Nanofluids in Desalination

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Contributor: Tejvir Singh

Desalination accounts for 1% of the total global water consumption and is an energy-intensive process, with the majority of operational expenses attributed to energy consumption. Moreover, at present, a significant portion of the power comes from traditional fossil-fuel-fired power plants and the greenhouse gas emissions associated with power production along with concentrated brine discharge from the process, pose a severe threat to the environment. Due to the dramatic impact of climate change, there is a major opportunity to develop sustainable desalination processes to combat the issues of brine discharge, greenhouse gas emissions along with a reduction in energy consumption per unit of freshwater produced. Nanotechnology can play a vital role to achieve specific energy consumption reduction as nanofluids application increases the overall heat transfer coefficient enabling the production of more water for the same size desalination plant. Furthermore, concentrated brine discharge harms the marine ecosystems, and hence, this problem must also be solved to support the objective of sustainable desalination. Several studies have been carried out in the past several years in the field of nanotechnology applications for desalination, brine treatment and the role of renewable energy in desalination.

The content is focused on reviewing existing desalination practices, along with identifying the gaps in the development of sustainable desalination systems. Furthermore, the role of nanofluids is discussed as a potential tool to develop cost-competitive and energy-efficient standalone desalination system. Desalination is an energy-intensive process, and it's exceptionally crucial to power the process with a reliable independent source of energy along with coupling the desalination process with advanced systems to treat the brine and take benefit of economies of scale by producing more products from the same raw material (seawater).

Keywords: thermal desalination ; reverse osmosis ; advanced heat transfer fluids ; sustainable desalination practices ; solar thermal nanofluids based desalination

1. Introduction

Water is critical for sustaining life on earth. The World Resources Institute reports that by 2040, 33 nations will face severe water challenges. Moreover, "World Data Lab" estimated water scarcity globally and reported that almost 2.327 billion people globally are living under water-scarce areas at present which is expected to surge up to 2.7 Billion people by 2030 [1]. As such, the United Nations has established the "Sustainable Development Goals" (SDGs) which serve to address critical issues facing modern human civilization such as those pertaining to water, food and energy security. The technologies outlined in this paper, which includes solar desalination systems for the provision of clean water, combating climate change and marine life, thus targeting SDGs 6, 13 and 14. Based on recent data from the World Health Organization, the global population will reach 9.3 billion in a "business as usual" scenario by 2050, which in turn will increase food demand by 60% while the urbanized population is expected to surpass 6.3 billion (UN DESA, 2011). Such pressures will likely exacerbate the rate at which freshwater resources will face severe stress. In 2019, there are at least 1.8 billion people who are devoid of reliable access to water, which is fit for human consumption [2]. If the current trend continues, water demand will surpass its supplies by 40% by the year 2031 [3]. Currently, global desalination produces 100 million cubic meters per day, which is less than 1% of the total water consumed globally [4]. As per International Desalination Association (IDA)—a United Nations recognized body, there are 19,744 desalination plants worldwide with a combined capacity of almost 100 million cubic meters per day situated in over 150 countries [5]. The desalination capacity is distributed globally with nearly 47.5% share in MENA region, 18.4% in East Asia and Pacific, 11.9% in North America, 9.2% in Western Europe, 5.7% in Latin America and the Caribbean, 3.1% in Southern Asia, 2.4% in Eastern Europe and Central Asia and 1.9% in Sub-Saharan Africa [6]. The maximum share of these desalination capacities comes through reverse osmosis (>65%). The total brine production from these desalination plants globally exceeds 141 million cubic meters per day, which is 141% higher than the total desalinated water production per day [6].

In order to achieve the objective of fulfilling the potable water demand for all the earth's population, there is a need to expand global desalination from oceans (the source of 97% of the world's water resources). Water scarcity can be classified in categories ranging from physical water scarcity to an economical one. Economical water scarcity is defined as the condition in which it is not economically feasible to extract fresh water from existing sources. Figure 1 illustrates the degree of water scarcity as a function of the country. Also, as estimated, the freshwater demand is expected to surge significantly, and Figure 2 illustrates this growth by comparing freshwater demand for various sectors between 2000 and 2050. The indicator 6.4.2 of SDG 6 defines water stress as the ratio of total freshwater withdrawn (TFWW) and the difference of total renewable freshwater withdrawn (TRWR) and environmental flow requirements (EFR) as per relation 1.

The water stress is calculated for several countries by utilizing relationship 1 which shows that the level of water stress is the highest in North Africa (112.2%) followed by Central Asia (79%) and other regions, with lowest water stress reported in Melanesia, Micronesia and Polynesia combined (0.1%) [7].

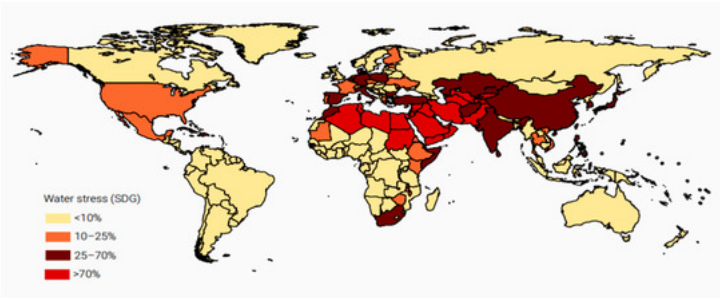

Figure 1. Levels of water stress by country (2000–2015) [7]. (© 2018 International Water Management Institute (IWMI) and the Food and Agriculture Organization of the United Nations (FAO) Aquastat).

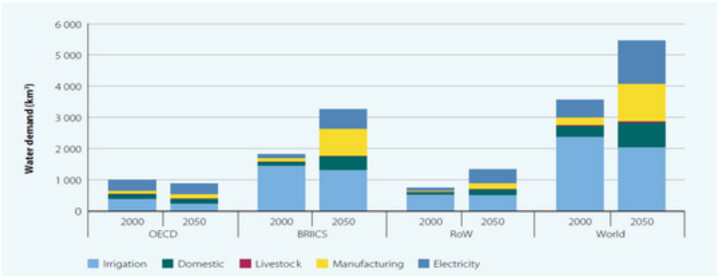

Figure 2. Global freshwater demand: baseline scenario, 2000 and 2050 [2]. (© UNESCO 2016). (OECD: Organization for Economic Co-operation and Development; ROW: Rest of the World; BRIICS: Brazil, Russia, India, Indonesia, China and South Africa).

Furthermore, sustainable desalination is of prime concern, and as with the increasing desalination capacity globally, the issue of brine production and discharge is creating grave concern for the sea ecosystems, and this issue must be addressed with the utmost urgency. As previously discussed the quantity of brine production is almost 141% of the total global desalination capacity, and it is damaging the oceans. Sustainability, as defined by Tester et al. [8][9], is a dynamic harmony between the equitable availability of energy-intensive goods and services to all people and the preservation of the earth for future generations. In order to protect the oceans from further damage and keep them in good health to maintain the ecosystem services for future generations, a brine management solution must be introduced. Moreover, energy consumption constitutes the majority of operational expenses for desalination projects. Hence, it is crucial to obtain this required energy sustainably through alternative means. Nanotechnology, on the other hand, allows a reduction in energy consumption for membranes as well for the operation of thermal desalination systems, which allows either a reduction in CO_2 emissions (if power is generated through hydrocarbons) or efficient utilization of renewable energy generating systems. Sustainable desalination is the basic necessity, and it includes two facets: appropriate brine management and providing power through sustainable means. Nanotechnology supports the second facet of sustainable desalination. Desalination costs have declined steadily throughout recent decades, increasing its competitiveness in comparison to other water supply alternatives. Electricity expenses vary from 30% to 60% of the cost of operating desalination facilities which in turn increases the uncertainty risk due to continually rising electricity prices causing the price cubic meter of desalinated water also to increase accordingly [10]. This uncertainty in pricing and fluctuations impedes the implementation of large-scale desalination facilities. As such, research is required in order to develop new integrated technologies based on renewable energy and new materials which can lead to highly efficient, more sustainable and reliable water producing systems.

2. Assessment of Desalination Processes

The complete desalination process consists of three different stages: Pre-treatment of raw seawater, desalination through various techniques and post-treatment. Apart from these three main processes, other activities include the intake mechanism of raw seawater, the discharge of toxic brine and permeate to the respective destinations.

3. Role of Nanofluids in Energy-Efficient Desalination

3.1. Basics of Nanofluids

Nanotechnology finds application in the membrane as well as thermal desalination. For thermal desalination, the thermal properties of the heat transfer fluid are crucial. Since the industrial revolution, water and some improved heat transfer fluids have been developed and commercialized. However, there are some demerits associated with traditional heat transfer fluids. Nanofluids, on the other hand, provide a basis for efficient heat transfer. Nanofluids are an engineered suspension of nanoparticles in base fluids (inorganic or organic) with the support of surfactants. In the past few years, different nanofluids have been prepared, characterized and tested for heat transfer applications. The experiments have shown an enhancement in the thermal properties of nanofluids as compared with the base fluids. To consider some examples, the specific heat capacity of nanofluids (prepared by suspending nanoparticles in molten salts base fluids) has increased by almost 25% 28% [11][12]. The enhancement of 25% in specific heat capacity of the nanofluids as compared with base fluids will lead to a 20% reduction in the thermal energy storage (TES) salt inventory and thus TES cost reduction. The research carried out with 50 MW solar thermal plant with 15 h TES exhibited 9% reduction in TES cost along with 0.9% reduction in total solar thermal plant cost (due to the reduced size of systems) in addition to the mitigation in prices of TES salt [12]. There is a range of studies which have exhibited that nanofluids possess higher thermal properties than traditional heat transfer fluids, which allow more efficient heat transfer for process heat production and other applications. The process heat from a wide range of sources is commonly utilized for thermal desalination and other applications within industry. The improvement in physical and thermal properties of the resultant nanofluid depends on the nature of nanoparticles, the base fluid and surfactant utilized. Generally, the viscosity of the nanofluid is higher than the base fluid for water and other liquid solvents. However, nanoparticles reduce the viscosity of the fluids when suspended in molten salt solutions. Hence, the selection of the nanofluid varies from one application to the other. Zhang et al. [13] and Kasaeian et al. [14] discussed the details on different mechanisms and role of different parameters on nanofluids effect on productivity enhancement in specific applications. Zhang et al. [13] focused on the effect of nanofluids on CO_2 absorption and overall effect on the carbon capture industry. The paper discusses various nanofluid manufacturing processes along with enhancement mechanisms which include Grazing effect, hydrodynamic effect and inhibition of bubble coalescence. Grazing effect defines the absorption rate of gas in liquids which enhances with the presence of solid particles in the gas-liquid-solid three-phase system. Hydrodynamic effect defines the gas-liquid boundary layer effects. Nanoparticles present around bubbles leads to a thinner effective layer as the nanoparticles break the diffusion layer. The thinner boundary layer promotes gas diffusion into the liquid film, which ultimately increases turbulence and mass transfer coefficient. However, due to factors like surface tension, surface forces and hydrodynamic effect, the thin layer may get rupture which leads to bubble coalescence which can be inhibited by the mixed liquid phase. The enhancement mechanism is resultant of these three fundamental mechanisms. In the CO_2 absorption process, grazing effect and hydrodynamic effect play a vital role [13]. Furthermore, the effect of various other factors such as temperature, particle size and concentration of nanofluid are also discussed. Kasaeian et al. [14] discussed the role of nanofluids in heat transfer in porous media. The paper reviewed the effect of nanofluids and porous media on heat transfer. The paper concluded that both nanofluids and porous media supports higher heat transfer rates as nanofluids possess higher thermal conductivity, whereas porous media provides enhanced surface area, which leads to higher heat transfer rates. Furthermore, the hypothesis of heat transfer enhancement in porous media was tested with the most popular models Buongiorno and Tiwari and Das. It has been reported that nanoparticles usually enhance fundamental thermal properties of the base fluid, which are essential in reducing the size of the system or producing more output for a similar size of the system. For integrated sustainable thermal desalination systems, the role of energy storage, overall heat transfer and economies of scale in products, is vital.

3.2. Application of Nanofluids for Thermal Desalination

The fundamental principle of thermal water desalination is similar to the concept of rain formation. The process of thermal distillation strips seawater with heavy metals along with other impurities. The produced water is as clean as pure rainwater. Thermal energy can be supplied from different sources, including solar thermal technologies. Nanofluids allow efficient heat transfer, and apart from studies in nanofluids thermal properties enhancement for CSP power generation, researchers also considered the application of nanofluids for efficient thermal desalination processes.

4. Conclusion

Advanced nanofluids based integrated systems will undoubtedly support the purpose of cost-effective heat transfer processes. The novel MED designs, along with advanced MEDAD systems, will support efficient operations of desalination projects with higher Gain Output Ratio or Performance Ratio. Moreover, if these desalination systems are powered by renewable sources such as CSP technologies which includes Linear Fresnel Collectors (LFCs), Parabolic Trough Collectors (PTCs), Central Receiving Towers or newly developed PV-Thermal technology along with PV, Wind, Tidal and Geothermal, then the issues of GHG emissions associated with present systems can also be mitigated. As discussed, in this study, the use of nanotechnology can be beneficial, especially in terms of energy efficiency improvements. The experimental analysis showed 5% enhancement in overall heat transfer coefficient along with enhancement in other vital thermal properties which ultimately reduces CAPEX and size of the system for the same output. The possibility of cost reduction for energy generation with nanofluids has been alluded to in many reported studies. Furthermore, it is necessary to assess the quality of the intake seawater and discharge of brine and assess the brines potential utilization in the chemical and fertilizer industry. Hence, if technologies and policies can both be aligned to achieve sustainable desalination objectives, then, highly efficient, cost-effective renewable desalination technologies with reduced impacts on the environment can be deployed commercially with support from nanofluids. Thus, nanotechnology has great potential to solve the desalination industries problems, and it will support the development of sustainable desalination systems integrated with brine management systems and acquiring power from solar thermal systems.

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