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Review

# Carbon nanotube-based membranes: Fabrication and application to desalination

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ABSTRACT

Membranes based on carbon nanotubes (CNTs) have been highlighted as an emerging technology for water purification system applications. With their ultra high water flux and low biofouling potential, CNT membranes are believed to lack various problems encountered when using the conventional membrane separation process that requires a large amount of energy and meticulous maintenance. Although diverse types of CNT membranes have been reported, no commercialized products are available. This article reviews the proper manufacturing methods for CNT membranes and speculates on their performances. Future applications of integrated CNT membrane systems are also outlined.


**Contents**



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## 1. Introduction

Water is under constant pressure as a resource. Due to population growth, economic development, rapid urbanization, large-scale industrialization, and environmental concerns, water stress has emerged as a real threat [1]. Additionally, climate aberrance will significantly affect water stress, change rainfall patterns, and shrink the snow and ice covers that feed rivers. While scarcity drives us to use lower quality and unconventional water sources, membrane separation technology can meet these global climate challenges [2]. Since their inception in the early 1960s, membranes have revolutionized fluid separation processes [3]. Membranes efficiently remove specific particles and molecules from liquids, which has been difficult to achieve using conventional water treatment technologies. Membranes are widely used not only to treat surface water but also to reuse wastewater and to desalinate seawater which can alleviate the problem of water scarcity [4].

However, one of the main problems with desalination membrane technology is the high level of energy consumption [5]. Although the capital and operation costs of membrane processes have fallen dramatically over the past decade [6], the use of membranes is still an energy-intensive process. For example, the energy consumption for seawater desalination using reverse osmosis (RO) membranes has dropped from 8.0 kWh/m$^3$ to 3.4 kWh/m$^3$ [7,8]. Advanced energy recovery devices are expected to be available soon, and the specific energy consumption (SEC) will decrease to $<$2.5 kWh/m$^3$ [9]. Nevertheless, this consumption is still higher than the theoretically limited value for seawater desalination of 1.06 kWh/m$^3$ (assuming 35,000 mg/L of salt in seawater and a typical recovery of 50%) [4].

One key for further decreasing energy consumption of using membranes is to develop novel membrane materials with high permeability. Nevertheless, the current thin film composite RO membranes suffer from a trade-off between salt rejection rate and permeability. To overcome the limits of current polymeric membranes, new types of membrane with higher permeability and rejection rate have been invented. These membranes use carbon nanotubes (CNTs) as membrane pores [10,11]. These CNT membranes could potentially provide a solution to water shortages, as they seem to outperform existing membranes by providing higher water flux and lower energy consumption. In contrast, the feasibility of CNT membranes has not fully investigated, as they are still in the laboratory stage of development and not yet commercially available. Fabrication of CNT membranes, which have controlled geometry, porosity, and pore shapes, is also challenging [12].

This paper reviews the state-of-art approaches for fabricating CNT membranes and critically evaluates the advantages and disadvantages of these approaches. Two types of CNT membranes are compared, including (1) vertically aligned (VA) CNT membranes, and (2) mixed (composite) CNT membranes. The prospect of using CNT membranes for water purification is also discussed.

## 2. Basic CNT information

Since Iijima's group created the first CNT synthesis protocol [13], which was originally intended to produce fullerenes, various CNT applications have been investigated, including their use in medical devices, chemical sensors, and environmental technologies [14–16]. A variety of techniques have been explored to produce CNTs, including arc discharge [17] and laser deposition [18]. Typically, the growth of CNTs on a metal catalyst such as iron, nickel, or cobalt is employed during the chemical vapor deposition (CVD) process [19]. The cylindrical shape of a single walled nanotubes (SWNTs) can be imagined virtually by wrapping them in a layer of graphite called graphene [20]. The way graphene winds can be described by a pair of indices $(n, m)$. The indices $n$ and $m$ are integers indicating the number of unit vectors along two directions of graphene (Fig. 1) [21]. The inner diameter of a nanotube can be calculated from the "rolled up" vector as follows [22].

$$d_{\text{in}} = \left(\frac{a}{\pi}\right)\sqrt{(n^2 + m^2 + nm)} - 2r_c \quad (1)$$

$d_{\text{in}}$, inner diameter (I.D.) of nanotubes; $a$, lattice parameter of graphene (=2.46 Å); and $r_c$, van der Waal's radius of a carbon atom (1.7 Å).

## 3. Nanofluidics of CNT membranes

The inner walls of CNTs are smooth and hydrophobic. Movement of water molecules passing through the interior a nanotube can be explained by the ballistic motion of water chains (1D wire) due to strong hydrogen bonding between water molecules and minimal interaction with the CNT inner wall [23–25] (Fig. 2).

The mass movement of water molecules through a CNT does not follow conventional fluid mechanics [26]. Thus, it is necessary to introduce a plausible transport phenomenon called "nanofluidics". In this novel theory, it is assumed that the fluid flowing through a

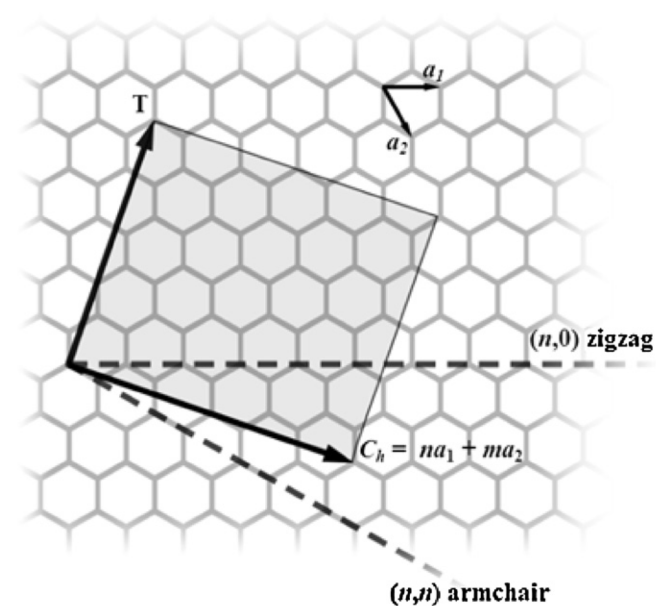


**Fig. 1.** Letters $(n, m)$ indicate the number of unit vectors in an infinite graphene sheet and $C_h$ is a 'rolled up' vector. $T$ denotes the tube axis, and $a_1$ and $a_2$ are the unit vectors of graphene. If $m = 0$, the CNTs are called 'zigzag'. If $n = m$, the CNTs are called 'armchair'. In other cases, the CNTs are 'chiral'.