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Current development and future prospect review of freeze desalination

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ABSTRACT

Freeze desalination (FD) is an emerging technology to overcome limitations of membrane- and thermal-energy-based desalination processes. Extant studies concerning FD have primarily focused on ice-quality and productivity enhancement. Numerous crystallizer designs operating under various conditions have been investigated to achieve highest possible fresh-water purity. Few post-treatment techniques have also been developed to boost quality and productivity of fresh water. Some obstacles, have been faced in attempts to scale-up the FD process, and possible remedies to these are discussed in this paper. In addition, there exists a possibility towards combining FD with other desalination technologies, thereby developing a hybrid process. The proposed paper discusses extant research trends in FD as a comprehensive review along with discussion of future prospects concerning utility of the FD process.

1. Introduction

Earth comprises 75% water, and 97.5% of all water available of the Earth's surface is saline while the rest of it manifests as fresh water. However, only 0.3% of this fresh water can be directly used for day-to-day purposes [1–3]. Global warming, climate change, human population growth, and rapid industrialization have led to continuous increase in the demand for water supply, thus, cornering the issue of water scarcity. Human population on Earth is projected to rise by a whopping 2.6 billion by the year 2025, and two-thirds of these people would be living under severe water shortage while the rest would have to face total water scarcity [3,4].

Desalination is a major technology that serves to fulfill water-supply demands by processing the saline water available in plenty on the Earth's surface. As of 2017, capacities of desalination plants have achieved values of the order of 99.8 million m^3/day [3,5]. Desalination, in general, can be categorized into two groups—(1) involving phase-change process; and (2) involving water-of-salt extraction [6]. Desalination processes involving phase changes, which were first developed, include thermal desalination processes, such as multi-effect distillation (MED), multi-stage flash distillation (MSF), and humidification–dehumidification desalination (HDH). The second category of desalination processes that require use of membranes include reverse osmosis (RO), forward osmosis (FO), and electrodialysis (ED). The RO process has been widely adopted as a popular desalination technology and has been used 80% of the times in over 15,000 desalination plants spread across the world. RO is superior to thermal desalination owing to its lower energy requirements, and development in membrane materials and manufacturing processes have also led to lower operating costs of RO processes [7].

Nowadays, yet another phase-change-based desalination technique—the freezing–melting process—has been introduced. Freezing desalination (FD) starts to gain recognition due to several favorable points compared to thermal and membrane-based desalination. This paper provides a comprehensive explanation and understanding of the FD process as a newcomer in desalination technology by highlighting the basic concept underlying the process and its development as well as describing its various applications and potential to be integrated along with other desalination technologies, thereby creating a hybrid system. Thenceforth, the paper illustrates promising future applications of FD from other aspects.

2. Limitation of major desalination technology

Several characteristics of FD can overcome drawbacks of the major desalination technology, thermal desalination and membrane desalination. Freeze desalination is insensitive to fouling phenomena which is the handicap of membrane-based desalination processes [6,8–10]. Unlike the RO process, FD does not require intensive pretreatment and chemical requirement when performing the process. In addition, RO essentially produces concentrated brine, which is harmful to environment. FD, on the other hand, possesses the potential to treat

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concentrated brine, produced by the RO process, close to zero liquid discharge (ZLD) [11]. Freeze desalination suffers minimum scaling and corrosion problems owing low operating temperatures when compared against thermal desalination process. In terms of energy requirement, thermodynamically, latent heat of ice fusion is 333 kJ/kg while evaporation of water requires 2500 kJ/kg [12,13]. The FD process, therefore, requires only one-seventh (approximately) the energy required during thermal desalination. The competitiveness of FD has been growing by facing the obstacles in the main desalination technology. Detailed information on the limitation of membrane-based and thermal desalination will be further explained below.

2.1. Thermal desalination disadvantages

Desalination technology by utilizing thermal energy is developed on the earliest time [14]. The Greek sailor used thermal desalination through evaporative process to desalinate fresh water in 4th century B.C [15]. Thermal desalination is a mature process to produce water at large capacity [16]. The reasons why the thermal desalination developed from the beginning of desalination era are the simple structure and long-lasting steady performance. In that sense, MSF has been built since the late 1950s [17]. However, MSF reaches 18 kWh/m^3 in energy consumption which causes high fossil fuel demands [18–21]. In addition, treating concentrated brine under high operational temperature leads corrosion problems, and it significantly effects on production rate [22,23]. The expensive capital cost is also disadvantage for installing more efficient MSF process because the water recovery depends on the number of distillation stages [24]. MED also known as multiple effect evaporation (MEE) is the advanced design to mitigate the high energy demand of MSF. MED utilizes lower operating temperature than MSF so that the process consumes 15 kWh/m^3 to produce desalinated water [18]. Though MED has advantages in relatively low specific capital cost and short start-up period, the general thermal desalination problems derived from operating at 60–70 °C was not solved [24,25]. Lower unit capacity when boiling point rises considerable than MSF process is another shortcoming of MED [26].

The more effort has made up for better energy efficiency. Another advanced thermal desalination such as HDH, multi effect humidification has been invented [27,28], and some elements of the process has been modified, such as thermal or mechanical hybrid vapor compressor [29] and natural vacuum [30]. Adsorption desalination (AD) then developed due to its low energy consumption compared to other thermal desalination method—1.5 kWh/m^3 [26]. On the other hand, AD requires high number of various adsorbent material [31–33], low production rate even with repeated cycle [34] and space-demanding system [35]. In general, thermal desalination still requires high electrical and mechanical energy which come from fossil fuel, and results in high CO_2 emission, another problem [36–38].

To achieve higher efficiency of the thermal process, some researches started to focus on utilization of renewable thermal energy. As example, in Africa and Middle East, the utilization of solar energy has grown tremendously [39]. Combining the solar energy to thermal desalination becomes a promising technology to resolve the energy demand. However, some research conducted on this issue haven't met this ambition.

The capital cost of solar collector is high, even at present, and the earnings is heavily affected by lifespan of the system, richness of solar radiation, meteorological condition, scale, and price of competing energy sources [40–43]. Payback period (PBP) is not feasible to achieve during its expected lifetime [44]. The manufacturing of the solar collector also may have harmful environmental impact [45]. Meanwhile, another technology such as solar still and solar chimney also have their own drawback, such as high area requirement [46,47], high water production and capital cost [48,49] and boiling brine might lower thermal efficiency of the system and lead to damage [50]. Though there were many works performed to increase energy efficiency, the developed thermal process still consumes more energy than membrane process [51].

To summarize, freezing requires much less heat than evaporation. The attempt to utilize solar energy to support energy requirement is still match the economical consideration. Therefore, the thermal desalination reaching 95% of total desalination capacity in 1960s, but nowadays, achieve only 27% capacity of overall desalination plants [52,53].

2.2. Membrane-based desalination disadvantages

Since the membrane-based desalination introduced to the industry, this method dramatically has been grown. However, utilizing membrane generates some drawbacks of membrane-based desalination. The main obstacles are high costs on maintenance, multi-steps of pretreatment and brine problems. Several factors are known to drive the maintenance cost of membrane-based desalination in water treatment systems, such as power requirements, labor, material, chemical needs for membrane cleaning and scale inhibition, as well as membrane life cycle [54]. The major factors that raise the cost of the maintenance of membrane processes is the membrane fouling resulting in the rapid decline of permeate flux during the process [55,56]. This tends to increase number of cleaning and membrane replacement, affecting the process efficiency as well as economical consideration. It leads to high operating and maintenance costs, thus, it is hard to apply this technology in low and middle income countries [57].

Parameters affecting the fouling rate are nature and concentration of solutes and solvents, membrane types, pore-size distribution, material selection, surface characteristics and hydrodynamics of the membrane module [58]. Fouling itself is stated as complicated phenomena with various mechanisms, which rely upon specific condition [59]. Thus, many studies were focused on how to overcome membrane fouling. Some researches focused on feed spacer coating with various material such as silver, copper, gold, polydopamine-g-poly(ethylene glycol) and polydopamine, and zinc oxide to control biofouling [60–64], modifying spacer strand size and alignment to control scaling and fouling [65] and adjusting spacer geometric to lower concentration polarization [66]. Besides, there are a lot of attempt on membrane coating and modification, to enhance antifouling characteristics, chlorine resistance and better hydrophilic surface [67–71]. On the other hand, FD won't ever deal with fouling problems throughout its process.

Besides modifying the membrane and spacer itself, to reduce fouling, various pretreatment processes are also applied to improve feed water quality. Pretreatment step is responsible to ensure reliable next step process and to prolong membrane life [72]. As example, biofouling could occur on RO membrane surface during desalination process, due to dissolved organic carbon (DOC), extracellular polymeric substances (EPS) or transparent exopolymer particles (TEP) in seawater [73]. Or else, the feed water contains high hardness level [72]. Thus, multi-steps of pretreatment are needed to reduce DOC, EPS, TEP, and hardness to prevent biofouling and membrane scaling. Generally, RO pretreatments include screening, chlorination, acid treatment, multi-media filtration, microfiltration and dechlorination [74]. Popular pretreatment studies are coagulation [75–77], electocoagulation [78,79], adsorption [80,81], and filtration using UF, MF or slow sand filtration [82,83]. Some researchers applied UV irradiation and ozone-GAC [84], combined coagulation and chlorination [85], and also sand-filtration [86].

However, some pretreatments, such as chlorine addition to control biological growth results in generation of hazardous by products, trihalomethanes and halo acetic acids. In addition, due to its strong oxidation potential, chlorination can deteriorate membrane integrity [87]. Ozone application as disinfectant is known to form bromine compounds that also carcinogenic as well as have a negative impact on membrane surface [88,89]. Since FD is insensitive to fouling phenomena, such pretreatment processes and also chemical addition as anti-scalant or chlorination are not necessary.

On the other hand, to maintain steady permeate flux and to deal