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Literature review on the application of graphene in the field of seawater desalination

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Abstract:

Seawater desalination technology is an important solution to global water scarcity, yet conventional methods such as reverse osmosis (RO) and distillation face challenges including high energy consumption and costly infrastructure. Graphene, as a novel nanomaterial, has demonstrated promising application prospects in desalination due to its unique physical and chemical properties. This study focuses on the applications of graphene in seawater desalination. Through comprehensive collection, organization, and analysis of relevant literature, the promotion effect of graphene on seawater desalination process in various forms such as permeable membrane and photothermal conversion membrane is analyzed and summarized. Finally, the existing research results, shortcomings and future development directions of graphene in the field of seawater desalination are summarized.

Keywords: Graphene, Seawater desalination, Application, Literature review

1. Introduction

The scarcity of global freshwater resources has become increasingly severe [1]. To address this challenge, numerous coastal nations have adopted various technologies to separate salt from seawater and extract potable water. These efforts supplement freshwater supplies in coastal regions while alleviating the burden of transporting freshwater resources from inland areas. Collectively referred to as desalination technologies, conventional methods primarily include distillation, membrane-based methods, and freezing, whereas emerging approaches focus on integrating renewable energy sources for desalination. Although traditional desalination technologies effectively mitigate global water shortages, their limitations—such as high operational costs and low energy conversion efficiency—have become more apparent with widespread implementation. Graphene, a novel nanomaterial with exceptional physical and chemical properties, offers promising avenues for enhancing conventional desalination technologies. Its applications span improving saltwater separation efficiency, reducing operational costs, and optimizing energy utilization. Furthermore, graphene demonstrates significant potential in renewable energy-driven desalination systems, such as those utilizing solar or wind energy. This review synthesizes extensive literature to elucidate the principles, case studies, and limitations of graphene in both traditional and renewable energy-based desalination technologies. By summarizing the current state of research, this work aims to provide a foundation for advancing graphene-centric innovations in future desalination applications.

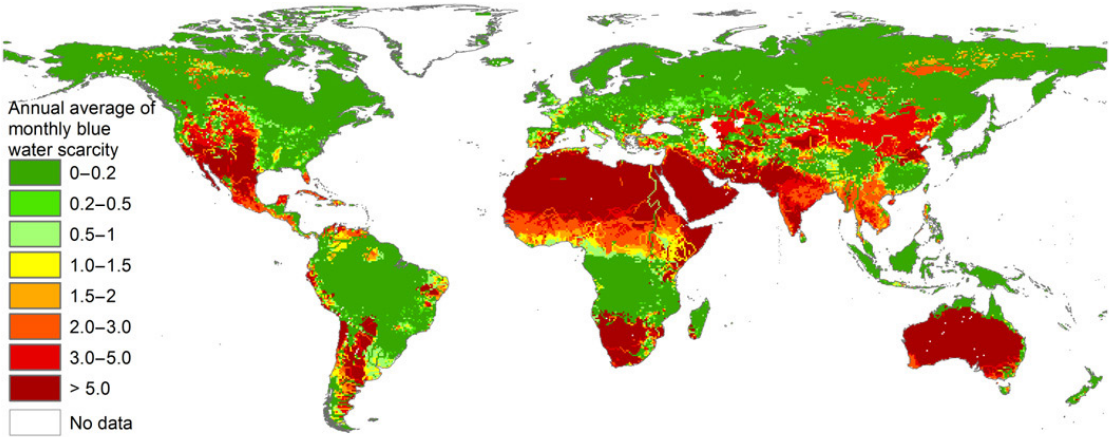

Figure 1 The world's average monthly water shortage distribution [1]

2. Overview of seawater desalination technology

2.1 . Development status of seawater desalination technology

Seawater desalination technology includes distillation, membrane method, freezing method and new energy method. Among them, the traditional seawater desalination technologies are distillation, membrane and freezing. Distillation comprises multi-effect distillation (MED), multi-stage flash (MSF) distillation, and vapor compression distillation (VC). Membrane-based methods include reverse osmosis (RO), electrodialysis (ED), and membrane distillation (MD). Freezing involves natural freezing and artificial freezing. Renewable energy-driven methods, emerging in recent years with advancements in renewable energy utilization, integrate technologies such as solar energy, wind energy, and nuclear energy with desalination processes to achieve saltwater separation.

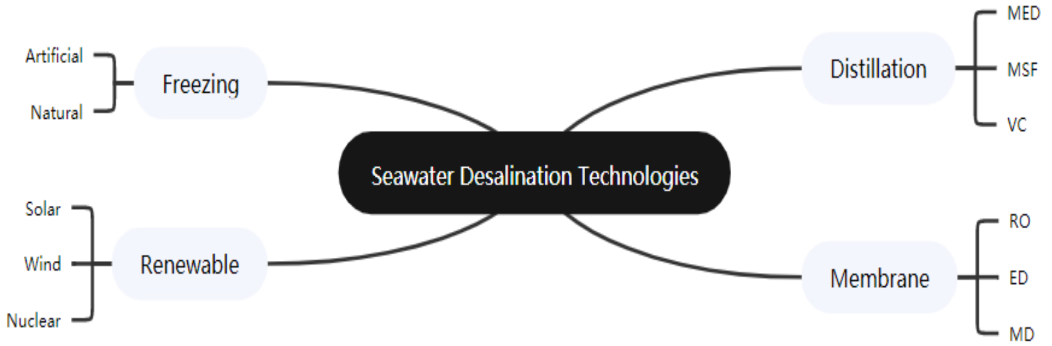

Figure 2 Seawater desalination classification method

2.2 Principles and characteristics of different seawater desalination technologies

2.2.1 Distillation methods

The fundamental principle of distillation-based desalination methods involves heating seawater to generate vapor, which is then condensed and collected as potable water. Key distillation methods include multi-effect distillation (MED), multi-stage flash (MSF) distillation, and vapor compression distillation (VC). Multi-effect distillation (MED) operates by connecting multiple evaporators in series, where the high-temperature vapor generated in one stage serves as the heat source for the subsequent stage [2]. The first evaporator is heated by external steam to

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vaporize seawater. The vapor then condenses and releases heat to warm seawater in the next evaporator. This cycle repeats across stages, enabling multiple evaporation and condensation cycles. The advantages are low energy consumption (6-10 kWh / m^3), low operating temperature (< 70 °C), and good water quality, but the disadvantages are high equipment investment, requiring multiple evaporators in series and covering a large area.

Multi-Stage Flash Distillation (MSF) involves preheating seawater to high temperatures (90-110°C) and introducing it into a series of flash chambers with progressively reduced pressure [3]. In each chamber, the heated seawater rapidly evaporates under low-pressure conditions. The vapor condenses into freshwater, while the residual brine flows to the next chamber for repeated flashing. The advantage is that it is suitable for large-scale treatment of high-salinity seawater treatment and is not easy to produce scale due to controlled temperature and pressure conditions, but the disadvantage is high energy consumption (10-15 kWh / m^3).

Vapor Compression Distillation (VC) utilizes mechanical or thermal compressors to pressurize and elevate the temperature of vapor. This high-temperature vapor then acts as a heat source to evaporate seawater, with the resulting vapor condensed into freshwater [4]. This process realizes the high purity of water produced by thermal energy recycling, which is suitable for the demand of industrial high purity water, but the demand for power supply is high and the cost of compressor is high.

2.2.2 Membrane-based methods

Membrane-based desalination relies on the selective permeability of membranes to separate salt from seawater. Key methods include reverse osmosis (RO), electrodialysis (ED), and membrane distillation (MD).

Reverse osmosis (RO) is to pressurize seawater through a high-pressure pump beyond its osmotic pressure, forcing water molecules through a semipermeable RO membrane while retaining salts and impurities [5]. The advantages are low energy consumption (3-4 kWh/m^3),cost close to conventional freshwater production, high salt rejection rate (>99%). but strict pretreatment requirements, limited membrane life and vulnerability to pollution.

Electrodialysis (ED) is the use of an electric field to drive ions in seawater through a selective ion exchange membrane (cation and anion alternately arranged) to achieve saltwater separation [6]. The advantages are that there is no need for high temperature and high pressure, the operation flexibility is large, and the proportion of salt water can be adjusted at any time, but the water recovery rate is low (50%), which is not suitable for high salinity seawater and cannot remove non-ionic substances such as organic matter and microorganisms, and the energy consumption is high (8-12 kWh/m^3).

Membrane distillation (MD) combines the principle of membrane separation and distillation: a temperature difference is formed on both sides of the hydrophobic microporous membrane, the seawater is heated and evaporated to produce steam, and the steam is condensed through the membrane pores to form fresh water [7]. Its advantage is that it is suitable for high salinity wastewater and the desalination rate is close to 100 % and can use low-grade heat sources, but the energy consumption is high and the membrane is susceptible to pollution.

2.2.3 Freezing methods

The fundamental principle of the freezing methods are to convert the seawater solution from the liquid phase to the solid phase, and the impurities are concentrated in the unfrozen liquid and the salt is discharged by the separation technology to extract pure fresh water, including natural freezing method and artificial freezing method. The principle of the natural freezing method is to use the low temperature of the natural environment to freeze the seawater naturally, so that the water in it excludes the impurities and first precipitates in the solid phase, and then separates the solid phase from the liquid phase and melts the ice crystals to obtain the water and seawater concentrate with low salinity, so that the seawater is desalinated, and a large amount of fresh water is obtained by collecting and melting the ice crystals [8]. The advantage is that there is no need for external energy consumption and the cost is extremely low, but it is only suitable for remote and cold areas such as high latitudes and high altitudes, with low efficiency and uncontrollable output.

The principle of artificial freezing method is to actively reduce the temperature of seawater by mechanical refrigeration technology, force the formation of ice crystals, and then separate ice crystals from concentrated brine. Taking the construction and commissioning of LNG receiving stations in the southeast coast of China as an example, the common technologies of artificial freezing include refrigerant direct contact freezing method and vacuum evaporation direct freezing method [9]. The principle of the refrigerant direct contact freezing method is to use the refrigerant to vaporize and absorb heat to make the seawater freeze and then separate from the refrigerant and melt, while the principle of the vacuum evaporation direct freezing method is to spray the cold seawater into the vacuum chamber. After part of the water vaporizes and absorbs heat, the remaining seawater freezes. Compared with the natural freezing method, the artificial freezing method has the advantages of strong controllability and excellent water quality, but the disadvantage is high energy consumption.

2.2.4 Renewable energy-driven methods

New Energy, in contrast to traditional fossil fuels (e.g., coal, oil, natural gas), refers to clean, renewable, or low-pollution energy sources, including solar energy, wind energy, and nuclear energy. The core principle of new energy-driven desalination is to replace fossil fuel-based power generation in desalination plants, thereby reducing fossil energy consumption, environmental pollution, and associated remediation costs. Nuclear-powered desalination utilizes electrical or thermal energy generated by nuclear reactors to produce potable water [10]. Compared with fossil fuel systems, nuclear energy is more competitive in terms of cost, lower environmental impact and lower market price. Solar-powered desalination integrates concentrated solar power (CSP) or photovoltaic (PV) systems with desalination plants to address electricity shortages [11]. Wind-powered desalination Converts onshore and offshore wind energy into electricity via wind turbines and energy storage systems to power desalination facilities [12].

3. Overview of Graphene

3.1 A brief history of graphene

Carbon, a ubiquitous element in nature, demonstrates remarkable structural versatility through the assembly of its atoms into diverse architectures. These configurations exhibit distinct physical and chemical properties properties, as exemplified by the graphite and diamond. Over time, carbon-based materials have been discovered, synthesized, and applied across multiple domains of human society, leveraging their tunable characteristics for industrial and technological advancements.

In 1934, Landau and Peierls theorized that quasi-two-dimensional crystalline materials would rapidly decompose under ambient conditions due to their thermodynamic instability. Subsequently, in 1947, physicist Philip Wallace pioneered the theoretical framework for graphene by proposing its electronic structure model through computational analysis, thereby establishing foundational principles for two-dimensional materials. A pivotal advancement occurred in 1985 when Kroto et al. serendipitously discovered the spherical carbon arrangement now known as C60 (fullerene) during laser ablation experiments, which indirectly catalyzed nanoscale investigations into graphene [13]. However, early attempts to synthesize graphene via chemical exfoliation and chemical vapor deposition (CVD) in 2003 faced significant challenges, including poor layer controllability and suboptimal material quality, limiting practical outcomes. A breakthrough emerged in 2004 when Andre Geim and Konstantin Novoselov at the University of Manchester successfully isolated monolayer graphene using repeated mechanical exfoliation of graphite with adhesive tape. This achievement earned them the Nobel Prize in Physics in 2010. Since then, graphene has garnered immense global scientific interest due to its exceptional two-dimensional structure and unparalleled electronic properties [14].

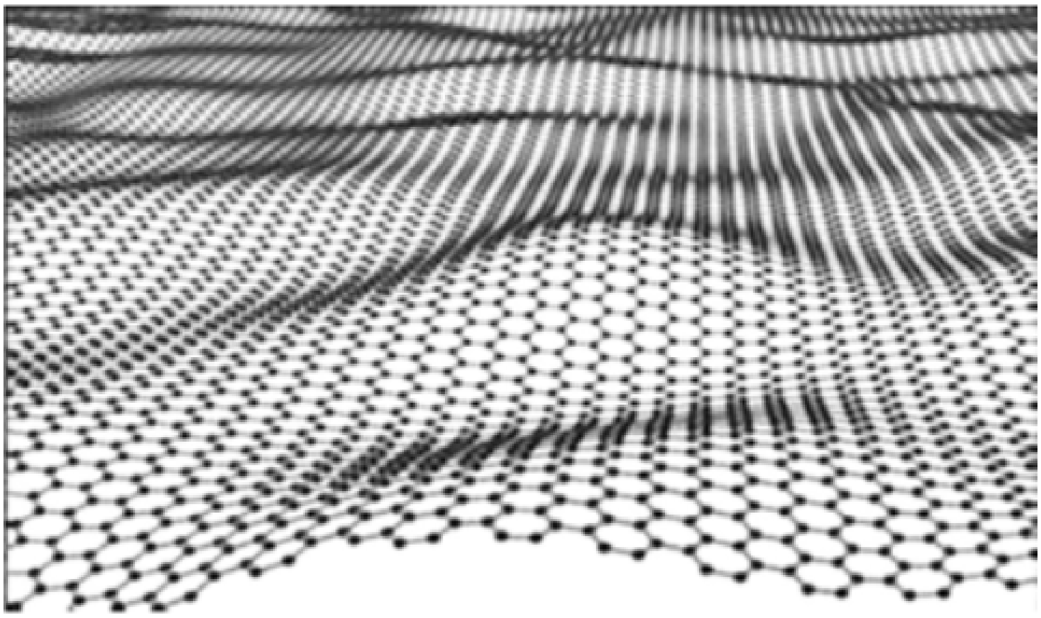

Figure 3 Schematic diagram of graphene structure [15]

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3.2 Properties of Graphene

Graphene is a honeycomb planar film formed by sp2 hybridization of carbon atoms. It is a quasi-two-dimensional material with only one atomic layer thickness (about 0.335 nm), so it is also called single atomic layer graphite. Graphene is one of the known materials with the highest strength. The theoretical Young 's modulus is 1.0 T pa, the ultimate tensile strength is 42 N/m, and the carbon-carbon bond is only 1.42 Å. The special hexagonal structure makes the carbon atomic plane deform rather than break under the action of external force to maintain the stability of the structure, while maintaining the flexibility and fracture resistance of the film. The specific surface area is 2630 m^3/g, and the thermal conductivity is 5300W/(m·K). It is far superior to traditional thermal conductive materials such as copper. The electron mobility at room temperature is as high as 150000 $cm^2/(V \cdot s)$, and the monolayer graphene is a zero-gap semiconductor. The electronic structure can adjust the carrier concentration by adsorbing or doping gas molecules to change the conductivity. In the visible light range (380-760 nm), the monolayer graphene has a transmittance of 97.7 % and a reflectivity of only 2.3 %. In addition to these excellent physical properties, it also has special chemical properties. Graphene can undergo redox reactions: for example, graphene oxide (GO) can be prepared by oxidation with concentrated acid, and reduced graphene oxide (RGO) can be obtained by reduction of graphene oxide (GO). Both materials are common derivatives of the graphene series; graphene can be modified by functional groups on its surface: the hydrophilicity of graphene oxide (GO) can be adjusted by chemical modification, and the efficient screening of water molecules and salt ions can be achieved by accurately adjusting the pore size, which can be used to design graphene nano-screening membranes. Graphene can also be compounded with other materials.

4. Application of graphene in the field of seawater desalination

4.1 . Applications of graphene in distillation methods

In multi-effect distillation (MED), graphene can be used as a material for evaporator surface coating and heat exchanger. Graphene can be used as a coating material for the inner wall of the evaporator to improve the heat transfer efficiency due to its ultra-high thermal conductivity. For example, in a series system of multiple evaporators, graphene coating can accelerate the seawater gasification process and reduce the energy consumption per unit of water production. In the preheating recovery process, graphene-based composites are used to manufacture corrosion-resistant heat exchangers. Its chemical stability can resist the erosion of high temperature and high salt environment to prolong the service life of the equipment and reduce the heat loss through efficient heat conduction.

In the multi-stage flash method (MSF), graphene can strengthen the flash chamber structure and improve the cascade utilization efficiency of thermal energy. The hydrophobic properties of graphene can be applied to the internal structure of flash chamber to reduce salt deposition. By spraying the graphene-ceramic composite coating, an anti-scaling layer is formed on the surface of the flash chamber to maintain long-term operating efficiency. The combination of graphene and phase change materials can design new energy storage modules, and heat storage materials with high energy storage density can recover industrial waste heat and achieve energy management [23]. Such materials have potential applications in flash waste heat storage, for example, storing waste heat for low-temperature flashing at night to improve energy efficiency.

In vapor compression distillation (VC), graphene can be used as a steam compressor coating and improve the performance of the condenser. Steam compressor is the core of pressurized gas distillation, and the high thermal conductivity and mechanical strength of graphene make it an ideal material for compressor impeller coating. The experiment shows that the graphene coating can reduce the operating temperature of the compressor by about 15 °C and reduce the friction loss. In the condensation stage, the nanoporous structure of the graphene film can accelerate steam liquefaction. For example, the nanoporous graphene membrane made by the team of Harbin Institute of Technology has an average water flux of 421.7 L /($m^2 \cdot h$) and a salt rejection rate of more than 99.8 % under the direct contact membrane distillation mode at a mild temperature of 65 / 25 °C, which is one order of magnitude higher than any reported polymer membrane. [24]

The existing problem is that the cost of large-scale preparation of graphene is high: due to the high cost of the existing graphene coating process (such as chemical vapor deposition), low-cost spraying technology needs to be further developed. In the future, multi-energy coupling schemes such as graphene materials and solar photothermal can be considered.

4.2 . Applications of graphene in Membrane-based methods

In reverse osmosis (RO), graphene can be used to fabricate high-precision filtration membranes with antifouling properties. The single atomic layer structure of graphene can form nanoscale channels, and high-efficiency salt ion interception can be achieved by precisely controlling the interlayer spacing, while allowing water molecules to pass quickly. Its chemical stability and hydrophobicity can reduce the adhesion of organic matter and microorganisms on the membrane surface to show anti-fouling and stability. The University of Manchester team found that the graphene oxide membrane can maintain a stable pore structure under high temperature and high salt environment. [19]. Graphene is widely used in reverse osmosis. For example, the water flux of graphene oxide composite membrane developed by East China University of Technology is 15 times that of traditional reverse osmosis membrane and the anti-pollution ability is significantly enhanced [20]. The Kust-I graphene membrane developed by Kunming University of Science and Technology has a pore size of 0.45 nm, high salt rejection (> 99 %) and self-cleaning function [21].

In electrodialysis (ED), graphene can modify the ion exchange membrane and can be used as an electrode material. Graphene modified ion exchange membrane can improve permeability and reduce electrode polarization. The hydrophilic groups (hydroxyl, carboxyl) of graphene oxide membrane can enhance the transport efficiency of cations and inhibit the reverse osmosis of anions. Graphene-based electrode materials (such as three-dimensional graphene foam) have ultra-high specific surface area ($2630m^2$ / g), and the adsorption capacity is more than 10 times that of activated carbon, which is suitable for low-salinity seawater pretreatment.

In membrane distillation (MD), graphene can be used to fabricate photothermal evaporation membranes. The hydrophobicity of the graphene membrane prevents liquid water penetration, and its high thermal conductivity accelerates vapor diffusion. For example, the team of Dalian University of Technology constructed a ceramic-based carbon nanotube composite membrane. Compared with the traditional membrane distillation process, the composite membrane had a flux increase rate of 33.7 % and a solar energy utilization efficiency of 22.7 % at a simulated light intensity of 4 kW / m^2. At the same time, the salt rejection rate (> 99.8 %) and the permeability side conductivity (< 60.0 μS / cm) remained stable during operation [22].

The existing problem is also that the cost of large-scale preparation of graphene is high, and it is also necessary to transform the coupling of multi-energy sources such as solar energy and graphene film. At the same time, it is necessary to solve the swelling problem of graphene oxide film in water, and the scheme of epoxy resin coating is still in the laboratory verification stage.

4.3 . Applications of graphene in freezing methods

In the natural freezing method, graphene materials can block salt. Graphene foam material can be used as the covering layer of natural freezing tank, and its porous structure can be used to adsorb surface salt and promote the formation of freshwater ice in the lower layer. In the ice crystal collection process after natural freezing, the graphene-based filter membrane can efficiently separate light ice and residual concentrated brine. Its nanoscale pore size (0.3-0.7 nm) can block salt ions and allow the rapid passage of melted fresh water.

In the artificial freezing method, graphene can regulate ice crystal formation, optimize heat conduction and anti-scaling. In the refrigerant direct contact method, the nanostructure of graphene can regulate the growth of ice crystals by surface modification. For example, the nanochannel selectivity of graphene oxide film allows water molecules to pass through and block salt ions, which can induce the formation of uniform ice crystal nuclei, reduce salt encapsulation, and improve the purity of light ice. Its high thermal conductivity can be used as a heat exchange coating for the refrigerant system to accelerate the transfer of cold energy. For example, Ren et al. prepared a graphene-enhanced epoxy thermally conductive coating. Compared with uncoated samples, the maximum temperature difference of the thermally conductive coating with 9 % graphene at room temperature can reach 5 °C, and the maximum temperature difference at -80 °C can reach 16 °C. This coating has potential application value in the field of quick-freezing [16]. Cao et al. obtained a high thermal conductivity interface material by vertically arraying large-diameter flake graphene oxide in polydimethylsiloxane using microwire shear technology. Compared with traditional thermal management materials, the composite material has a cooling efficiency of 93% in thermal management tests at a load of 14.8 % (volume fraction) [17]. A graphene-ceramic composite coating is sprayed on the inner wall of the refrigerant contact equipment. Its hydrophobicity and chemical stability can reduce salt deposition and prolong the maintenance cycle. Lu prepared a heat-resistant and corrosion-resistant high-strength graphene superhydrophobic coating in his experiments and verified that the coating can be strongly bonded to the ceramic substrate [18]. In the vacuum evaporation direct freezing method, the hydrophobicity and porous structure of graphene can accelerate vapor diffusion and condensation in a vacuum environment. Graphene can also be used as a coating on the surface of the evaporator. Its high thermal conductivity can accelerate heat transfer and reduce vacuum evaporation energy consumption.

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The existing problem is that the large-scale preparation cost of graphene is high and it is easy to swell in low temperature and humid environment. It also needs to be coupled with cold circulation system, solar refrigeration and other technologies to build an efficient low-carbon freeze desalination system

4.4 . Applications of graphene in Renewable energy-driven methods

In solar-driven seawater desalination technology, graphene achieves a combination of photothermal conversion and energy storage. Graphene has become the core material for solar evaporation due to its ultra-high solar absorption and thermal conductivity. Zhu Jia 's team of Nanjing University developed a graphene-foam polystyrene composite structure, which transports seawater to the surface of graphene film through capillary action, and achieves efficient evaporation under solar heating, with an energy conversion efficiency of 80 % [25]. The device does not require external energy and can directly convert seawater into fresh water that meets drinking standards, especially for remote areas or emergency scenarios. Combining graphene with phase change materials, an energy storage module can be designed. The solar energy absorbed during the day is stored in the phase change material, and the heat is released at night to maintain the evaporation process and achieve all-weather desalination. The hydrophobicity and chemical stability of graphene can reduce salt deposition on the evaporator surface.

In nuclear-powered seawater desalination technology, graphene can be used as an extreme environment-resistant material to improve system reliability. Graphene can be used as a coating material for reactor pipes and heat exchangers in nuclear-powered multi-effect distillation systems. Its high temperature resistance (> 600 °C) and radiation resistance characteristics can improve the stability of the equipment in extreme environments and reduce the risk of corrosion. The high thermal conductivity of graphene can accelerate the transfer efficiency of nuclear reaction waste heat to seawater evaporation system. For example, in a nuclear-multistage flash coupling system, graphene coating can increase the steam generation rate while reducing heat loss.

In wind-driven seawater desalination technology, graphene can optimize energy utilization efficiency. The high-water flux characteristics of graphene membrane can reduce the operating pressure demand of reverse osmosis system. This makes it easier for wind-driven intermittent power output to match the desalination device, reducing dependence on a stable grid. The mechanical strength and anti-pollution ability of graphene membrane can cope with the maintenance frequency of wind-driven reverse osmosis system and adapt to the high salt environment of marine environment. The intermittency of wind power generation can be stored by graphene-based supercapacitors to drive the seawater desalination system to operate at night.

The existing problem is that the preparation cost of graphene is high, and low-cost technologies (such as solution spraying) need to be developed. At present, the size of laboratory-grade graphene film is small, and large-area continuous preparation technology is needed.

5. Conclusion

This study reviews the application progress and application prospects of graphene in distillation, membrane, freezing and new energy methods in the field of seawater desalination. Graphene plays a role in the distillation method mainly by improving the efficiency of thermal energy utilization and the durability of equipment. The core advantages in the membrane method are high water flux and ion screening. The role in the freezing method is mainly to optimize the purity of light ice, and the core value in the new energy method is the efficient conversion of energy. Although graphene has performed well in various fields, especially in seawater desalination, solar photothermal evaporation film has shown great application potential, it still faces some challenges and limitations. If the preparation method needs to be further optimized, the stability and life of the material also need to be improved, the cost of the material is still high, and the actual scene adaptability is insufficient, it is necessary to further reduce the preparation cost and further verify its reliability in complex water quality, extreme climate or industrial equipment. In future research, the following directions can be considered to promote the development of graphene materials in seawater desalination.

(1) Development of low-cost preparation technology. Explore new processes such as solution spraying and 3D printing to replace traditional CVD methods to reduce the production cost of graphene films.

(2) Development of graphene-related energy storage modules. Non-continuous power output equipment (such as wind turbines) can be stored for a long time until all-weather continuous operation is achieved.

(3) Design of multi-technology coupling system. A multi-energy-driven low-carbon desalination system is constructed by combining graphene with solar evaporation, nuclear waste heat recovery and other technologies.

(4) It is necessary to systematically analyze the life cycle energy consumption, environmental impact and economic feasibility of large-scale application of graphene materi-

als.

(5) Although graphene materials have made some progress in seawater desalination, it is still necessary to further study the engineering and practical application effects of materials. By forming graphene-based composites with other non-metallic or metal materials, the efficiency and feasibility of graphene-based materials can be further improved. In summary, the research progress of graphene materials in seawater desalination provides a way to improve the existing seawater desalination technology. Its core value is to break through the bottleneck of efficiency and energy consumption of traditional technology. Future research needs to focus on collaborative innovation of materials, processes and systems, and promote the transformation of laboratory results to industrialization and inclusive applications, so as to further promote the development of graphene materials in seawater desalination and provide sustainable solutions to the global shortage of freshwater resources.

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