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Recent advances in utilization of graphene for filtration and desalination of water: A review

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HIGHLIGHTS

- Graphene shows good potential for water desalination and filtration systems.
- NG membranes show high salt rejection and feasibility in RO applications.
- CDI is heavily material dependent but feasible in water desalination.
- GO sieving is a novel method and needs further improvement for desalination.

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ABSTRACT

Water as a basic necessity is an influential factor in our everyday lives but water pollution, urbanization, and huge population growth has led humankind to the brink of water resource scarcity. To address this issue, water filtration as well as desalination got enormous interest by the research community. Recently graphene, a new two dimensional material with exceptional capabilities and characteristics, has become apposite in the field of water filtration and desalination. This paper reviews the recent progress in Graphene research for water desalination using novel methods such as Nanoporous Graphene (NG) sheets as well as Capacitive Deionization (CDI) method. Among which most promising uniform NG sheets can be used for water filtration and desalination at a removal efficiency of 33–100% depending on the pore size as well as the applied pressure [1] and has a water flow rate of 10–100 L/cm^2/day/MPa [1] and by adjusting the pore size, different mineral filtrations can take place [1]. The main drawback which limits the widespread utilization of NG is the mechanical stability of NG sheets as the pore number increases since water permeability is directly proportional to the number of pores, pore distribution as well as the mass production of graphene sheets which has not been solved [1,2]. Apart from this, in CDI method, filtration is done by applying a certain potential difference between arrays of paired electrodes. The mentioned CDI method has moderate removal efficiency but has higher energy efficiency compared to the reverse osmosis method due to minimal energy requirement of only 0.1–2.03 kWh/m^3 [3]. Graphene oxide based desalination is another emerging desalination method which is gaining popularity because of its ease of fabrication, industry scale production, and strong mechanical stability [4,5]. It uses the "ion sponging" effect and can block hydrated ions with a radius greater than 4.5 A°. But still this method should be further improved as small seawater salts are able to pass from the GO sieve [6,7].

Contents

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1. Introduction

Water has always been one of the basic needs of human beings. With the rapid growth of the population, consumable water has become very scarce and is expected to worsen between now and 2040, thus, novel solutions must be implemented. The use of underground and sea water is limited due to the contamination and the huge cost for contamination removal, salt and unwanted particle separation [8,9]. It is necessary to deploy low cost water purification techniques to purify contaminated water as well as desalination for sea water. Many methods have been implemented for water treatment such as ion exchange, reverse osmosis and distillation [9]. The widespread utilization of these methods is limited due to self-contamination [9], huge power requirements [9], and utilization of intense resources [9] and not being economically viable. As an example, reverse osmosis is used among wealthy countries such as Saudi Arabia and Israel which have the necessary resource for deploying such plants when confronted with water shortage [10]. This process was implemented in the 1990s to replace multistage flash distillation and multiple-effect distillation due to their high power consumption [1,11] requirements. In RO, a polymer membrane is used in which seawater is pressurized from one side of the membrane and because of the structural gaps of the membrane, only water will be able to pass through and hydrated ions such as sodium and chloride ions will be filtered and will not be able to pass [12]. In addition, this method can produce an average of 250 million gallons of fresh water per day [13]. But still as an example, reverse osmosis method was not successful in Almeria—a Spanish province due to high consumption of electricity [14]. Moreover the membrane filter technology can be summarized in the table below.

So the problem that needs to be addressed is to find cost and power efficient processes for water purification and desalination, eliminate self-contamination and more importantly should be industrially applicable. As such, nanotechnology has opened a window of opportunity for researching on water purification and improving the environment by studying on a selection of new materials [16]. But nowadays, many of these materials have proven to be inefficient in this application. For example, low salt rejection is a serious problem in carbon nanotube based membranes and in addition high-aligned and high-density CNT arrays are very difficult to produce [17,18]. In addition, another material that was considered but was not successful was Zeolite for its comparatively low water permeability [19] and for comparison purposes, the salt rejection vs. water permeability of graphene is presented in Fig. 1.

As a consequence, graphene has been investigated and identified as a new material for certain characteristics and properties suitable for the purpose of water purification. Besides, graphene is very light and also can withstand high water pressure which makes it advantageous to other nanofiltration materials [21]. This paper will summarize recent research works for water purification and desalination using graphene and will provide a detailed investigative result in applied and application perspectives which includes description of graphene, its characteristics, fabrication, and characterization methods. In the next part, graphene based water desalination methods namely NG as well as graphene based CDI will be discussed in details and the possibilities of graphene oxide sieves will also be briefly discussed and the paper will end with summarizing of the reported and expected results and findings for better clarification, comparison and benchmarking purpose.

1.1. Graphene: characteristics, synthesis and opportunities

Graphene is a new material which was first synthesized in 2004 using a scotch tape and a piece of graphite, although a single atomic sheet of graphite was first defined as graphene in 1986 by Boehm et al. [22]. Graphene has a honeycomb lattice structure and a carbon–carbon bond length of 0.142 nm [23] and has many superiorities over conventional materials, one of the most fascinating properties of graphene is that it is only one atom thick and thus instead of being a 3D material, this material is only 2D. It has high thermal conductivity (5300 W/mK) and electrical conductivity (2000 S/cm) and in addition, it has the fastest electron mobility [24]. It is 30 times harder than diamonds and 200 times harder than steel [25,26]. Moreover, it also has interesting optical properties and can absorb about 2.3% of white light which makes it an excellent choice for the production of more efficient solar cells [26]. With all of the mentioned advantages, there is a problem with graphene and it is that a band gap is not present and thus it can never be switched off and thus an engineered band gap needs to be implemented so that it can be used in different applications [26]. Apart from this, due to the defects introduced during the exfoliation time, high quality graphene is hardly obtainable [27]. Despite these limitations, graphene is considered suitable for lots of applications such as transistor fabrication, super capacitors, improved batteries, solar cells and water purification [28]. Graphene can be fabricated in both bottom-up and top-down methods. The preparation of Graphene from chemical reaction of organic and small molecules is called bottom-up method. Epitaxial growth using silicon carbide, thermal CVD and PECVD can be used to grow graphene on many substrates [24]. In the top-down method, fine graphene with good yield can be produced by using the following methods: chemical reduction, electrochemical synthesis and chemical derivations [24]. Fig. 2 shows some of the methods mentioned for fabricating graphene.

In addition, many other ways have also been developed for preparing graphene and by these fabrication methods, different characteristics of the material can be modified and catered for specific needs and purposes. For example, for obtaining graphene-polymer films with large-area which are flat and single layered, Langmuir–Blodgett assembly is used [30,31].

1.2. Reduced graphene oxide fabrication process

Since producing graphene is not an easy process, instead a substitution can be used which has a very similar structure to genuine graphene and it is called the Reduced Graphene Oxide (RGO). For creating RGO a few steps should be taken, firstly graphite is oxidized and thus graphite

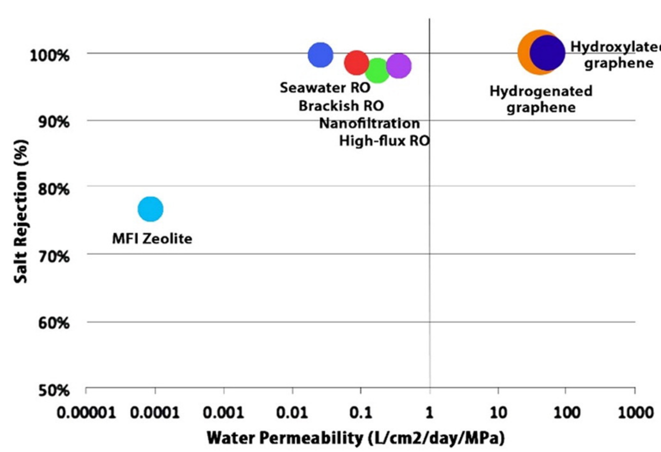

Fig. 1. Salt rejection vs. water permeability of different filtration methods [20].