

Multistage Freeze Desalination Process for High-Purity Water Production and Optimized Energy Consumption

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Abstract:

Freeze desalination (FD) has emerged as an innovative technology for water treatment, utilizing ice crystallization to exclude dissolved salts and other impurities (Petzold & Aguilera, 2009). FD offers several advantages over conventional desalination techniques, including lower energy requirements, reduced corrosion risks, and the ability to treat high-salinity water (Janajreh et al., 2023). The energy requirements for FD are significantly lower compared to vaporization-based processes, with FD needing approximately 1/7th of the latent heat required by evaporation-based methods. This energy efficiency is a key factor in the potential commercial viability of FD systems. Nonetheless, unlike Reverse Osmosis (RO), which achieves near-complete desalination in a single pass, FD typically yields a desalination efficiency between 30-70% per stage (El Kadi et al., 2021; Zhang, Alabdouli, et al., 2021). This efficiency varies based on factors such as ice recovery ratio, freezing configuration, and operational conditions.

For FD to be viable as a standalone large-scale desalination technology, a multistage approach is essential to meet high purity levels water standards. According to the World Health Organization (WHO), drinking water must contain no more than 500 mg/L of total dissolved solids (TDS) (≤ 0.05 wt.%) (WHO, 1963). Implementing multiple freezing and separation cycles not only improves desalination efficiency but also reduces energy consumption, with multistage FD plants estimated to lower operational costs by 50–70% compared to single-pass systems (Rahman et al., 2007). The concept of multistage freezing for seawater desalination was first introduced by (Griffiths, 1989), demonstrating that ice purity could reach 99.99% after four consecutive crystallization stages. However, research on this approach has been limited (Badawy, 2022; Eghtesad et al., 2020; Salakhi et al., 2022; Zambrano et al., 2018; Zhang, Janajreh, et al., 2021). For instance, (Eghtesad et al., 2020) have reported that WHO drinking water standards could be achieved within three indirect FD stages, provided that the applied negative heat flux remained above 750 W/m². Additionally, their study observed an increase in ice production in later stages due to the progressive reduction in brine salinity. (Badawy, 2022) have also conducted sequential freezing-separation-melting experiments on synthetic seawater (4.1% NaCl) at -20°C , demonstrating an exponential decline in ice salinity over eight successive stages, achieving a 98.5% salt removal efficiency. However, a significant drawback was noted, with water recovery reduced to 35% by the end of the process. Similarly, (Salakhi et al., 2022) have employed a three-stage of continues falling film FD system, successfully reaching WHO drinking water standards. Their findings highlighted that while increasing the Reynolds number of the refrigerant improved water recovery, it had an adverse effect on desalination efficiency. In a more recent study, (Zhang, Janajreh, et al., 2021) demonstrated that four freezing stages with 50% ice recovery per stage could yield potable water. These studies collectively confirm that multistage FD is highly effective for achieving ultrapure water. However, the critical challenge remains in improving water recovery rates while maintaining high desalination efficiency. Further research is necessary to enhance ice yield per stage without compromising product quality. Once these challenges are addressed, FD has the potential to become a highly competitive alternative to conventional desalination technologies.

This work focuses on optimizing a multi-stage freeze desalination (MFD) process, where sequential crystallinity and ice recovery cycles are employed to improve water purity while preserving the thermodynamic advantages of FD. This research aims to systematically determine the optimal number of stages necessary for achieving application-specific water quality, from industrial-grade to an acceptable-purity outputs. By adjusting ice recovery ratios for each FD stage and assessing the trends of salinity reduction, the trade-offs between purity enhancement and energy input is established. Preliminary experiments on MFD were conducted using an indirect batch crystallizer with bottom cooling configuration (Zhang, Alabdouli, et al., 2021), starting with seawater salinity (~ 35 g/L NaCl) and operating at 50% water recovery per stage. After five successive freezing-melting cycles, the salinity progressively decreased from 35 g/L to 17.5 g/L, then to 8 g/L, 4 g/L, and finally from 2 g/L to almost 1.2 ± 0.032 g/L, achieving an overall desalination efficiency of 96.3% (Figure 1 and 2). However, the total water recovery remains a critical limitation, requiring further optimization. A key strategy to enhance MFD performance is increasing desalination efficiency per stage, which directly reduces the number of required stages to achieve potable water quality. For instance, incorporating efficient stirring mechanisms can enhance salt exclusion during

crystallization, leading to a 40% improvement in desalination efficiency per stage (Zhang, Alabdouli, et al., 2021). This enhancement can potentially reduce the required number of stages by approximately two-thirds, thereby improving overall ice recovery. The optimization of MFD requires balancing trade-offs among energy consumption, desalination efficiency, and water recovery rates. By fine-tuning these parameters, this work aims to enhance the feasibility of MFD as a sustainable and energy-efficient desalination solution for diverse applications, including potable water production and industrial use. Refining freezing conditions, improving ice recovery efficiency, and optimizing multi-stage configurations to maximize desalination performance are considered to ensure that MFD can serve as a stand-alone energy-efficient water

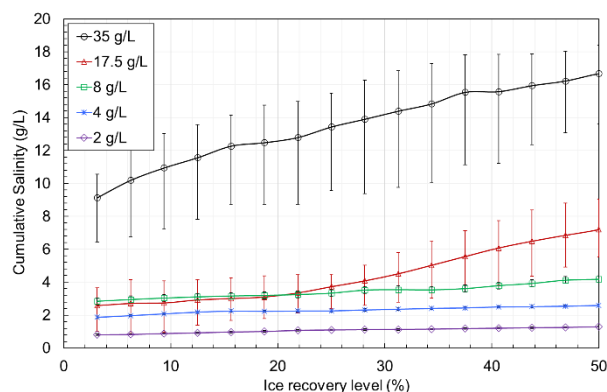


Fig.1. Cumulative salinity of each FD stage

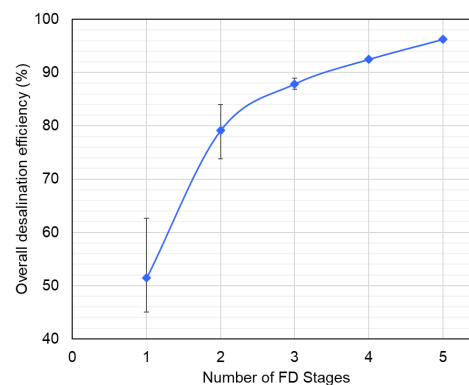


Fig. 2. Enhanced desalination efficiency at increasing number of FD stages

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