Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2012.750792

51 (2013) 2836–2849
March

Large-scale water desalination methods: a review and new perspectives

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Received 17 May 2012; Accepted 25 September 2012

ABSTRACT

In this paper, modern large-scale industrial water desalination technologies are briefly reviewed and a comparison between their technological characteristics and field of application is presented to indicate possible areas for technology advancement. In addition, recent developments in distillation processes and new desalination methods are introduced for relevant technologies, offering more accessible water supplies. The research was based on both work with analytic materials from large information agencies involved in the desalination industry and research carried out by individual authors and research institutions. The authors discuss the possibility of applying their own technology for water distillation, so called supercavitating evaporation. Analysis of the current situation indicates an increasing trend for reverse osmosis technology for water desalination, the rise of newer technologies and further limitation of thermal methods for heat utilization purposes.

Keywords: Desalination; Distillation; Reverse osmosis; Thermal methods

1. Introduction

Sea water desalination is the treatment process during which dissolved substances are separated from the sea water feed stream to obtain a relatively pure product: desalinated water. Although there are many proven desalination technologies available, there is no universal desalination method that satisfies the production of fresh water regardless of the source water conditions. However, analysis of the desalination schemes and their developing trends gives some evidence that the most perspective methods are thermal distillation and membrane desalination. Currently, primary technologies that use thermal processes include multi-stage flash, multiple effect distillation and vapour compression distillation, whereas membrane-based processes include reverse osmosis, nanofiltration and electrodialysis. In this work, we consider only large-scale industrial water desalination methods such as multi-stage flash, multiple effect distillation and reverse osmosis, which are used by operating plants with relatively high capacities.

The development of desalination capacity [1] by membrane and thermal processes shows that, by 1980, thermal distillation methods accounted for up to 75% of the cumulative installed capacity. The charts shown in Fig. 1 reveal that in the past 15 years, reverse osmosis technology based production has been growing fast, and in the year 2000 it equalled the thermal processing rates [2], the annual growth of which has been close to linear. Moreover, starting from the year of

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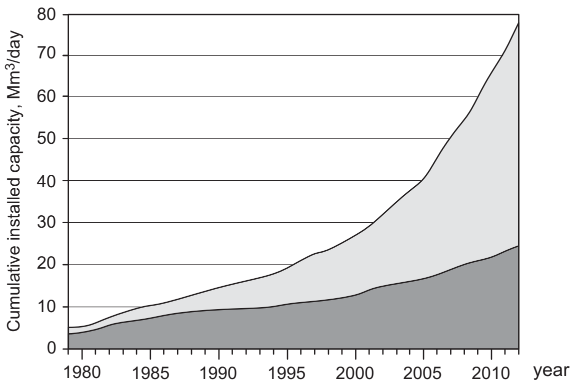

Fig. 1. Development of desalination capacity by membrane and thermal processes, dark grey—thermal; pale grey—membrane.

equal installed output, over recent years the availability, efficiency and reliability of membrane systems have increased significantly, while the capital and operational costs of these systems have dropped considerably. These developments have resulted in worldwide exponential growth of membrane treatment plants, which accounted for up to 59.85% of the worldwide fresh water production at the end of 2011, making membrane treatment the leading technology. Therefore, from the installed capacity point of view, this indicates overall higher engineering-and-economic performance of reverse osmosis for water desalination. Membrane desalination is the fastest growing technology, and is expected to become the prevalent desalination technology for the twenty-first century [3]. In recent years, this has become possible due to the fact that sea water reverse osmosis has become a reliable commercial process, applicable on a large scale [4].

On the other hand, thermal distillation plants are often coupled with power plants in a cogeneration configuration. Waste heat—in the form of steam from the bleedings of the counter-pressure, cogeneration or condensing turbines from the power plant—is used to heat the seawater at the thermal distillation plants, and is also used for the cooling functions of the condenser for the power plant at the same time [5]. This reduces the energy consumption for desalinisation by 30–50% [6], which seriously improves the economics of the plant, since energy is by far the largest operating cost of the thermal distillation plants.

2. Thermal distillation method

Modern thermal desalination facilities are not only different in the construction and scheme of the distillant evaporation, but also vary by operating as the energy source and connection type in the power plant thermal cycle. Thermal energy, as primary source for evaporation, is usually used in the form of low temperature heat, and a secondary source is electric energy—a great partition of which is used to drive the feeding or vacuum pumps of the system. The most widespread are the following two types of thermal distillation method: multi-stage flash and multiple effect distillation, which accounted for 25.99 and 8.2% [2] of the worldwide fresh water production at the end of 2011, respectively.

2.1. Multi-stage flash

Multi-stage flash is a counter current heat exchanger (Fig. 2) that uses the negative pressure difference near the saturation point to flash sea water through multiple stages and to condense water vapour in order to collect desalinated water. The demister, placed in between the flashing brine and the condenser coil, captures the entrained brine droplets from the flashed-off vapour, therefore decreasing the salinity of the product water and scale formation on the outer surface of the condenser tubes. Non-condensable gases at each stage are continuously evacuated by the vacuum system to permanently ensure a high heat transfer coefficient during steam condensation.

A multi-stage design provides a developed scheme of heat regeneration, as a higher overall temperature utilization of the heated brine increases the production efficiency of the device and diminishes specific heat consumption. A multi-stage flash facility is also characterised by the stable work of the steam volume. The pressure in the chamber remains constant as equal amounts of steam are formed. When new warm brine enters the stage partition, the steam is condensed. The equilibrium is stable because pressure increases during vapour formation thus reducing evaporation and increasing condensation.

During the multi-stage flash distillation, the percentage of the water flowing through the system

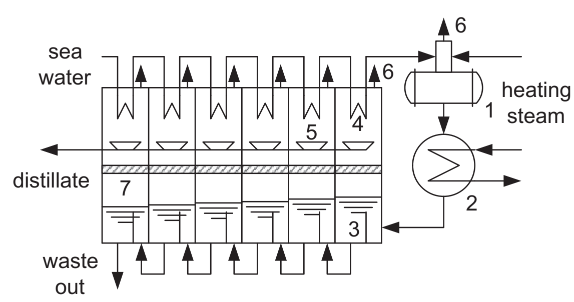

Fig. 2. Multi-stage flash distillation facility: 1—deaerator; 2—brine heater; 3—flashing chamber; 4—condenser coil; 5—condensate collector; 6—to the vacuum system; 7—demister.

and distillating reaches 15%; this requires high capacity pumps for large-scale operation. With increasing temperature, there are growing difficulties of scale formation and corrosion. A temperature limit of 120˚C appears to be a maximum, while total scale avoidance requires temperatures less than 70˚C [7]. However, wider temperature ranges between the first and the last stages increase the number of stages, resulting in cheaper production. Typically, pre-treatment of the sea water is achieved by adding acid or advanced scale-inhibiting reagents. In general, polyphosphate is dispensed into the feed water to prevent calcium carbonate scale formation on the heat transfer surfaces.

2.2. Multiple effect distillation

Multiple effect distillation is a concurrent heat exchanger (Fig. 3) that uses secondary steam, generated in the previous stage, to evaporate water by condensing steam into the heat exchanger of the current stage, thus producing desalinated water. Before flowing to the next stage, the generated vapour first flows through a mist separator—a demister—which removes the entrained brine droplets. Each intermediate stage substantially reuses the heat from the previous stage, while the first and last stages need external heating and cooling, respectively. The pre-treatment of seawater for multiple effect distillation plants is similar to that used in multi-stage flash plants. The vacuum system serves the same purpose as in the multi-stage flash plant.

The heat exchanging arrangement has different combinations of particular types: steam tube, water tube; water immersed, thin water film, water spray; vertical tube and horizontal tube. Among the different technological schemes, a horizontal steam tube falling water film arrangement has higher thermal physics characteristics, a simple construction, and low specific heat and energy consumption. In short, horizontal-tube falling film evaporation is an industrial standard for thermal desalination technology. This is due to the fact that a small volume of water during evaporation of the thin water film improves the stability of the evaporator while operating under inconsistent heat flux conditions. A short time of contact between the brine and the heat transfer surface decreases scaling, and as a result allows a higher degree of evaporation. Moreover, high heat transfer coefficients are achieved on both sides of the heat transfer surface: outside, due to the low thermal resistance of the thin film and inside, due to the high heat emission coefficient during vapour condensation. However, the horizontal falling film arrangement limits operation to temperatures below 70˚C to reduce cleaning shutdowns caused by scaling of the outside surface [8].

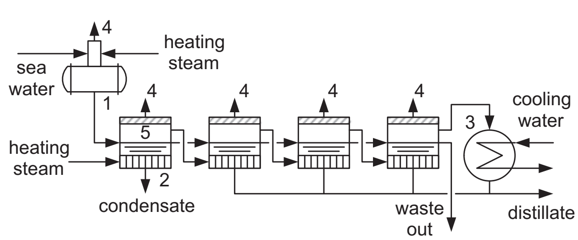

Fig. 3. Multi-effect distillation facility: 1—deaerator; 2—heat exchanger; 3—condenser; 4—to the vacuum system; 5—demister.

A recent numerical simulation of the comprehensive distributed parameter model of a practical horizontal-tube falling-film evaporator has been developed and validated by Hou et al. [9]. This model predicts the distribution of thermal parameters in the tube-side and shell-side, providing data for heat and mass exchange processes taking place during seawater desalination. The authors conclude that the computational time is reduced significantly in comparison with the computational fluid dynamics.

There may be difficulties in the distribution of the water film, because boiling ruptures the thin water film and dramatically decreases the water—heat transfer interface, enabling water droplet entrainment to reduce the quality of the distillate, while a thick water film reduces heat transfer. Yang et al. [10] researched internal condensation in a horizontal-tube falling-film evaporator and pointed out that interfacial shear stress has a significant effect on the condensation rate, and the presence of even a very small mass fraction of non-condensable gases hinders heat transfer. With a view to the coolant flow side, authentic brine water causes fouling, which significantly lowers the value of the overall heat transfer coefficient vs. operation time.

Adding to the common anti-fouling approaches improving thermal performance, Galal et al. [11] compared corrugated and smooth aluminum-brass material tubes in a simulated multi-stage flash technique. Under deliberated constraints, it is demonstrated that the amount of condensated water from the outer-side surface of the corrugated tube is 1.22 times higher than that from the smooth tube, and the fouling thermal resistance is 0.56. Results also prove that the heat performance for the corrugated tube is superior to the plain tube for the chosen range of coolant flow speeds.

Thermal method efficiency is represented by the gain output ratio: the volume of water produced per unit mass of steam supplied to the system. An analytical approach for modeling the modern multiple effect distillation facility has been confirmed by experimental observations in work by Yang et al. [12], who evaluated and measured its thermodynamic performance. In results, increasing the flow rate of feed seawater decreases the gain output ratio, but increasing the flow rate of heating steam increases the gain output ratio.

To further increase the efficiency and output of thermal desalination plants, a new technology nanofiltration softening membrane will allow the maximum brine temperature to be increased, consequently allowing higher production with almost the same desalination trains. Hornayoonfal and Akbari [13] have studied the properties of polysulfone nanofiltration membranes, capable of removing metal ions from water, with rejection rates of 96.3 and 58.8% of Na_2SO_4 and $MgSO_4$ solutions, respectively. However, membrane graft-modification resulted in a significant decline of pure water flux, along with an improvement of sulphate rejection. A performance comparison of nanofiltration and conventional hot lime softening by Khedr [14] revealed similar efficiency in hardness rejection by nanofiltration which in addition resolved the attendant drawbacks of hot lime softening. Nanofiltration used for the separation of trace heavy metal cations, high modulus carbon, Cd^{2+}, Ag^{+}, and Hg^{2+} from mixed salt solutions, revealed 98% separation at recovery above 90%, which is more efficient than conventional removal by precipitation as hydroxides or sulphides, or by means of chelating ion exchange resins, under the same conditions. In addition to the above mentioned advantages, polysulfone nanofiltration enabled optimum recycling of the permeate as process water, and the safe disposal of the minor volume reject after precipitation of the high modulus carbon to the sewer stream. Low et al. [15] pointed out that in applications where the water hardness and total dissolved solids are marginally higher, the nanofiltration membrane is found to be the best application due to its ability to reduce the permeate total dissolved solids at reasonable energy costs. In this work, tests also showed that a thick monomer solution and a denser polyacrylonitrile structure would lead to a membrane of better solute rejection.

Improvements in the operation of thermal processes (besides having a better heat transfer coefficient, using a combination of multi-stage flash and multiple effect distillation schemes, and advanced ancillary equipment) can also be obtained by incorporating new materials from the thermal desalination industry. Polymeric hollow fiber heat exchangers made of polypropylene and polyetheretherketone have been tested by Zarkadas et al. [16]. These heat exchangers offer the same or better thermal performances than the common metallic heat exchangers while occupying a much smaller volume, and develop considerably lower pressure drops. In addition, a plastic heat exchanger is compact, lightweight and able to handle corrosive media, thus ensuring ultra-high purity of the working flows. Rather than creating a new type of heat exchanger, Christmann et al. [17] developed and tested a multiple effect distillation pilot plant with a falling film plate evaporator made of polyetheretherketone films with a thickness of 25 μm. Experimental investigations have shown its sufficient mechanical stability; the resulting thermal resistance for heat conduction is comparable to 1.5 mm thick stainless steel. The recent use of new stainless steels in the desalination water industry has been exampled by Peultier et al. [18]. Duplex grades UNS S32304 and UNS S32205 have been selected for a new concept of evaporation cells. As a result, these new steels better withstand corrosion compared with standard 316L. Finally, thanks to the low nickel content of the duplex grades, the market price of these materials is less volatile.

Thermal distillation methods have both industrial applications by waste heat utilization and small scale applications coupled with electric heating units, fossil fuel burners or renewable energy sources. Solar energy is considered highly competitive compared with fossil fuels by Ettouney and Rizzuti [19], Chaibi and El-Nashar [20], especially in remote areas; but Banat and Qiblawey [21] report that solar energy systems still cannot compete favourably with fossil fuel based energy desalination, while Dev and Tiwari [22] emphasize the challenges associated with the effects of various parameters and technology transfer. Successful computer simulation and experimental studies of solar-powered multiple effect distillation, conducted by Leblanc and Andrews [23], showed the technical and economical feasibility of the system. Both teams conclude that solar based technology has the potential to power both membrane based desalination plants and solar thermal processing plants. In addition, a pioneering system design of solar water desalination, developed by Adel and Abdel [24], has revealed that a combination of both solar and auxiliary energies is the most efficient and adaptable for water desalination. Al-Karaghouli et al. [25] consider solar-powered desalination technologies to be suitable and may be the only technically and economically competitive renewable energy alternative for small desalination capacities up to $10\,m^3$/day in areas without access to fuel, electricity and technical expertise.

3. Reverse osmosis method

The development of renewable energy has led to direct usage of the electric current in the form of fields or mechanical work for distillation processes, avoiding the disadvantages associated with heating such as scaling, corrosion and high steel intensity. These comparatively new desalination methods are generally of reverse osmosis type, which utilize high pressure on to the compartment with a high concentration side of semi permeable membrane to force (permeate) fresh water through it (Fig. 4). In practice, the seawater after pre-treatment system 5 can be pressurized as high as 70–80 bars to overcome the natural osmotic process. Utilization of the residual pressure of the brine leaving the membrane module is a key process, as according to Fig. 4, feed water leaves the energy recovering device 3 and mixes with the discharge of the high-pressure pump 1 to supply the membranes, therefore recovering otherwise wasted discharged energy. A typical energy recovering device uses hydraulic power to cause a positive displacement within it, and the hydraulic energy is directly transferred in one step [26]. Booster pump 4 accounts for pressure losses in the system. Commercially successful reverse osmosis configurations usually consist of the spiral-wound and hollow fibre modules.

The effectiveness and reliability of the energy recovering device for membrane distillation technology are widely considered to have made large-scale reverse osmosis economically sound. There are, consequently, fundamental differences between the way the Pelton and Francis turbine devices and modern approaches use energy recovering devices.

Al-Hawaj [27] presents a theoretical analysis of a novel energy recovering device: the sliding vane work exchanger. This device combines a positive displacement pump and a positive displacement turbine. A parametric study has indicated that the viability of the sliding vane work exchanger is highly dependent on low values of vane tip friction and leakage. Exergy analysis of a reverse osmosis desalination plant has been conducted by Sharqawy et al. [28], using the most up-to-date thermodynamic properties of seawater. It is found that the energy recovery system using the pressure retarded osmotic method has a second law efficiency of 20%, and the power consumption can be

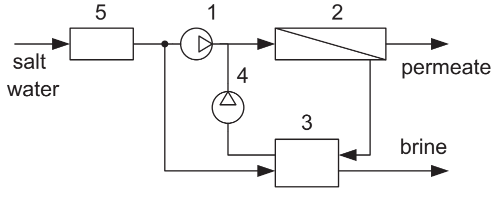

Fig. 4. Reverse osmosis distillation facility: 1—high pressure pump; 2—reverse osmosis membrane; 3—energy recovering device; 4—booster pump; 5—water pre-treatment system.

significantly reduced. Li [29] addresses the effect of an energy recovering device on specific energy consumption in multi-stage reverse osmosis water desalination. Analysis made at both the theoretical limit and practical conditions has shown that a 90% efficiency of the energy recovering device is sufficient for operation. Nevertheless, net transfer efficiency up to 97% has been obtained by Penate and García-Rodríguez [30] with their isobaric energy recovering device, transferring the energy from the membrane reject stream directly to the membrane feed stream.

Research and development over the last 25 years has reduced normalized salt passage 7-fold, increased membrane life from 3 years to over 7 years, doubled fluxes of the elements and reduced the cost of elements on a normalized basis more than 10-fold. Overall, the development of reverse osmosis membrane technology faces the following challenges [31]: obtaining sustained high permeate water quality combined with lower pressure membrane elements, lower energy consumption and reducing membrane fouling by applying an organic fouling resistant reactive coating. Note that a considerably lower pressure process takes place in forward osmosis membrane technology which leads to relatively lower energy consumption and will be discussed later in this article.

Polymer and inorganic science, organic chemistry, advanced membrane and resin technologies in membrane development address the current problems. Some examples of modern applications for enhancing permeation flux while maintaining the wetting resistance of the polyvinylidene fluoride membrane using dual-layer architecture are proposed by Wang et al. [32]. They state that the permeation flux increases due to the coupling of a higher driving force and a lower mass transfer resistance of a finger-like macrovoid inner-layer and a sponge-like outer-layer. Another article, by Ji et al. [33], provides a novel method for introducing zwitterionic polymers into composite nanofiltration membranes, achieving high water flux and good anti-fouling performance.

Fouling is addressed by using new starting monomers for manufacturing, improvement of the interfacial polymerization process, surface modification of the conventional reverse osmosis membrane by physical and chemical methods as well as the introduction of a hybrid organic/inorganic reverse osmosis membrane. Fuctionalization methods for membrane surfaces [34] also reduce membrane fouling by minimizing undesired adsorption or adhesion on the surface. Below are some examples of successful applications of antifouling measures. McCloskey et al. [35,36] have applied a surface deposition of polydopamine to a reverse osmosis membrane, which improved the fouling resistance of the polyamide membrane modules without too much loss of the membrane's intrinsic pure water permeability. Further modification by grafting fouling-resistant macromolecules of poly(ethylene glycol) could increase the short-term fouling resistance of microfiltration membranes [37]. The method of making the composite membrane applicable for high pressures and salinities with high yield, high salt rejection of 99.5%, high flux and increased fouling resistance is presented by Kurth et al. [38]. Both reversible and irreversible fouling properties of modified ultrafiltration membranes have improved due to the incorporation of an end carboxyl group methoxy polyethylene glycol in the work by Yu et al. [39]. Azari and Zou [40] incorporated L-DOPA onto a commercial reverse osmosis membrane SW 30 XLE and created a zwitterionic surface that resists membrane fouling. Greater control of bio-fouling, presented in a study by Lee and Kim [41], utilizes the diagnosis and prediction of microbial bacteria bio-film community structure and membrane operational problems.

There is also an extensive method for sea water reverse osmosis improvement by using a reverse osmosis unit with a larger diameter. Full utilization of the 16-inch element volume allows a 15–30-fold increase in permeate flow with a 5–8-fold reduction of salt passage vs. early 4-inch elements. A paper by Johnson and Busch [42] focuses on this transition process in reverse osmosis module configuration and how it helped to achieve these performance improvements. In addition, sea water reverse osmosis modules with 16-inch elements have been adopted for single units [43] with 4.5×10^4 (m^3/d) of freshened water production. Large modules aimed [44] to both decrease sea water reverse osmosis membrane fouling by 50% and reduce the total energy consumption of a whole plant to less than $4\,kWh/m^3$.

Comparing the reverse osmosis method with thermal methods has an essential disadvantage: the need for stringent water pre-treatment before charging it through the membrane to prevent fouling. Related actions to prevent or control fouling by appropriate cleaning methods and conventional or membrane-based pre-treatment are presented in Curcio and Drioli [45] who overviewed the fundamentals of the modern membrane processes. Conventional water pre-treatment, according to the intake water quality, may include the following: coagulation followed by separation, deferrization, chlorination, dechlorination, softening, acidification and sterilization. During the membrane-based water pre-treatment microfiltration, ultrafiltration and nanofiltration are progressively used. The source water consumption required for reverse osmosis is 1.5 times higher than that required for thermal distillation for the same desalinated water output [46]. In addition to this, if the temperature of the intake water decreases below the design variable then the productivity of the membrane drops drastically, so the higher temperature facilitates higher production; on the other hand, decreasing the temperature also enhances the permeate quality as reported by Guler et al. [47]. Supaiman et al. [48] extensively analysed the performance of direct contact polymeric membranes and discovered that a higher temperature gradient resulted in a flux decay of about 70%. Nevertheless, reverse osmosis technology provides high water quality by suspension parameters and biological and organic pollutants and requires minimal quantities of chemical reagents.

Adding to the membrane pre-treatment discussion, Halpern et al. [49] observed that membrane pre-treatment worked well for source waters of low bio-fouling potential, namely for subsurface or deep open ocean intakes. Plants with dissolved air flotation, described by Bonnelye et al. [50,51] or other pre-treatments [52–56] apart from microfiltration and ultrafiltration membranes have shown satisfactory operation even during unstable intake water quality.

Research by Jeong et al. [57] has shown that the high turbidity of the raw water in shallow open intakes impedes the application of membranes. Choi and Kweon [58] have conducted experiments in the natural environment and investigated that turbidity increased by natural particles showed a relatively greater flux decline compared with laboratory results, probably due to organic matter absorbed in the particles. A complex yet successful pilot plant setup and operation has been demonstrated by Xie et al. [59] under tropical conditions requiring particular attention to optimise the pre-treatment process and to minimise membrane fouling.

As an alternative, Peters and Pinto [60] have shown that consistent high quality pre-treatment of the feed water can be obtained using directed drilled horizontal drains below the seabed for seawater intake and as a partial pre-treatment system. This system eliminates the need for conventional filtration of seawater and the dosage of different pre-treatment agents; also it operates without impingement and entrainment of aquatic organisms. This research by Perez-Gonzalez et al. [61] has also focused attention on potential treatments to overcome the environmental problems associated with the direct discharge of reverse osmosis concentrates.

Recent problems with systems designed for overly high flux rates based on long-term piloting have been overcome by Wei et al. [62] during the investigation of the critical flux and chemical cleaning-in-place in a long-term operation of a pilot-scale submerged membrane bioreactor for municipal wastewater treatment. Steady filtration under a high flux of 30 L/m^{2}h was successfully achieved due to effective membrane fouling control by sub-critical flux operation and chemical cleaning-in-place with sodium hypochlorite under several controlling modes.

Table 1 [1,4,8,25] presents a generalization of the technical parameters of the desalination technologies discussed above. The demand for desalinated water typically defines the production capacities of interest that usually fall into two broad ranges: from 8×10^4 to 10^5 m^3/d, and between 2×10^5 and 5×10^5 m^3/d of potable water, while the large-scale production capacity of a single multi-stage flash or multiple effect distillation unit of approximately 7.5×10^4 m^3/d is sufficient to supply 3×10^5 inhabitants. Sea water reverse osmosis desalination technology is used at large—over 5×10^4 (m^3/d) and mega—over 2×10^5 (m^3/d) desalination plants. Since 2010 there are 3×10^5(m^3/d) sea water reverse osmosis plants in Australia (Adelaide [63,64]) and Israel (Ashkelon [65–67]).

Hereby, comparison of the mainstream and perspective water desalination methods shows that the application of each scheme depends on a number of factors. Preference is given to the scheme which, along with maximal productivity, provides the highest distillate quality, the lowest energy consumption, the lowest cost of desalinated water and causes the smallest impact on the environment. It should be observed that a thorough and well-grounded analysis of industrially mature desalination methods and their economical estimation under a broad range of different conditions has been completed by the International Atomic Energy Agency [4]; their work [8] gives a complete description of the established desalination processes, together with the main modelling equations.

4. New approaches for water desalination

The diversity of thermal and membrane distillation schemes and construction characteristics determines the different methods of desalination process intensification. Improvements in the effectiveness of these processes can be made by advancing the existing methods, or by inventing new methods of distillation based on the previously unemployed physical phenomena. These technologies tend to reduce the following factors: scaling, steel intensity, energy consumption, environmental effects, labour and maintenance input.

Thermal methods development is based on increasing the thermal transfer coefficient which determines the construction material consumption and pumping costs. However it must also obey the scaling formation limit [68], and that is the main restriction for technology progress.

As for the membrane methods, prevention of the fouling of the membrane by the intake water treatment and the increase of the recovery factor of the desalination process [69] are considered as the main aims for technology advancement. However, in this work we would like to emphasise improving the effectiveness of desalination through the invention of brand new processes based on different physical effects and phenomena. The most perspective approaches for water desalination include the following methods: (1) ion concentration polarization; (2) forward osmosis; (3) carbon nanotube technology; (4) capacitive deionization; and (5) supercavitating evaporation. Table 2 presents a generalization of the specific electrical energy consumption of the new desalination technologies stated above. Table 3 summarizes the distinctive features and the remaining limitations of the present and new desalination technologies at their current development stages.

Ion concentration polarization for water desalination has been developed by Kim et al. [70] as a microfluidic device using a phenomenon that occurs when an ion current is passed through ion-selective membranes. During the process, seawater flows through microchannels connected by a Nafion nanochannel or a nanoporous membrane—an ion-selective material. With an electrostatic field across the membrane, electrostatic forces repel salts or larger particles (cells, viruses and microorganisms) contained in the seawa-

Table 1
Technical parameters of desalination technologies (MSF—multi-stage flash; MED—multiple effect distillation; RO—reverse osmosis)

Item	Energy type/technology	MSF	MED	RO
1	Electrical equivalent of specific thermal energy consumption (kWh/m^3)	9.5–11.0	3.0–4.5	0
2	Specific electrical energy consumption (kWh/m^3)	3.2–4.0	1.2–1.5	2.2–5.0
3	Total electrical energy equivalent (kWh/m^3)	12.7–15	4.2–6.0	2.2–5.0
4	Operation temperature (℃)	90–120	50–70	<40

Table 2
Specific electrical energy consumption of new desalination technologies

Technology	Specific electrical energy consumption (kWh/m^3)
Ion concentration polarization	3.5
Forward osmosis	0.25
Capacitive deionization	0.1
Carbon nanotube technology	2
Supercavitating evaporation	3

ter from the membrane, thus fouling and salt accumulation are avoided. The ion-selective membrane eliminates the need for high pressure, but the amount of electricity required by this method is actually slightly more than that for the present large-scale industrial methods ($3.5\,kWh/m^3$), so currently this technology is only considered for portable desalination units used in resource-limited settings or in a disaster scenario. In addition, Shannon [71] suggests the use of a nanochannel-based device that requires only low-voltage electricity to separate salt water into desalted and saltier streams; while Gong et al. [72] have designed a novel molecular water pump for seawater desalination, providing possibilities for developing water transport that functions without osmotic pressure or a hydrostatic pressure gradient.

Researchers at Yale University and in Singapore [73] are investigating forward osmosis technology. The forward osmosis process exploits the natural tendency of liquid to move in the direction of higher osmotic pressure, which occurs between two aqueous solutions with different salinity separated by a semi-permeable membrane. Note that reverse osmosis membranes are not suitable for forward osmosis and pressure retarded osmosis [74] processes due to severe internal concentration polarization phenomena. However, coating the membrane support layers with polydopamine resulted in increased hydrophilicity and reduced the internal concentration polarization [75]. This is promising and enables the use of commercially available thin film composite reverse osmosis membranes for all engineered osmosis applications. Salt water, driven by the higher osmotic pressure of dissolved CO_2 and ammonia, flows across the semi-permeable membrane into a highly concentrated "draw water", thus effectively separating salts from the feed water. Heating the diluted draw solution at a low pressure allows solute gases to be removed and pure water to be obtained. The CO_2 and ammonia driven off by heating are recycled; the released heat is recycled by means of a heat pump system and used for heating the diluted draw solution at a higher temperature. Others [76] suggest using waste heat for recovering the solute instead of the heat pump. McGinnis et al. [77] modeled the osmotic heat engine, which uses depressurization of the increased draw solution volume in a turbine to produce electrical energy with a membrane power density over $200\,W/m^2$. Besides CO_2 and ammonia draw solutions for forward osmosis applications, there are polyelectrolytes [78], low energy fertilizers [79] and

Table 3
Distinctive features of present and new desalination technologies

Technology	Fundamental advantage	Remaining limitations
Multi-stage flash	Operates with low temperature brine	Upper brine temperature is limited by 120℃
Multiple effect distillation	Lowest total specific energy consumption among traditional thermal desalination methods	Upper brine temperature is limited by 70℃
Reverse osmosis	Produces highest quality water	Requires fine water pre-treatment
Ion concentration polarization	Fouling and scaling of the membrane are avoided	Only for portable desalination units
Forward osmosis	Lowest total specific energy consumption among membrane desalination methods	Membrane scaling
Capacitive deionization	Lowest total specific energy consumption among all desalination methods	Only for brackish water applications
Carbon nanotube technology	Greatly improves reverse osmosis membrane	High membrane cost
Supercavitating evaporation	High energy intensity of the heat mass transfer steam-water interface	Cavitation damage

inorganic-based [80] draw solutions. Kim et al. [81] have developed a systematic approach for solute selection from the OLI (http://www.olisystems.com/index.shtml) and ASPEN (http://www.aspentech.com/process-optimization-overview/) chemical databases, contributing to the design of commercially viable forward osmosis desalination systems. Forward osmosis technology has the following predicted technical characteristics: energy consumption 0.25 kWh/m^3 [82], water flux 541/m^{2}h [83] and recovery ratio up to 75%. The world's first fully commercial application of forward osmosis technology [84,85] is being built in Oman by Modern Water plc.

Forward osmosis, as well as thermal desalination technologies, has problems concerned with scaling. Thus, Mi and Elimelech [86] have researched gypsum scaling and cleaning in forward osmosis and found that membrane surface modification and new material development can be an effective strategy to mitigate membrane scaling. Van Driessche et al. [87] have stated that understanding the gypsum formation mechanism can lead to more efficient anti-scaling strategies for water desalination overall. Research by Zhao et al. [88] focuses on other critical challenges, including internal concentration polarization [89,90]; membrane fouling [91,92]; reverse solute diffusion [93,94]; and the need for new membrane development [95,96] and draw solute design [97–99] in forward osmosis process. In addition, the numerical simulation of plate and frame type forward osmosis membranes by Jung et al. [100] showed spatial variation of the concentration profile on a 2-dimensional membrane area, which yields unexpected fouling in a specific area of a membrane.

The comparatively new capacitive deionization method [101] uses carbon aerogel electrodes which electrosorb ions in solution by the electric field upon polarization of each electrode pair by a direct current power source. Upon saturation, following electrical discharge, the regeneration phase may recover 50–70% of consumed energy due to the fact that each cell acts as a capacitor. Carbon aerogel possesses a low electrical resistivity, a high specific surface area and a controllable pore size distribution; therefore it is an ideal nano-pore electrode material for the selective removal of ions. Capacitive deionization uses electrical regeneration without the need for handling secondary chemical waste streams. The resistance of carbon aerogel to acids and oxidizing agents makes de-scaling and de-fouling easy if required. The first industrial capacitive deionization prototype by Welgemoed and Shutte [102] for brackish water applications without the need for high-pressure pumps contributes to 0.594 kWh/m^3 of brackish water (1,000 mg/l), with the potential for 0.1 kWh/m^3 shown by laboratory test work. This makes it very cost effective when compared to reverse osmosis for brackish water applications. Higher salinity competition requires a reduction of the capital costs for the production of capacitive deionization modules. Dietz [103] has developed a route to monolithic carbon electrodes with more penetrable surfaces and a useful capacity that is much easier and much less expensive to make than carbon aerogel electrodes. The desalination performance of capacitive deionization has been increased by Kim and Choi [104] and Li and Zou [105], by adding a cation-exchange polymer coating, improving the salt-removal to 97% and the current efficiency of the electrode. The composite capacitive deionization electrode by Yang et al. [106], made of MnO_2 and nanoporous carbon, has a 3-fold higher salt removal efficiency and a 2-fold higher capacitance compared with commercially available activated carbon. The mathematical formulation and simulation of the behaviour of the capacitive deionization module have been done by Ryu et al. [107], confirming the results based on actual experimental data. Besides desalination, the capacitive deionization shows promise for treating coal bed methane produced water, as reported by Atlas and Wendell [108].

Meanwhile, at the New Jersey Institute of Technology [109], Mitra et al. incorporated carbon nanotubes into membrane pores, allowing high water vapour flux but preventing salt from flowing through at pressures much lower than those required for conventional reverse osmosis membranes. Immobile carbon nanotubes increase the vapour permeation and prevent liquid water from fouling the membrane pores. Another advantage is that the new process can facilitate membrane distillation at a relatively lower temperature, higher flow rate and higher salt concentration. Compared to a plain membrane, for a feed water temperature of 80°C, the carbon-nanotube-enhanced membrane demonstrates a 15-fold increase in salt reduction and a 1.85-fold higher flux. Research conducted by Corry [110] previously confirmed that membranes incorporating carbon nanotubes can, in principle, achieve a high degree of desalination at flow rates far in excess of existing reverse osmosis membranes. Ken and Somenath [111] report that methanol flux and mass transfer coefficients increased by 61 and 519%, respectively for a carbon nanotube immobilized membrane in their research. A water flux increase of 63% has been detected by Majeed et al. [112] for polyacrylonitrile ultrafiltration membranes blended with hydroxyl functionalized multi-walled carbon nanotubes. Membrane tensile strength has also been increased over 97% compared to a membrane without treatment. The anti-biofouling properties of the membrane are enhanced by modification with nanosilver particles in work by Kim et al. [113]. Gethard et al. [114] report an enrichment effect of concentrating medium increase by 421% and mass transfer coefficient increase by 543% for carbon nanotube immobilized membranes compared to membranes without the nanotubes. Future applications of integrated carbon nanotube based membranes for water purification system applications and their manufacturing methods are reviewed by Ahn et al. [115].

Hybrid desalination plants integrate power, membrane and thermal processes to deliver high efficiency, lower the cost of power and water generation and minimize the environmental foot print. The paper by Kamal [116] discusses the range of application of hybrid plants, emphasizing some misconceptions that have contributed to the continued use of thermal desalination processes.

Comparative analysis of the different schemes for desalination and the methods of heat transfer improvement in the evaporator installations [117] shows that the most effective methods change the hydrodynamic characteristics of the flow, which leads to increases in the energy intensity of the heat mass transfer surface. In this direction, the most promising phenomenon is a developed cavitation. The cavitating evaporator construction enables a relatively stable interface region between the liquid and steam phases to be maintained and allows the extraction of steam from the supercavity volume.

One example of the cavitating desalination device has been designed by the scientific and technical center "TJEROS-MIFI", directed by V.S. Afonasiev. The device uses so-called "hydrowave" physical processes which create chemical and thermal conditions for intensive evaporation of a solution that is being purified. Practically, overheated water after electromagnetic treatment discharges on specially designed stationary obstacles, form a supercavity behind them and subsequently steam is extracted from multiple places. Steam extraction from multiple supercavities is carried out at an ultrasonic rate; therefore it is a periodical process. Their commercial device "WATERFALL-1200" with a productivity of 1,200 m^3/d [118], can process polluted salt water, industrial and domestic wastes containing surface-active substances, petroleum products and heavy metals—producing freshened water, without the need for the consumables during operation. Moreover, the device features a scale free operation and the release of waste products in the form of solid sediment [119], under operation on the source water with mineralization up to 65 g/l, consuming up to 3 kWh/m^3, and ensures a more than 99% pollutant extraction rate.

5. Prospection and concluding remarks

The major drawbacks of thermal distillation are low energy intensity, corrosion and scaling of the heat transfer surface and, therefore, new, environmentally safer technologies with lower maintenance and production costs are sought as replacements. As a result, the design of new devices needs to optimise energy consumption for desalinisation, eliminate corrosion and scaling formation, maintain construction simplicity and produce higher quality fresh water.

To achieve the above-stated goals we use the supercavitation phenomenon, which advances evaporation performance in comparison to well-known methods, determining the advantages of the supercavitating method for water desalinisation. In fact, supercavitation changes the hydrodynamic characteristics of the flow, leads to increase in the energy intensity of the heat mass transfer, eliminates thermal resistance induced by the conventional heat transfer surface, and maintains evaporation by the latent heat of the flow. Therefore, research into the supercavitating flow with steam extraction from the cavity for the design of a desalination device with high energetic and economic characteristics is topical as part of the general actual mission to provide access to desalinated safety water resources and to reuse wastewater in the closed systems of the water supply.

Our future research will be concerned with the rotating cavitator for the evaporation of water under conditions of continuous steam generation and steam extraction rates, opposite to the stationary cavitator and periodical extraction rate. Fig. 5 shows an

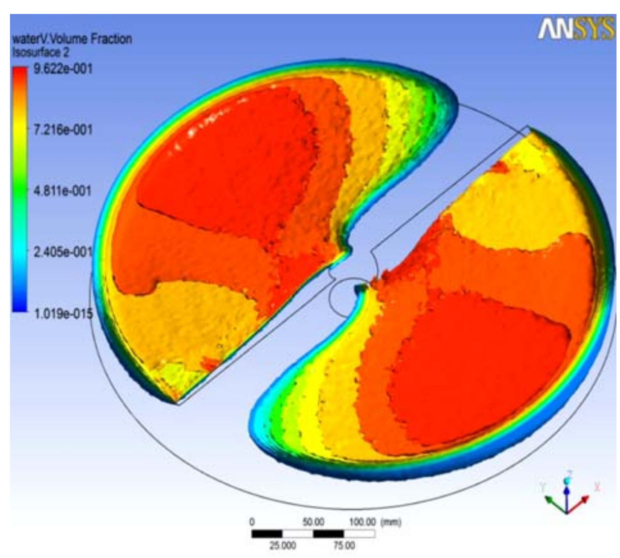

Fig. 5. An example showing the numerical simulation result for supercavitation in a rotating cavitator.

example of the supercavitation phenomenon in a rotating cavitator, realized by our numerical simulation. This problem also gains more viable theoretical and practical value when combined with steam extraction in opposition to the cavity ventilation. In addition, a common problem introduced with devices using the cavitation phenomenon is damage caused to the working parts and interiors.

Incidentally, Pozdunin [120] first pointed out the capability of the developed cavitation against cavitation erosion on the marine propellers. Therefore, the rotating cavitator has been designed with rotating blade wheels with alternating thicknesses of exit edge. This design limits the cavity length along the blade radii and ensures safety against cavitation erosion; it also yields the supercavity with the maximum volume. We are interested in using reliable physical simulation software and experimental studies to show the high steam extraction rate and erosion safety of the rotating supercavitator.

Acknowledgement

This study is sponsored by National Natural Science Foundation of China (51121004, 51076036), the Fundamental Research Funds for the Central Universities (HIT.BRET1.2010008) and Specialized Research Fund for the Doctoral Program of Higher Education of China (No. 20112302110020).

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