Graphene Oxide- Inorganic Composite Membrane: A Review

M Zunita1,* , I G B N Makertiharta1, R Irawanti1, N Prasetya2, I G Wenten1

1 Department of Chemical Engineering, Institut Teknologi Bandung, Ganesha Street 10, 40132, Bandung, West Java, Indonesia
2 Barrer Centre, Department of Chemical Engineering, Imperial College London, Exhibition Road, London, SW7 2 AZ, United Kingdom

*m.zunita@che.itb.ac.id

Abstract. Nowadays, membrane technology is one of excellent separation method. However, membranes as usual used have the heterogeneous pore size, poor mechanical property, thermally unstable, and fouling problem, therefore becomes a major challenge for many researchers. One of the most promising ways to address this issue is by making a composite membrane by introducing graphene oxide (GO). Graphene oxide (GO) is a two-dimensional material endowed with unique physicochemical, electrical, and thermal properties. Furthermore, GO has a large area and ultrathin layer surface, which is suitable for membrane technology as separation technology method. Its properties can be reducing volume area ratio of membrane to maximize flux and minimize transport resistance. Because of these exceptional properties, GO is then considered of being able to improve the separation performance of the native membranes. Recent developments in this area have shown the improvement of separation property coming from the GO-composite membrane. This is also followed by improvement in the physicochemical property of the resulting composite membrane such as in thermal and mechanical properties. In practical application, such GO-composite membranes have also been shown to be feasibly applied to separate heavy metal ions, mixture of gases, and organic materials. In addition, the GO-composite membrane is also suitable to be applied in fuel cell technology and has shown the antifouling and antibacterial property. This review paper will then focus on the recent developments of GO-composite membrane and factors affecting its successful synthesis so it can deliver exceptional separation performance.

1. Introduction
Membrane filtration is an advanced technology in fluid separation. Membrane technology offers several advantages such as operation simplicity, low footprint, energy intensive, intensified process, and low operating cost, which is made it a promising alternative to competing conventional technologies in almost industrial processes. Therefore, membrane has been widely adopted in various industrial processes including water treatment, wastewater treatment, chemical reaction, product purification, gas separation, and energy conversion [1,2].

In membrane-based processes, membrane material has to have mechanical integrity, thermal stability, and good selectivity, especially when encountering intense process condition. Furthermore, membrane fabrication also needs to consider the economic feasibility.

In order to address the above issues, graphene oxide (GO) is a promising material that has attracted numerous researchers in order to improve membrane properties and separation performance. [3–5]. This is because GO has exceptional physicochemical properties including mechanical resistance, thermal stability and chemically robust. Such a property is then beneficial once a GO-based membrane
can be fabricated on a support membrane since the latter usually suffer from fouling, defect problem, permselectivity trade-off, and unstable that renders it unsuitable for industrial application. Thus, it is expected that the resulting GO-based composite membrane can have an exceptional property suitable for industrial application. In this century, the number of research related to graphene oxide membrane significantly increased since it was introduced in 2004, as shown in Figure 1. So, those works necessary to be reviewed to summarise it and as a reflection for the future work. This article will then give a brief summary of the recent studies related to fabrication and performance of GO-based composite membrane for fluid separation.

![Composite Graphene Oxide Membrane](chart.png)

**Figure 1.** Number of graphene oxide membrane publications indexed by Scopus.

### 2. Graphene Oxide

Graphene has a structure like a honeycomb, which is a two-dimensional material that is built from a hexagonally arrayed sp²-bonded carbon and only a single-atom in thickness [6]. Meanwhile, graphene oxide (GO) is a chemical derivative of graphene that contains oxygen functionalities such as carboxyl, epoxy, carbonyl and hydroxyl groups [7], as illustrated in Figure 2. The location of these functional groups are both on the edges and basal plane of the GO sheet. The presence of these functional groups renders GO to be attractive to be applied as a membrane because its microstructure, chemical and physical property of the resulting membrane can be positively affected by these functionalities [8]. The strong hydrogen bonds in the graphene oxide nano-sheet hold the sheet compact and form a lamellar structure.

![Chemical structures of (a) graphene and (b) graphene oxide](structures.png)

**Figure 2.** Chemical structures of (a) graphene and (b) graphene oxide.
The potential of GO to be used as a membrane material was firstly discovered by the work of Nair et al. [9]. In their publication, they revealed that the GO membrane produced on a copper foil - which was etched later on to produce a freestanding GO - was able to let water vapour to pass through while on the other hand, it did not let any gas including helium to pass through. However, helium could start to permeate once the humidity level in the permeation system was increased. They argue that the GO membrane actually consists of pristine graphene capillaries whose pore opening depend on the surrounding humidity. Since then, considerable amount of works have been devoted to GO membrane since its wide-ranging potential applications such as for producing a molecular sieving membrane, water filtration, proton exchange membrane, desalination, etc. [4,10].

3. Preparation and Modification of Composite Graphene Oxide Membrane

3.1. Preparation

Generally, GO can be synthesized through two consecutive steps: oxidation of graphite that is followed by exfoliation of graphite oxide [8,11], as shown in Figure 3. GO was firstly synthesized by Brodie in 1859 [12] using graphite as the starting material which was oxidized using fuming nitric acid with potassium chlorate. Although more practical and convenient, all of these early methods produce toxic gases and not environmentally friendly [11].

![Figure 3. Synthesized process to obtain graphene oxide.](image)

In 20th century, the production process of GO was then significantly improved. In terms of chemical, fuming nitric acid was no longer required in Hofmann’s method. This method was then further improved by Hummers and Offeman who used a mixture of potassium permanganate, sulfuric acid and sodium nitrate [14].

Various methods have also been developed recently. For example, Luo et al. [15] have proposed the use of microwave heating method before exfoliation of graphite takes place. The aim of microwave heating is to expand the graphite and reduce its thickness. By doing so, they were able to produce a macroscopic-size GO membrane with the resulting area up to 2000 µm². But, the main objective is still how to largely produce a GO so it can be industrially attractive and environmentally friendly [11]. Among of them, the most common method to produce GO currently is through modified Hummer’s method. In this process, graphite is firstly oxidized using various oxidizing agent to obtain a monolayer GO sheets. The sheets are then exfoliated to produce GO flakes [5]. Methods to produce graphene oxide membrane composite on a membrane support or substrate are briefly described in this section include filtration, spin coating, surface functionalization, and other techniques.

3.1.1. Filtration. A simple way to prepare a GO membrane is by filtration method. In this technique, GO is homogeneously suspended in a solution. Afterwards, the GO solution filtered using a porous support to obtain a uniform coating. Filtration process can be vacuum- or pressure-assisted. The efficacy of this technique has been proven. For instance, Zhang et al. [16] have prepared a crosslinked
GO membrane on a PVDF support. This technique has also been proven to prepare a GO membrane on inorganic substrate. Li et al. [17] have shown the feasibility to fabricate a GO membrane on an anodized aluminum oxide substrate through this technique. The thickness of the resulted membrane was found to be less than 20 nm, approaching 1.8 nm. The resulting membrane also showed promising separation when tested to separate H₂/CO₂ and H₂/N₂ mixture. Recent developments have also shown the possibility to fabricate a GO membrane on a ceramic hollow fiber by using this technique [18–21]. In this technique, it was found that in order to have a stable GO membrane for real application, the prepared GO membrane needs to be stored in water in order to prevent any shrinkage caused by initial drying [18].

3.1.2. Spin coating. Another simple technique to prepare a GO composite membrane using inorganic substrate is by spin-coating. The benefit of this technique is its ability to produce uniform layer of film compared with other techniques such as drop casting and solvent-induced precipitation. It can also produce a very thin film [22] which is more suitable for membrane application.

This technique has been used to coat GO layer on a SiO₂/Si substrate to obtain a very thin layer of GO (about 1 nm in height) [23] and glass and quartz substrate for electronic application [22]. Hu et al. [24] recently prepared a GO membrane on Al₂O₃ substrate using this technique. The resulting composite membrane contains three different layers: membrane support, membrane interlayer, and the active membrane material where the GO lies. Both the support and membrane interlayer parts are fabricated from a mixture of Al₂O₃ powder and polyvinyl alcohol (PVA). In addition, the membrane interlayer also contains dispersant aside from the two main components. The difference between the support and the membrane interlayer is the former is more porous than the later (400 nm compared to 80 nm pore size). As the final step, they spin coated a GO membrane by spin coating followed by drying. The thickness of the resulting membrane was found to be 800 nm and exhibited a good performance regarding its phenol rejection.

3.1.3. Surface functionalization. The essential part of this technique is functionalize the substrate (polymer or inorganic) to make it more active layer so that it can be stronger bonding between GO and the substrate can be established. Unlike the blending method, an active layer is required in this technique to build a covalent bonding between GO layer and the polymer layer. This technique has been used to functionalize a polyamide thin film composite by using 1-ethyl-3-[3-(dimethylamino)propyl] carbodiimide hydrochloride and N-hydroxysuccinimide. This step is necessary to bind GO to the active layer resulting in a functionalized GO-polyamide [25]. Moreover, its process ensures that chemical bonding will be established once the modified substrate was dip coated in a GO solution to fabricate a GO membrane. It was also found that the pH of GO solution should be around 5-6 to obtain a robust GO membrane [26]. Another compound that can be used to functionalize alumina substrate is polydopamine [27]. The polydopamine deposited on the alumina substrate founded not to give any additional mass transfer resistance to the alumina disc. After modification, GO layer deposited on the substrate through vacuum filtration.

3.1.4. Other possible techniques. A composite GO membrane can also be prepared by direct blending with another material, usually polymer. After blending process takes place, the resulting dope solution is usually cast in a porous support. This will result a mixed matrix composite membrane with dispersed GO particles. This method has been used to prepare a GO-PBI membrane for PEM fuel cell membrane [28], GO-PVDF for membrane bioreactor [29], and GO-PVA [30]. This technique can be slightly modified by employing porous inorganic support when casting the resulting dope solution. The casting process itself can be completed using drop-casting or spin coating technique that have been established for other GO-composite membrane.

The mechanical strength of composite graphene oxide membrane has discovered by the work of some researchers. [31–36]. The improvements of tensile strength and Young’s modulus are attributed to the homogenous dispersion of GO nano-sheet at the surface or matrix membrane. Furthermore, there is a strong interaction between GO oxygen-containing functional groups and support or substrate membrane via hydrogen bonding [35].
3.2. Modification
Graphene oxide-based membrane can be constructed in the form of freestanding or self-assembly GO layer [37,38], modified support membrane [39–41], thin film composite [25,42–45], and mixed matrix membrane array [46–49]. Freestanding GO membrane utilises GO as a separating layer directly. Self-assembly or freestanding GO has shown ultrafast permeance and high rejection of solute [50]. In another hand, this multilayer GO had a weak mechanical strength if applied in high-pressure operation. Furthermore, the swelling effect in freestanding GO due to intercalation of water molecules in the interlayer spacing leads to unstable framework due to increase of interlayer spacing d [51–53].

Improve mechanical strength and stability of membrane could be approached by chemical crosslinking of GO layer [54]. Chemicals such polydopamine [55], isocyanate [56,57], metal ions [58], diamine monomers [59], glutaraldehyde [60] have been reported to elevate mechanical resistance and stability of the membrane. Covalent bonding between GO layer and crosslinker agent sufficiently suppress the interlayer spacing d [59]. Hence, the stability and integrity of GO membrane could be maintained.

Incorporated-graphene oxide into material support has been reported enhance the separation performance and property of membrane. The amount of graphene oxide which embeds in support membrane will affect permeance, solute rejection, mechanical strength, and pH resistive of membrane. The higher amount of GO added into membrane could enhance the mechanical integrity of membrane [32], however it will induce aggregation of GO which blocking the water/gas permeation. [61,62]. The lower GO addition into membrane the more sensitive the as-prepared GO against pH [32]. So, the proper quantity of GO to be embedded into support membrane need to be considered to achieve satisfied separation performance and stability of membrane.

4. Application and Separation Performance of Composite Inorganic Graphene Oxide Membrane

4.1. Gas Separation
Graphene oxide membranes have been shown to be capable of performing gas separation process. This phenomenon has been discovered and studied by numerous scientists through either experimental and simulation. Graphene oxide was incorporated into polymer support layer with expectancy to alleviate the trade-off between permeability-selectivity and plasticization [63,64]. Thus, graphene oxide was an appropriate nanomaterial to be used as fillers in the gas separation membrane [65].

The gases permselectivity are relying on the diffusivity and solubility of the gas in a membrane. Several gases have been identified their permeation performance through graphene oxide-based membranes, which are the gas separation performance follows in order CO$_2$ > H$_2$ > CH$_4$ > N$_2$ [66–68]. In the availability of water, the permeability of carbon dioxide gas significantly increases compared in dry condition. The high CO$_2$ permeance in GO membrane can be assumed in the high CO$_2$ diffusivity, and the high CO$_2$ selectivity can be ascribed to the high CO$_2$ solubility [66,69]. This property of GO membrane corresponds to carbon dioxide gas give an amplified that GO membrane can be utilised for the CO$_2$ capture [70–74].

Selective gas diffusion can be achieved via controlling interlayer spacing between GO layer and nano-pores between the inter-edge of GO sheets [75,76]. Romanos et al. have successfully carried out variation filtration rate of the as-prepared GO suspension. The finding was that fast filtration rate led to a random rearrangement of GO layer, on the other hand very slow filtration resulted in order structures. The as-prepared GO membranes by slow filtration were more hydrophobic than another GO which prepared by fast filtration. The more hydrophobic membrane result in higher water vapour permeation. So, this finding offers the opportunities of GO membrane to be applied for distillation process [77].

The support membrane in the performance of gas separation membrane also possesses a key role. The support membranes have to have thermal stability and swelling resistant. Incorporated graphene oxide into support polymer membrane has obviously enhanced the performance of membrane for gas separation. The permeability-selectivity, include thermal stability of membrane was significantly improve [78,79]. Polymer-support membrane which intercalated graphene oxide have been successfully produced by some researchers include polysulfone [80–82], Pebax [71,83], polyether
Table 1. Separation performances of several GO membranes in gas separation.

| No. | GO-based membrane                        | Permeance (mol/m²sPa) | Selectivity | Ref. |
|-----|-----------------------------------------|-----------------------|-------------|------|
| 1.  | GO-AAO                                  | $P_{H2} = 3.400 \cdot 10^{-4}$ | $a_{H2/(CO2)} = 240$ | [86] |
| 2.  | Annealed-GO-polycarbonate               | $P_{H2} = 1.758 \cdot 10^{-7}$ | $a_{H2/(CO2)} = 10$ | [87] |
| 3.  | Aminated-GO/polyethersulfone mixed matrix membrane | $P_{CO2} = 4.21 \cdot 10^{-9}$ | $a_{CO2/CH4} = 37.88$ | [84] |
| 4.  | GO-Uio66-NH2-S                          | $P_{H2} = 3.900 \cdot 10^{-8}$ | $a_{H2/(CO2)} = 6.35$ | [88] |
| 5.  | GO/α-Al2O3 ceramic hollow fiber membrane | $P_{H2} = 1.300 \cdot 10^{-7}$ | $a_{H2/(CO2)} = 15$ | [89] |
| 6.  | ODA-GO/polydimethysiloxane              | $P_{CH4} = 6.355 \cdot 10^{-7}$ | $a_{CH4/(N2)} = 67$ | [90] |

4.2. Water Treatment

Graphene oxide is known can be well-dispersed in water because of the electrostatic repulsion between the ionized functional group in GO nano-sheet [63]. Wei et al. have examined the fast permeation of water through graphene oxide, water molecules pass through the nano-porous between the edge of GO sheets and between the interlayer spacing of GO layer [91]. Because of its characteristic and behaviour in water, the application of graphene oxide-based membrane in water purification including heavy metal removal [47,92], oil/water separation [38,93], dye removal [94] and desalination [95,96] is highly promising.

Embedded-graphene oxide in membrane support has proven to enhance the water permeation flux and solute rejection. Moreover, the fouling resistance and antibacterial properties of membrane become more favourable than the bare membrane [97–104]. Hydrophilicity properties of GO membrane leading to high water flux. The enhancement of hydrophilicity is induced as a result of the surface functionalization of graphene oxide membrane [105]. The high solute rejection was explained by three mechanisms of filtration, include size exclusion [106,107], electrostatic interaction [106,108,109], and/or adsorption [110,111]. Separation performances of several GO membranes in water treatment are summarized in Table 2.

Table 2. Separation performances of several GO membranes in water purification.

| No. | GO-based membrane                        | Application | Testing condition | Water flux (L/m²hbar) | Rejection (%) | Ref. |
|-----|-----------------------------------------|-------------|-------------------|-----------------------|--------------|------|
| 1.  | COOH-GO self assembly membrane (NF)     | Desalination | NaCl feed = 2000 ppm P = 15 bar | 4.89          | 39.16          | [96] |
| 2.  | rGO/TiO2 polysulfone TFC membrane (RO)  | Desalination | NaCl feed = 2000 ppm P = 15 bar | 3.42          | 99.45          | [61] |
| 3.  | Aminated-GO/polyamide TFC membrane (RO) | Desalination | NaCl feed = 2000 ppm P = 15.5 bar | 0.903         | 96.4           | [112] |
| 4.  | GO-palygorskite nanohybrid membrane      | Oil/Water Separation | Stirring rate = 200 rpm P = 0.5 bar | 3734         | 99.9           | [38] |
| 5.  | GO/Torlon hollow fiber membrane          | Heavy Metal Removal | Pb²⁺ feed = 1000 ppm P = 3 bar Initial feed (cono red) = 20 mL pH 7 | 4.7           | 95.88          | [113] |
| 6.  | GO-IPDI membrane                        | Dye Removal |                | 80–100         | 99.3           | [57] |
4.3. Electrochemical Energy

Nowadays, clean energy production was preferably carried out due to efficient and environmentally friendly process. Electrochemical energy sources divided into several types, such as fuel cell. Membrane technology in these processes has based on electro-ionic separation, such as cation exchange membrane, anion exchange membrane, or a bipolar membrane. Proton exchange membrane in fuel cell application has to give a good performance such in proton conductivity, mechanical and thermal stability, oxidation stability, water uptake and low ion permeability.

The addition of nano-additives or nano-fillers (e.g. graphene oxide) into polymer membrane is one of the alternatives to improve the performance (ion exchange capacity, water uptake, and proton conductivity) of proton exchange membrane [114–118]. Jiang et al. found that the introduction of Si-GOs into polymer membrane improve the mechanical stability without diminished the proton conductivity [119]. The mechanical stability of polymer membrane with the inclusion of graphene oxide also has been demonstrated by various authors [115,120–123]. Separation performances of several GO membranes in fuel cells application are summarized in Table 3.

Table 3. Separation performances of several GO membranes in fuel cells application.

| No. | GO-based membrane | Application | Testing condition | Proton conductivity (S cm$^{-1}$) | Power density (mW cm$^{-2}$) | Ref. |
|-----|-------------------|-------------|-------------------|----------------------------------|-------------------------------|-----|
| 1.  | Sulfonated-GO/Nafion membrane | Direct Methanol Fuel Cells | Methanol = 1 M | 0.0363 | 42.9 | [124] |
| 2.  | Freestanding GO membrane | Polymer Electrolyte Membrane Fuel Cells | T = 70°C RH = 100% | 0.0011 | 33.8 | [125] |
| 3.  | Aryl sulfonated-GO/poly(vinyl alcohol) mixed matrix membrane | Polymer Electrolyte Membrane Fuel Cells | T = 30°C | 0.0500 | 16.15 | [126] |
| 4.  | Sulfonic acid-GO/sulfonated polyether ketone composite membrane | Polymer Electrolyte Membrane Fuel Cells | T = 80°C RH = 30% | 0.0550 | 378 | [127] |
| 5.  | GO/sulfonated polyether ketone-histidine composite membrane | Direct Methanol Fuel Cells | T = 25°C RH = 100% Methanol = 2 M | 0.0694 | 43 | [128] |

5. Summary and Outlook

Composite Inorganic Graphene Oxide Membrane with all its exceptional physicochemical properties has gained increased interest recently. Graphene oxide is hydrophilic, its property due to oxygen-containing functional groups in the GO sheet. When fabricated as a membrane, GO can act as a selective layer that selectively let some components pass through while rejecting the rest.

Graphene oxide membrane can be constructed in the form of self-assembly or free-standing GO layer, modified support membrane, thin film composite or mixed matrix membrane. Composite inorganic graphene oxide membrane can be prepared by filtration vacuum, spin/spray/dip coating, surface functionalization and other possible technique such as blending GO into a polymer matrix.

According to several reported studies, composite graphene oxide membranes have showed the enhanced separation performance in various applications such as gas separation, water treatment, and fuel cell. However, the stability of composite GO membrane needs further development. Among others approached by adding crosslinker to bind the GO inter-sheets. Another aspect need to be considered is the quantity of GO added into support membrane. With expectancy to enhance the
stability and separation performance of membrane, an appropriate quantity of GO added into support membrane is important to determine.

6. References
[1] Wenten I G 2003 Recent development in membrane science and its industrial applications Songklanakarin J. Sci. Technol. 24 1009–23
[2] Le N L and Nunes S P 2016 Materials and membrane technologies for water and energy sustainability Sustain. Mater. Technol. 7 1–28
[3] Zhang Y and Chung T 2017 Graphene oxide membranes for nanofiltration Curr. Opin. Chem. Eng. 16 9–15
[4] Joshi R K, Alwarappan S, Yoshimura M, Sahajwalla V and Nishina Y 2015 Graphene oxide: The new membrane material Appl. Mater. Today 1 1–12
[5] Chong J, Wang B and Li K 2016 Graphene oxide membranes in fluid separations Curr. Opin. Chem. Eng. 12 98–105
[6] Kim H, Abdala A A and MacOsko C W 2010 Graphene/polymer nanocomposites Macromolecules 43 6515–30
[7] Dreyer D R, Park S, Bielawski C W and Ruoff R S 2010 The chemistry of graphene oxide Chem. Soc. Rev. 39 228–40
[8] Liu G, Jin W and Xu N 2015 Graphene-based membranes Chem. Soc. Rev. 44 5016–30
[9] R. R. Nair, H. A. Wu, P. N. Jayaram, I. V. Grigorieva and A. K. Geim 2012 Unimpeded Permeation of Water Through Helium-Leak–Tight Graphene-Based Membranes vol 335(American Association for the Advancement of Science)
[10] Abraham J, Vasu K S, Williams C D, Gopinadhan K, Su Y, Cherian C T, Dix J, Prestat E, Haigh S J, Grigorieva I V., Carboni P, Geim A K and Nair R R 2017 Tunable sieving of ions using graphene oxide membranes Nat. Nanotechnol. 12 546–50
[11] Ma J, Ping D and Dong X 2017 Recent Developments of Graphene Oxide-Based Membranes: A Review Membranes (Basel). 7 52
[12] Brodie B C 1859 On the Atomic Weight of Graphite Philos. Trans. R. Soc. London 149 249–59
[13] Staudenmaier L 1898 Verfahren zur Darstellung der Graphitsäure Eur. J. Inorg. Chem. 31 1481–7
[14] Hummers W S and Offeman R E 1958 Preparation of Graphitic Oxide J. Am. Chem. Soc. 80 1339–1339
[15] Luo Z, Lu Y, Somers L A and Johnson A T . 2009 High Yield Preparation of Macroscopic Graphene Oxide Membranes High Yield Preparation of Macroscopic Graphene Oxide Membranes J. Am. Chem. Soc. 131 898–9
[16] Zhang P, Gong J, Zeng G, Deng C, Yang H, Liu H and Huan S 2017 Cross-Linking to Prepare Composite Graphene Oxide-Framework Membranes with High-Flux for Dyes and Heavy Metal Ions Removal Chem. Eng. J. 322 657–666
[17] Li H, Song Z, Zhang X, Huang Y, Li S, Mao Y, Ploehn H J, Bao Y and Yu M 2013 Ultrathin, molecular-sieving graphene oxide membranes for selective hydrogen separation. Science. 342 95–8
[18] Aba N F D, Chong J Y, Wang B, Mattevi C and Li K 2015 Graphene oxide membranes on ceramic hollow fibers - Microstructural stability and nanofiltration performance J. Memb. Sci. 484 87–94
[19] Huang K, Liu G, Lou Y, Dong Z, Shen J and Jin W 2014 A Graphene Oxide Membrane with Highly Selective Molecular Separation of Aqueous Organic Solution Angew. Chemie Int. Ed. 53 6929–32
[20] Zhu J, Meng X, Zhao J, Jin Y, Yang N and Zhang S 2017 Facile hydrogen/nitrogen separation through graphene oxide membranes supported on YSZ ceramic hollow fibers J. Memb. Sci. 535 143–50
[21] Huang K, Yuan J, Shen G, Liu G and Jin W 2017 Graphene oxide membranes supported on the ceramic hollow fibre for efficient H2 recovery Chinese J. Chem. Eng. 25 752–9
[22] Becerril H A, Mao J, Liu Z, Stoltenberg R M, Bao Z and Chen Y 2008 Evaluation of Solution-
Processed Reduced Graphene Oxide Films as Transparent Conductors ACS Nano 2 463–70

[23] Luo Z, Lu Y, Somers L A and Johnson A T C 2009 High Yield Preparation of Macroscopic Graphene Oxide Membranes J. Am. Chem. Soc. 131 898–9

[24] Hu X, Yu Y, Ren S, Lin N, Wang Y and Zhou J 2017 Highly efficient removal of phenol from aqueous solutions using graphene oxide/AI2O3 composite membrane J. Porous Mater. 1–8

[25] Perreault F, Tousley M E and Elimelech M 2013 Thin-Film Composite Polyamide Membranes Functionalized with Biocidal Graphene Oxide Nanosheets Environ. Sci. Technol. Lett. 1 71–6

[26] Lou Y, Liu G, Liu S, Shen J and Jin W 2014 A facile way to prepare ceramic-supported graphene oxide composite membrane via silane-graft modification Appl. Surf. Sci. 307 631–7

[27] Xu K, Feng B, Zhou C and Huang A 2016 Synthesis of highly stable graphene oxide membranes on polydopamine functionalized supports for seawater desalination Chem. Eng. Sci. 146 159–65

[28] Xue C, Zou J, Sun Z, Wang F, Han K and Zhu H 2014 Graphite oxide/functionailized graphene oxide and polybenzimidazole composite membranes for high temperature proton exchange membrane fuel cells Int. J. Hydrogen Energy 39 7931–9

[29] Zhao C, Xu X, Chen J, Wang G and Yang F 2014 Highly effective antifouling performance of PVDF/graphene oxide composite membrane in membrane bioreactor (MBR) system Desalination 340 59–66

[30] Lecaros R L G, Mendoza G E J, Hung W S, An Q F, Caparanga A R, Tsai H A, Hu C C, Lee K R and Lai J Y 2017 Tunable interlayer spacing of composite graphene oxide framework membrane for acetic acid dehydration Carbon N. Y. 123 660–7

[31] Sridi N, Lebental B, Azevedo J, Gabriel J C P and Ghis A 2013 Electrostatic method to estimate the mechanical properties of suspended membranes applied to nickel-coated graphene oxide Appl. Phys. Lett. 103

[32] Jiang Z, Xia D, Li Y, Li J, Li Q, Chen M, Huang Y, Besenbacher F and Dong M 2013 Facilitating the mechanical properties of a high-performance pH-sensitive membrane by cross-linking graphene oxide and polyacrylic acid. Nanotechnology 24 335704

[33] Lee S, Choi B G, Choi D and Park H S 2014 Nanoindentation of annealed Nafion/sulfonated graphene oxide nanocomposite membranes for the measurement of mechanical properties J. Memb. Sci. 451 40–5

[34] Thampi S, Muthuvijayan V and Parameswaran R 2015 Mechanical characterization of high-performance graphene oxide incorporated aligned fibroporous poly(carbonate urethane) membrane for potential biomedical applications J. Appl. Polym. Sci. 132 41808–16

[35] Gan S, Zakaria S, Chia C H, Chen R S and Jeyalaldeen N 2015 Physico-mechanical properties of a microwave-irradiated kenaf carbamate/graphene oxide membrane Cellulose 22 3851–63

[36] Wang X, Wang X, Xiao P, Li J, Tian E, Zhao Y and Ren Y 2016 High water permeable free-standing cellulose triacetate/graphene oxide membrane with enhanced antibiofouling and mechanical properties for forward osmosis Colloids Surfaces A Physicochem. Eng. Asp. 508 327–35

[37] Xu W L, Fang C, Zhou F, Song Z, Liu Q, Qiao R and Yu M 2017 Self-Assembly: A Facile Way of Forming Ultrathin, High-Performance Graphene Oxide Membranes for Water Purification Nano Lett. 17 2928–33

[38] Zhao X, Su Y, Liu Y, Li Y and Jiang Z 2016 Free-Standing Graphene Oxide-Palygorskite Nanohybrid Membrane for Oil/Water Separation ACS Appl. Mater. Interfaces 8 8247–56

[39] Gao Y, Hu M and Mi B 2014 Membrane surface modification with TiO2-graphene oxide for enhanced photocatalytic performance J. Memb. Sci. 455 349–56

[40] Huang X, Marsh K L, McVerry B T, Hoek E M V and Kaner R B 2016 Low-Fouling Antibacterial Reverse Osmosis Membranes via Surface Grafting of Graphene Oxide ACS Appl. Mater. Interfaces 8 14334–8

[41] Lou Y, Liu G, Liu S, Shen J and Jin W 2014 Applied Surface Science A facile way to prepare ceramic-supported graphene oxide composite membrane via silane-graft modification Appl.
[42] Yin J, Zhu G and Deng B 2016 Graphene oxide (GO) enhanced polyamide (PA) thin-film nanocomposite (TFN) membrane for water purification Desalination 379 93–101

[43] Shen L, Xiong S and Wang Y 2016 Graphene oxide incorporated thin-film composite membranes for forward osmosis applications Chem. Eng. Sci. 143 194–205

[44] Chae H-R, Lee C-H, Park P-K, Kim I-C and Kim J-H 2016 Synergetic effect of graphene oxide nanosheets embedded in the active and support layers on the performance of thin-film composite membranes J. Memb. Sci. 525 99–106

[45] Park M J, Phuntsho S, He T, Nisola G M, Tijing L D, Li X M, Chen G, Chung W J and Shon H K 2015 Graphene oxide incorporated polysulfone substrate for the fabrication of flat-sheet thin-film composite forward osmosis membranes J. Memb. Sci. 493 496–507

[46] Kaleekkal N J, Thangaiavelan A, Rana D and Mohan D 2016 Studies on carboxylated graphene oxide incorporated polyetherimide mixed matrix ultrafiltration membranes Mater. Chem. Phys. 186 pp. 146-158

[47] Mukherjee R, Bhunia P and De S 2016 Impact of graphene oxide on removal of heavy metals using mixed matrix membrane Chem. Eng. J. 292 284–97

[48] Mohd Akhair S S, Harun Z, Jamalludin M R, Shuhor M F, Kamarudin N H, Yunos M Z, Ahmad A and Azhar M F H 2017 Polymer Mixed Matrix Membrane with Graphene Oxide for Humic Acid Performances Chemical Engineering Transactions 56 697–702

[49] Zhao L, Cheng C, Chen Y F, Wang T, Du C H and Wu L G 2015 Enhancement on the permeation performance of polyimide mixed matrix membranes by incorporation of graphene oxide with different oxidation degrees Polym. Adv. Technol. 26 330–7

[50] Jang J H and Lee J 2015 Ultrathin graphene oxide membranes for water purification 2015 IEEE 15th International Conference on Nanotechnology (IEEE-NANO) pp 212–5

[51] Zheng S, Tu Q, Urban J J, Li S and Mi B 2017 Swelling of Graphene Oxide Membranes in Aqueous Solution: Characterization of Interlayer Spacing and Insight into Water Transport Mechanisms ACS Nano 11 6440–50

[52] Xu X L, Lin F W, Du Y, Zhang X, Wu J and Xu Z K 2016 Graphene Oxide Nanofiltration Membranes Stabilized by Cationic Porphyrin for High Salt Rejection ACS Appl. Mater. Interfaces 8 12588–93

[53] Heo Y, Im H and Kim J 2013 The effect of sulfonated graphene oxide on Sulfonated Poly (Ether Ether Ketone) membrane for direct methanol fuel cells J. Memb. Sci. 425–426 11–22

[54] Jia Z and Shi W 2016 Tailoring permeation channels of graphene oxide membranes for precise ion separation Carbon N. Y. 101 290–5

[55] He Y, Wang J, Zhang H, Zhang T, Zhang B, Cao S and Liu J 2014 Polydopamine-modified graphene oxide nanocomposite membrane for proton exchange membrane fuel cell under anhydrous conditions J. Mater. Chem. A 2 9548

[56] Zhao H, Wu L, Zhou Z, Zhang L and Chen H 2013 Improving the antifouling property of polysulfone ultrafiltration membrane by incorporation of isocyanate-treated graphene oxide Phys. Chem. Chem. Phys. 15 9084

[57] Zhang P, Gong J, Zeng G, Deng C, Yang H and Liu H 2017 Cross-linking to prepare composite graphene oxide-framework membranes with high-flux for dyes and heavy metal ions removal Chem. Eng. J. 322 657–66

[58] Rao Z, Feng K, Tang B and Wu P 2017 Surface decoration of amino-functionalized metal-organic framework/graphene oxide composite onto polydopamine-coated membrane substrate for highly efficient heavy metal removal ACS Appl. Mater. Interfaces 9 2594–605

[59] Hung W, Tsou C, Guzman M De, An Q, Liu Y, Zhang Y, Hu C, Lee K and Lai J 2014 Cross-Linking with Diamine Monomers To Prepare Composite Graphene Oxide-Framework Membranes with Varying d-Spacing Chem. Mater. 26 2983–90

[60] Sarkar G, Saha N R, Roy I, Bhattacharyya A, Adhikari A, Rana D, Bhowmik M, Bose M, Mishra R and Chattopadhyay D 2016 Cross-linked methyl cellulose/graphene oxide rate controlling membranes for in vitro and ex vivo permeation studies of diltiazem hydrochloride RSC Adv. 6 36136–45
[61] Safarpour M, Khataee A and Vatanpour V 2015 Effect of reduced graphene oxide/TiO2 nanocomposite with different molar ratios on the performance of PVDF ultrafiltration membranes Sep. Purif. Technol. 140 32–42

[62] Wu X, Field R W, Wu J J and Zhang K 2017 Polyvinylpyrrolidone modified graphene oxide as a modifier for thin film composite forward osmosis membranes J. Membr. Sci. 540 251–60

[63] Yoo B M, Shin J E, Lee H D and Park H B 2017 Graphene and graphene oxide membranes for gas separation applications Curr. Opin. Chem. Eng. 16 39–47

[64] Zahri K, Goh P S and Ismail A F 2016 The incorporation of graphene oxide into polysulfone mixed matrix membrane for CO2/CH4 separation IOP Conf. Ser. Earth Environ. Sci. 36 12007

[65] Li X, Cheng Y, Zhang H, Wang S, Jiang Z, Guo R and Wu H 2015 Efficient CO2 capture by functionalized graphene oxide nanosheets as fillers to fabricate multi-permselective mixed matrix membranes ACS Appl. Mater. Interfaces 7 5528–37

[66] Kim H W, Yoon H W, Yoo B M, Park J S, Gleason K L, Freeman B D and Park H B 2014 High-performance CO2-philic graphene oxide membranes under wet-conditions Chem. Commun. 50 13563–6

[67] Karunakaran M, Shevate R, Kumar M and Peinemann K 2015 CO2-selective PEO–PBT (PolyActivet)/graphene oxide composite membranes Chem. Commun. 51 14187–90

[68] Shen J, Liu G, Huang K, Jin W, Lee K R and Xu N 2015 Membranes with fast and selective gas-transport channels of laminar graphene oxide for efficient CO2 capture Angew. Chemie - Int. Ed. 54 578–82

[69] Koolivand H, Sharif A, Kashani M R, Karimi M, Salooki M K and Semsarzadeh M A 2014 Functionalized graphene oxide/polyimide nanocomposites as highly CO2-selective membranes J. Polym. Res. 21 599

[70] Karunakaran M, Villalobos L F, Kumar M, Shevate R, Akhtar F H, Peinemann K-V, Noble R D, Bauer E M, Nasillo G, Caponetti E, Choi J Y and Park H B 2017 Graphene oxide doped ionic liquid ultrathin composite membranes for efficient CO2 capture J. Mater. Chem. A 5 649–56

[71] Dai Y, Ruan X, Yan Z, Yang K, Yu M, Li H, Zhao W and He G 2016 Imidazole functionalized graphene oxide/PEBAX mixed matrix membranes for efficient CO2 capture Sep. Purif. Technol. 166 171–80

[72] Shen Y, Wang H, Liu J and Zhang Y 2015 Enhanced Performance of a Novel Polyvinyl Amine/Chitosan/Graphene Oxide Mixed Matrix Membrane for CO2 Capture ACS Sustain. Chem. Eng. 3 1819–29

[73] Lim M, Choi Y, Kim J, Kim K, Shin H, Kim J, Myung D and Lee J 2017 Cross-linked graphene oxide membrane having high ion selectivity and antibacterial activity prepared using tannic acid-functionalized graphene oxide and polyethyleneimine J. Membr. Sci. 521 1–9

[74] Dong G, Zhang Y, Hou J, Shen J and Chen V 2016 Graphene Oxide Nanosheets Based Novel Facilitated Transport Membranes for Efficient CO2 Capture Ind. Eng. Chem. Res. 55 5403–14

[75] Kim H W, Yoon H W, Yoon S M, Yoo B M, Ahn B K, Cho Y H, Shin H J, Yang H, Paik U, Kwon S, Choi J Y and Park H B 2013 Selective Gas Transport Through Few-Layered Graphene and Graphene Oxide Membranes Science (80-. ). 342 91–5

[76] Jiao S and Xu Z 2015 Selective gas diffusion in graphene oxides membranes: A molecular dynamics simulations study ACS Appl. Mater. Interfaces 7 9052–9

[77] Romanos G, Pastrana-Martinez L M, Tsoufis T, Athanasekou C, Galata E, Katsaros F, Favvas E, Beltsios K G, Siranidi E, Falaras P, Psycharis V and Silva A M T 2015 A facile approach for the development of fine-tuned self-standing graphene oxide membranes and their gas and vapor separation performance J. Membr. Sci. 493 734–47

[78] Wang T, Zhao L, Shen J N, Wu L G and Van Der Bruggen B 2015 Enhanced Performance of Polyurethane Hybrid Membranes for CO2 Separation by Incorporating Graphene Oxide: The Relationship between Membrane Performance and Morphology of Graphene Oxide Environ. Sci. Technol. 49 8004–11
[79] Ha H, Park J, Ando S, Kim C Bin, Nagai K, Freeman B D and Ellison C J 2016 Gas permeation and selectivity of poly(dimethylsiloxane)/graphene oxide composite elastomer membranes J. Memb. Sci. 518 131–40
[80] Sarfraz M and Ba-Shammakh M 2015 Synergistic effect of incorporating ZIF-302 and graphene oxide to polysulfone to develop highly selective mixed-matrix membranes for carbon dioxide separation from wet post-combustion flue gases J. Ind. Eng. Chem. 36 154–162
[81] Sarfraz M and Ba-Shammakh M 2016 Synergistic effect of adding graphene oxide and ZIF-301 to polysulfone to develop high performance mixed matrix membranes for selective carbon dioxide separation from post combustion flue gas J. Memb. Sci. 514 35–43
[82] Zahri K, Wong K C, Goh P S and Ismail A F 2016 Graphene oxide/polysulfone hollow fiber mixed matrix membranes for gas separation RSC Adv. 6 89130–9
[83] Dong G, Hou J, Wang J, Zhang Y, Chen V and Liu J 2016 Enhanced CO2/N2 separation by porous reduced graphene oxide/Pebax mixed matrix membranes J. Memb. Sci. 520 860–8
[84] Ebrahimi S, Mollati-Berneti S, Asadi H, Peydayesh M, Akhlaghian F and Mohammadi T 2016 PVA/PES-amine-functional graphene oxide mixed matrix membranes for CO2/CH4 separation: Experimental and modeling Chem. Eng. Res. Des. 109 647–56
[85] Wang T, Cheng C, Wu L G, Shen J N, Van Der Bruggen B, Chen Q, Chen D and Dong C Y 2017 Fabrication of Polyimide Membrane Incorporated with Functional Graphene Oxide for CO2 Separation: The Effects of GO Surface Modification on Membrane Performance Environ. Sci. Technol. 51 6202–10
[86] Chi C, Wang X, Peng Y, Qian Y, Hu Z, Dong J and Zhao D 2016 Facile Preparation of Graphene Oxide Membranes for Gas Separation Chem. Mater. 28 2921–7
[87] Achari A and Eswaramoorthy M 2016 Casting molecular channels through domain formation: high performance graphene oxide membranes for H2/CO2 separation J. Mater. Chem. A 4 7560–4
[88] Jia M, Feng Y, Liu S, Qiu J and Yao J 2017 Graphene oxide gas separation membranes intercalated by UiO-66-NH2 with enhanced hydrogen separation performance J. Memb. Sci. 539 172–7
[89] Huang K, Yuan J, Shen G, Liu G and Jin W 2017 Graphene oxide membranes supported on the ceramic hollow fibre for efficient H2 recovery Chinese J. Chem. Eng. 25 752–9
[90] Shen G, Zhao J, Guan K, Shen J and Jin W 2017 Highly Efficient Recovery of Propane by Mixed-Matrix Membrane via Embedding Functionalized GO Nanosheets into PDMS Am. Inst. Chem. Eng. J. 63 3501–10
[91] Wei N, Peng X and Xu Z 2014 Understanding water permeation in graphene oxide membranes ACS Appl. Mater. Interfaces 6 5877–83
[92] Zhang Y, Zhang S, Gao J and Chung T S 2016 Layer-by-layer construction of graphene oxide (GO) framework composite membranes for highly efficient heavy metal removal J. Memb. Sci. 515 230–7
[93] Hu X, Yu Y, Zhou J, Wang Y, Liang J, Zhang X, Chang Q and Song L 2015 The improved oil/water separation performance of graphene oxide modified Al2O3 microfiltration membrane J. Memb. Sci. 476 200–4
[94] Zhu Z, Wang L, Xu Y, Li Q, Jiang J and Wang X 2017 Preparation and characteristics of graphene oxide-blending PVDF nanohybrid membranes and their applications for hazardous dye adsorption and rejection J. Colloid Interface Sci. 504 429–39
[95] Ali M E A, Wang L, Wang X and Feng X 2016 Thin film composite membranes embedded with graphene oxide for water desalination Desalination 386 67–76
[96] Yuan Y, Gao X, Wei Y, Wang X, Wang J, Zhang Y and Gao C 2017 Enhanced desalination performance of carbonyl functionalized graphene oxide nanofiltration membranes Desalination 405 29–39
[97] Zhang J, Xu Z, Shan M, Zhou B, Li Y, Li B, Niu J and Qian X 2013 Synergetic effects of oxidized carbon nanotubes and graphene oxide on fouling control and anti-fouling mechanism of polyvinylidene fluoride ultrafiltration membranes J. Memb. Sci. 448 81–92
nanofiltration membrane for improving flux and anti-fouling in water purification RSC Adv. 6 82174–85
[99] Salehi H, Rastgar M and Shakeri A 2017 Anti-Fouling and High Water Permeable Forward Osmosis Membrane Fabricated via Layer by Layer Assembly of Chitosan/Graphene Oxide Appl. Surf. Sci. 413 99–108
[100] Kumar M, McGlade D, Ulbricht M and Lawler J 2015 Quaternized polysulfone and graphene oxide nanosheet derived low fouling novel positively charged hybrid ultrafiltration membranes for protein separation RSC Adv. 5 51208–19
[101] Safarpour M, Vatanpour V, Khataee A and Esmaeili M 2015 Development of a novel high flux and fouling-resistant thin film composite nanofiltration membrane by embedding reduced graphene oxide/TiO2 Sep. Purif. Technol. 154 96–107
[102] Vatanpour V, Shokravi A, Zarrabi H, Nikjavan Z and Javadi A 2015 Fabrication and characterization of anti-fouling and anti-bacterial Ag-loaded graphene oxide/polyethersulfone mixed matrix membrane J. Ind. Eng. Chem. 30 342–52
[103] Hegab H M, Wimalasiri Y, Ginic-Markovic M and Zou L 2015 Improving the fouling resistance of brackish water membranes via surface modification with graphene oxide functionalized chitosan Desalination 365 99–107
[104] Zambare R S, Dhopte K B, Patwardhan A V. and Nemade P R 2017 Polyamine functionalized graphene oxide polysulfone mixed matrix membranes with improved hydrophilicity and anti-fouling properties Desalination 403 24–35
[105] Ayyaru S and Ahn Y 2017 Application of sulfonic acid group functionalized graphene oxide to improve hydrophilicity , permeability , and antifouling of PVDF nanoporous ultrafiltration membranes J. Memb. Sci. 525 210–9
[106] Hu M and Mi B 2013 Enabling Graphene Oxide Nanosheets as Water Separation Membranes Environ. Sci. Technol. 47 3715–23
[107] Fang Q, Zhou X, Deng W, Zheng Z and Liu Z 2016 Freestanding bacterial cellulose- graphene oxide composite membranes with high mechanical strength for selective ion permeation Sci. Rep. 6 1–11
[108] Liu G, Ye H, Li A, Zhu C, Jiang H and Liu Y 2016 Graphene oxide for high-efficiency separation membranes : Role of electrostatic interactions Carbon N. Y. 110 56–61
[109] Fathizadeh M, Xu W L, Zhou F, Yoon Y and Yu M 2017 Graphene Oxide: A Novel 2-Dimensional Material in Membrane Separation for Water Purification Adv. Mater. Interfaces 4(5) 1600918
[110] Tan P, Sun J, Hu Y, Fang Z, Bi Q and Chen Y 2015 Adsorption of Cu 2+ , Cd 2+ and Ni 2+ from aqueous single metal solutions on graphene oxide membranes 297 251–60
[111] Tan P, Hu Y and Bi Q 2016 Competitive adsorption of Cu2+, Cd2+ and Ni2+ from an aqueous solution on graphene oxide membranes Colloids Surfaces A Physicochem. Eng. Asp. 509 56–64
[112] Choi W, Choi J, Bang J and Lee J 2013 Layer-by-Layer Assembly of Graphene Oxide Nanosheets on Polyamide Membranes for Durable Reverse Osmosis Applications ACS Appl. Mater. Interfaces 5 (23) 12510–12519
[113] Zhang Y, Zhang S, Gao J and Chung T S 2016 Layer-by-layer construction of graphene oxide (GO) framework composite membranes for highly efficient heavy metal removal J. Memb. Sci. 515 230–7
[114] Neelakandan S, Noel Jacob K, Kanagaraj P, Sabarathinam R M, Muthumeenal A and Nagendran A 2016 Effect of sulfonated graphene oxide on the performance enhancement of acid-base composite membranes for direct methanol fuel cells RSC Adv. 6 51599–608
[115] Oh K, Son B, Sanetuntikul J and Shanmugam S 2017 Polyoxometalate decorated graphene oxide/sulfonated poly(arylene ether ketone) block copolymer composite membrane for proton exchange membrane fuel cell operating under low relative humidity J. Memb. Sci. 541 386–92
[116] Jiang Z J, Jiang Z, Tian X, Luo L and Liu M 2017 Sulfonated Holey Graphene Oxide (SHGO) Filled Sulfonated Poly(ether ether ketone) Membrane: The Role of Holes in the SHGO in
Improving Its Performance as Proton Exchange Membrane for Direct Methanol Fuel Cells

ACS Appl. Mater. Interfaces 9 20046–56

[117] Kim B G, Han T H and Cho C G 2014 Sulfonated Graphene Oxide/Nafion Composite Membrane for Vanadium Redox Flow Battery J. Nanosci. Nanotechnol. 14 9073–7

[118] Aziz M A, Oh K and Shanmugam S 2017 A sulfonated poly(arylene ether ketone)/polyoxometalate-graphene oxide composite: High ion selective membrane for all vanadium redox flow battery Chem. Commun. 53 917–20

[119] Jiang Z, Zhao X and Manthiram A 2013 Sulfonated poly(ether ether ketone) membranes with sulfonated graphene oxide fillers for direct methanol fuel cells Int. J. Hydrogen Energy 38 5875–84

[120] Lue S J ., Pai Y-L ., Shih C-M ., Wu M-C . and Lai S-M . 2015 Novel bilayer well-aligned Nafion/graphene oxide composite membranes prepared using spin coating method for direct liquid fuel cells J. Memb. Sci. 493 212–23

[121] Sha Wang L, Nan Lai A, Xiao Lin C, Gen Zhang Q, Mei Zhu A and Lin Liu Q 2015 Orderly sandwich-shaped graphene oxide/Nafion composite membranes for direct methanol fuel cells J. Memb. Sci. 492 58–66

[122] Bayer T, Selyanchyn R, Fujikawa S, Sasaki K and Lyth S M 2017 Spray-painted graphene oxide membrane fuel cells J. Memb. Sci. 541 347–57

[123] Dai W, Shen Y, Li Z, Yu L, Xi J and Qiu X 2014 SPEEK/Graphene oxide nanocomposite membranes with superior cyclability for highly efficient vanadium redox flow battery J. Mater. Chem. A 2 12423

[124] Chien H C, Tsai L D, Huang C P, Kang C Y, Lin J N and Chang F C 2013 Sulfonated graphene oxide/Nafion composite membranes for high-performance direct methanol fuel cells Int. J. Hydrogen Energy 38 13792–801

[125] Bayer T, Bishop S R, Nishihara M, Sasaki K and Lyth S M 2014 Characterization of a graphene oxide membrane fuel cell J. Power Sources 272 239–47

[126] Beydagi H, Javanbakht M and Kowsari E 2014 Synthesis and characterization of poly(vinyl alcohol)/Sulfonated graphene oxide nanocomposite membranes for use in proton exchange membrane fuel cells (PEMFCs) Ind. Eng. Chem. Res. 53 16621–32

[127] Kumar R, Mamlouk M and Scott K 2014 Sulfonated polyether ether ketone – sulfonated graphene oxide composite membranes for polymer electrolyte fuel cells RSC Adv. 4 617

[128] Yin Y, Wang H, Cao L, Li Z, Li Z, Gang M, Wang C, Wu H, Jiang Z and Zhang P 2016 Sulfonated poly(ether ether ketone)-based hybrid membranes containing graphene oxide with acid-base pairs for direct methanol fuel cells Electrochim. Acta 203 178–88

Acknowledgments

Financial assistance for this work has been provided by Institut Teknologi Bandung under a scheme ‘Program Penelitian, Pengabdian, kepada Masyarakat, dan Inovasi (P3MI)’.