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A Review on Desalination using Membrane Distillation: Status and Potential

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Abstract : The availability of fresh water is dwindling in many parts of the world, a problem that is expected to grow with populations. Desalination has been increasingly adopted over the last decades as an option, and sometimes as a necessity to overcome water shortages in many areas around the world. Today, several thermal and physical separation technologies are well established in large scale production for domestic and industrial purposes. One promising source of potable water is the world's virtually limitless supply of seawater, but so far desalination technology has been too expensive for widespread use. Membrane distillation is a novel thermally-driven process that can be adapted effectively for water desalination or water treatment in industrial applications, due to its potential lower energy consumption and simplicity. The general objective of this paper is to contribute to the technical understanding of membrane distillation as a new technology in water treatment for both industrial and drinking water purposes, as a starting point for further improvement. This study includes experimental and numerical investigations that highlight some aspects of the technology application and fundamental aspects. A new approach using a different kind of filtration material: sheets of graphene, a one-atom-thick form of the element carbon, which can be far more efficient and possibly less expensive than existing desalination systems.
Keywords: Membrane distillation; Desalination; Membranes; grapheme.

Introduction

During the past fifty years, membrane technologies have been incessantly progressing because the demand for good quality drinking water is increasing steadily world-wide. Although over two thirds of the planet is covered with water, 99.3% of the total water is either too salty (seawater) or inaccessible (ice caps). Since water becomes potable if it contains less than 500 ppm of salts, much research has gone into finding efficient technologies for removing salt from seawater and brackish water called desalination processes.

Membrane technology is today well recognized as the most convenient desalination technology. Currently, it seems that there is no limit for the future progress of membrane processes. The growing interest towards membrane science and technology is evident. Most of membrane transport processes are isothermal and their driving forces are transmembrane hydrostatic pressures, concentrations, electrical potential, etc. For example the well known reverse osmosis (RO) used specially in desalination of seawater or brackish waters is an isothermal process. However, less membrane processes are non-isothermal technologies requiring a thermal driving force to establish the necessary transmembrane chemical potentials or transmembrane partial vapor pressures. Among these processes, one can find membrane distillation (MD) process that is applied also in desalination of seawater and brackish waters.`[1]

MD is a process mainly suited for applications in which water is the major component present in the feed solutions to be treated and refers to a thermally driven transport of vapor through non-wetted porous hydrophobic membranes. The driving force of this technology is the partial pressure difference between each side of the membrane pores.

The potential applications of MD are:

• Production of high-purity water, concentration of ionic, colloid or other non-volatile aqueous solutions and removal of trace volatile organic compounds (VOCs) from waste water.

• Desalination, environmental/waste cleanup, water-reuse, food, medical, etc.

The advantages of MD are:

• Lower operating temperatures than the temperatures normally applied in conventional distillation. The process can be performed at feed temperatures considerably lower than the boiling point of water (i.e., temperatures as low as 30ºC have been used). This permits the efficient use of low-grade or waste heat streams as well as the alternative energy sources (solar, wind or geothermal).

• Lower operating hydrostatic pressures than the pressure-driven processes, for example RO. The MD process can be performed at operating pressures generally near the atmospheric pressure.

At first it may seem ironic that we are dealing with a water crisis on a planet which has water covering 70% of its surface. However, only 1% of the water on earth is fresh water directly available for human use.[1] The obvious solution to this problem is to take advantage of the massive supply of water held in our oceans. Desalination allows humans to utilize a constant, expansive and accessible source of water. The current method of desalination is Reverse Osmosis. In a reverse osmosis plant water is filtered through a diffusion-solution process, where the osmotic property of water is utilized. Even though Reverse Osmosis technology is advancing there are many disadvantages to this method including: High pressure is required, transport of water over the various membranes is very slow, the individual membranes are very thick and the membranes can only operate under very specific temperature and pressure conditions.

Currently there are 13,000 reverse osmosis plants on Earth, however these plants only account for 0.2 percent of the world's water consumption.[2] Nanotechnology first appeared as a solution to water desalination in the form of Carbon Nanotubes. Carbon Nanotubes are networks of carbon atoms which have been arranged to form a cylinder. Carbon Nanotubes allow the water molecules to pass through them at a rapid rate, while excluding the larger salt ions. Unfortunately, the salt rejection rate of Carbon Nanotubes is low and it is very difficult to produce a large array of organized and properly aligned carbon nanotubes.[3] For these reasons, an additional method of desalination is needed.

Key issues in Desalination

The pretreatment includes the entire necessary treatment step ahead of the reverse osmosis plant. It is determining for plant life time and to minimize chemical cleaning and membrane replacement. It has a direct impact on the plant performance [4.]

The reverse osmosis process can also be build with one or two passes, depending on the product water requirements and the seawater salinity and temperature. In most cases, 1 pass is sufficient to reach the EU drinking water standards, especially regarding the boron content (1 mg/L). To reach WHO boron guideline (0.5mg/L), a second pass might be necessary (Boron removal process)

The energy recovery device is the key factor that determines the plant electrical costs. It must be chosen carefully based on the local energy costs and environment policies

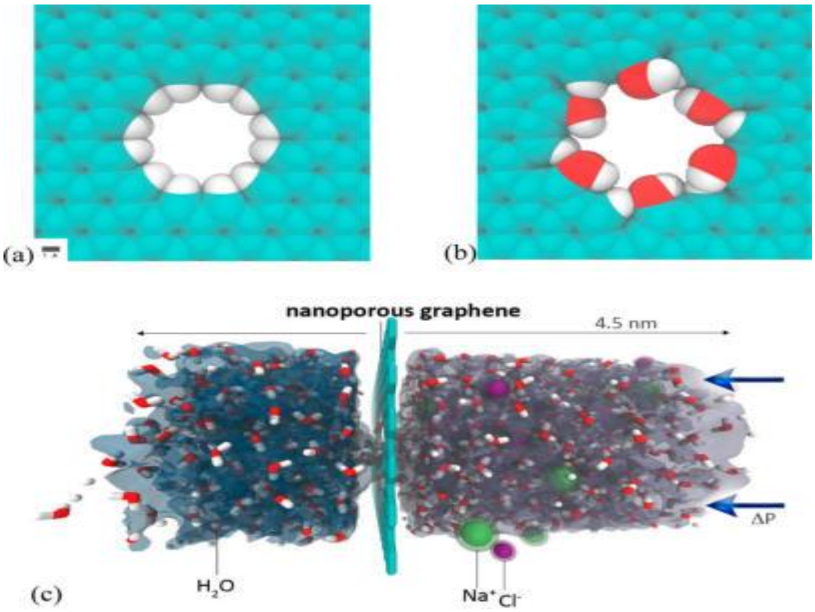
Post-treatment and/or polishing steps are required to condition the water after the reverse osmosis membrane process to make it suitable to your application

Brine disposal can be an environmental and economical issue in some areas where the fauna and flora are sensitive to local seawater salinity increase. Brine disposal should be studied and engineered case by case. Nanoporous materials have a great deal to offer over existing technologies for desalination. In contrast with classical RO membranes, where water transports slowly via a solute on diffusion process, nanoporous membranes can allow for fast convective water flow across well-defined channels. [4]

Nanoporous Graphene

Graphene is a sheet of carbon atoms bonded together in a honeycomb crystal lattice. Graphene is one of the strongest materials humans have found, with a breaking strength 200 times greater than steel.[5] Human production of graphene is still in the experimental phase and currently, graphene is obtained from graphite, which is composed of layers of grapheme (Figure- 1). Nanoporous graphene is synthesized by introducing pores into the graphene using Focused Electron Beam Induced Etching. In Focused Electron Beam Induced Etching, a beam of electrons is projected onto the surface of the soon-to-be Nanoporous material.

Figure 1. (a.) Hydrogenated graphene pores (b) hydroxylated graphene pores, and (c) side view of the computational system[5]



The beam interacts with a pressured gas on top of the material which then bonds with the material's atoms and thus corrodes the surface. This process can be used to create nanometer sized holes in graphene, among other materials. The diameter of the pores is controlled by adjusting the pressure of the gas and the amount of time the material is exposed to the electron beam[6]. The ability to adjust pore size is crucial to desalination across Nanoporous graphene; a difference in just a few angstroms can be the difference between a properly functioning pore and a useless one. In fact, the need for extremely precise pore sizes has led to researchers utilizing even more fine tune technology such as helium ion beam drilling and diblock copolymer templating.[7]

Filtration

Water desalination across nanoporous graphene functions on a basic elementary chemistry concept: Salt ions dissolved in seawater have a larger atomic radius than the actual water molecules themselves. The goal of nanoporous desalination researchers is to create a hole which water molecules can pass through but salt ions cannot. Using the abovementioned techniques, pores are created in graphene which allowed H_2O molecules to pass through them, but block Na+ and Cl- salt ions due to their large size. 5.5 angstroms was experimentally determined to be the diameter at which water could pass through the pore but salt ions could not. The nanoporous graphene membranes are designed to be periodical, so several of them are lined up to insure maximum desalination.[7]

There are various factors which influence the rate of water desalination and the amount of salt ions rejected from the membrane. Researchers experimented with placing hydrogen ions and hydroxide ions on the inside of the pores and then tested the flow rate of each of the pores. Water flow across hydroxyl group lined pores was significantly higher than the water flow across hydrogen lined pores. This increase is water flow was attributed to two factors. First, the structure that the hydroxyl groups formed in the pore allowed for more water molecules to pass through them. In order to attach the hydroxides, hydrogens had to be placed between them so that they wouldn't bond with each other. This pattern created more area for the water to pass through, in comparison to the area created by the pore completely lined with hydrogens. However, this increase in water permeability area is not the only reason the hydroxide lined pore experienced greater water flow.

The arrangement of the hydroxides in the pore means that they can easily form bonds with passing water molecules. This allows water to flow through the pore in any orientation it is naturally in. In contrast, the hydrophobic nature of the hydrogens in the hydrogenated pore means that they force the water molecules to pass through the pore in an ordered way, slowing down the flow of water.[7] Unfortunately, the placement of hydroxides in the graphene pore results in a decrease in salt rejection rate. This too is a result of the chemical nature of the Hydroxides. Since the hydroxides are hydrophilic, they can actually substitute themselves into the place of a water molecule surrounding a salt ion and allow it to pass[7]. In order for water to be desalinated across a nanoporous membrane, pressure must be applied to it so that the water can filter through the membrane at an efficientrate. A pressure gradient was applied to both pores The tests reveal an additional negative side effect of the hydroxide lined pore. As the pressure increased, so did the amount of salt ions which were allowed to pass through the pore.[7]

Graphene, which consists of a 2D sheet of sp2-bonded carbon atoms in a hexagonal honeycomb lattice, is the ultimate thin membrane. This relatively new material has advanced quickly toward largescale manufacturability with roll-to-roll production of 30 in. graphene films already available.[8] Potential advantages of graphene over existing RO membranes include negligible thickness (one or several atomic layers) and high mechanical strength,[9] which may enable faster water transport, low pressure requirements, and a wider range of operating conditions than previously possible. Nanopores can be introduced into graphene's structure with the unsaturated carbon atoms at the pore edge passivated by chemical functional groups. Recently, experimental studies have begun to explore a wide variety of methods for introducing nanopore in graphene with rapid progress in performance. Earlier approaches relied on electron beam exposure, but the most recent methods make use of diblock copolymer templating, helium ion beam drilling, and chemical etching to achieve both higher porosity and a more precise pore size distribution.[10−13] Although existing studies have already found potential applications of nanoporous graphene in fields such as DNA sequencing and gas separation,[14−18] the potential role of this material for water desalination remains largely unexplored. The scientists explain that there are two main challenges facing the use of nanoporous graphene for desalination purposes. One is achieving a narrow pore size distribution, although rapid experimental progress in synthesizing highly ordered porous graphene suggests that this may soon be feasible. The other challenge is mechanical stability under applied pressure, which could be achieved using a thin-film support layer such as that used in RO materials. This paper highlights the promise of atomically thin, periodic nanostructures like graphene for water desalination. Our approach strongly suggests that a bottom-up, systematic redesign of desalination membrane materials can yield significant improvements over existing technological methods. We expect that this work will add to the understanding of next generation membranes for clean water technology.

Conclusion

Hence Water desalination across nanoporous graphene offers a promising solution to our water crisis. The amount of desalinated water produced by the grapheme pores ranged from 39 to 66 L per cm2•day•MPa while reverse osmosis membranes range from 1-5 L per cm2•day•MPa.9 Another exciting perk of water desalination across nanoporous membranes is that it is easy to manufacture[7]. Graphene is easily obtained and there are a variety of methods accessible for creating pores in the graphene. Even though this technology is very young, it will advance quickly as the world turns to nanotechnology to solve its water crisis. As manufacturing techniques become more advanced, the possibility of implementing nanoporous graphene desalination in a real-world setting is becoming more and more likely.

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