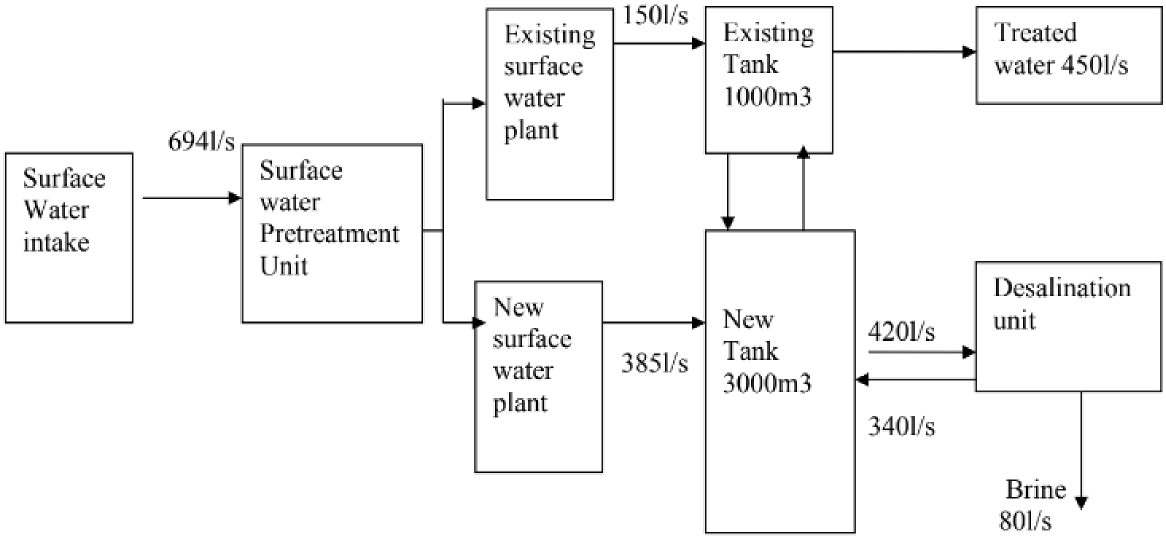

Fig. 2. General plant design of Khénifra Plant.

characterized by strong variations in the concentration of total dissolved solids (TDS) and high chlorides (due to the geological nature of the land crossed by these waters) [23].

The water from Oued Oum Rbiâa is treated at the treatment plant of the city of Khénifra by a conventional treatment followed by a demineralization by reverse osmosis. The treatment plant set up is constituted by the following works [21].

- Pre-treatment process based on settling by circular scraper to lower the suspended solids to values <2 g L^{-1} with addition of polymer;
- Treatment process, based on the multiflow system which consists of coagulation by aluminium sulphate, flocculation with addition of anionic polymer, and lamellar decantation, with sludge recirculation and finally filtration on sand filters;
- Desalination process is composed by a microfiltration unit that allows the removal of particles larger than 5 μm and provide a final protection for the high-pressure pumps, an acidification by sulfuric acid (H_2SO_4) to bring the pH to 6.9 to prevent the precipitation of calcium carbonate. Injection of a sequestering agent upstream of the microfilters to reduce the precipitation of complexes on the membranes and an injection of sodium bisulfite to de-chlorinate the water;
- Reverse osmosis unit composed of three trains of membranes belonging to the FILMTEC family;
- A demineralization by mixing with the filtered water and by adding lime water.

Aluminium sulphate is the main coagulant used for the treatment of these waters. The water produced (by conventional means) is characterized by levels of aluminum residues that meet the requirements of the drinking water quality standard (0.2 mg L^{-1}), but this value is frequently high for the membrane process, for which membrane producers demand values of residual aluminum in the water fed to the membranes to be lower than (<0.05 mg L^{-1}) [34].

2.7. Challenges of Khénifra station

The demineralization station of brackish surface water by reverse osmosis of Khénifra combines the conventional treatment and the desalination process. The conventional treatment implemented uses an aluminum-based reagent in the form of aluminum sulfate. The treatment of water by aluminum sulfate can cause leakage of aluminum called "residual aluminum" in the filtered water if the coagulation pH is not optimized. Indeed, it has been confirmed that in order to obtain a better reduction of residual aluminum (0.03 mg L^{-1}), it is necessary to reach a pH of 6.5, using sulfuric acid [23]. The optimal dose of aluminum sulfate coagulant determined under the test conditions is about 18.5 mg L^{-1}. Thus, and in order to determine the causes of reverse osmosis membrane clogging, an autopsy of the used membrane was deemed necessary to identify the origin of the membrane clogging. It was found that the fouling layer is mainly composed of: $CaCO_3$ (38.70%), Al_2O_3 (17.42%), $Ba(SO_4)_2$ (15.23%), $MgCl_2$ (15.02%) and SiO_2 (13.64%) which is due to scaling of the RO membranes [19,23].

3. Perspectives

In the long view, it is very important to develop desalination technologies to meet the challenges of the global water crisis. Desalination technologies in Morocco are crucial for both the extraction of fresh water from the sea and the improvement of the environment and water ecology. Specifically, the focus should be on the following aspects.

3.1. Innovative desalination technologies

In addition to traditional seawater reverse osmosis (SWRO) desalination technologies, emerging technologies, including MD, CDI, and ED desalination processes, require more research efforts, from the exploitation of new membrane materials to the manufacture of basic components and equipment. In addition, hybrid systems combining traditional and emerging technologies should be further promoted to make the most of less popular technologies.

3.2. Environmental pretreatment methods.

Attention should be paid to the development of environmentally friendly pretreatments involving green antiscalants and agent-free biological methods. Various electrocoagulation and dissolved air flotation techniques should be investigated.

3.3. Technology innovation

Further improve the performance of large-scale SWRO plants. Efforts include the enlargement of single unit capacity, decrease of energy consumption, improvement of system integration, operational stability and reliability, and desalination cost. Further endeavours should be made towards pretreatment and system instrumentation, high-performance RO membranes and elements, high-pressure pumps and energy recovery devices, etc.

Through continuous research and development in the field of desalination, Morocco is ranked among the top countries in the international desalination market, with remarkable openness and inclusiveness, providing state-of-the-art desalination technologies, facilities and services for the benefit of water-stressed countries and regions around the world.

4. Conclusion

This article is a review of the process of water desalination. Different methods have been used for desalination of sea and surface water, including distillation, electrodialysis and reverse osmosis. RO desalination remains the most widely used technique at the global level than at the national level, since it constitutes a better compromise between seawater and surface water desalination. However, this technique has some disadvantages: it was found that the pretreatment used for sea water "sand filtration and microfiltration" resulting in the passage of substances less than 5 μm which causes a periodic fouling of the membranes whereas the conventional pretreatment based on coagulation and flocculation helps to agglomerate the fine particulates to sediment them easily. The pretreatment allows to improve the performance of the demineralization system by reverse osmosis and to decrease the clogging rate of the membranes.

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