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Recent developments in membranes for efficient hydrogen purification

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ABSTRACT

Hydrogen has been extensively accepted as a clean and efficient energy carrier to alleviate the mounting global energy and environmental crisis. Therefore, an ever-increasing demand for high-quality hydrogen provides a strong driving force towards developing efficient hydrogen purification technologies. Membrane-based gas separation technology for hydrogen purification has attracted considerable attention owing to the inherent advantages over other conventional separation techniques. Benefited from the booming development of chemical science, materials science and membrane science, an increasing number of advanced membrane materials and membranes have been developed for hydrogen purification in recent years. This review primarily focuses on the latest developments in design and fabrication of H_2-selective membranes and CO_2-selective membranes for hydrogen purification, and the comparison of H_2-selective membranes and CO_2-selective membranes will be briefly discussed. In addition, future direction to further explore energy-efficient membranes for hydrogen purification will be presented for discussion. It is anticipated that the present review will provide the guidance for the future research and development of membrane materials and membranes for hydrogen purification, and hence promote the development of sustainable and clean hydrogen energy.

Contents

Abbreviations: WGS, water gas shift; AIPO, aluminophosphate; SAPO, silicoaluminophosphate; PES, polyethersulfone; APTES, 3-aminopropyltriethoxysilane; DIC-4, 1,4-diisocyanate; CPTMS, 3-chlropropylyrimethoxysilane; CCD, catalytic cracking deposition; MDES, methyldiethoxysilane; TEOS, tetraethylorthosilicate; CMS, carbon molecular sieve; OMs, oxometalates; POMs, polyoxometalates; PSf, polysulfone; PAN, polyacrylonitrile; PVDF, polyvinylidenefluoride; DOP, dopamine; PDA, polydopamine; LDH, layered double hydroxide; PI, polyimide; PBI, polybenzimidazole; 6FDA, hexafluorisopropylidene-diphtatic anhydride; TR-PBO, TR-polybenzoxazole; PAHs, poly(hydroxylamide)s; PAA, poly(acrylic acid); PEI, polyethylenimine; PMMA, poly(methyl methacrylate); PVP, poly(vinylpyrrolidone); SBI, sprobisindane; SBF, spirobifluorene; EA, ethanoanthracene; Trip, triptycene; TB, Troger's base; PAF, porous aromatic framework; PTMSP, poly(trimethylsilylpropyne); PMP, poly(4-methyl-2-pentyne); PEO, poly(ethylene oxide); PEG, poly(ethylene glycol); PEGDA, poly(ethylene glycol) diacrylate; PEGA, poly(ethylene glycol) acrylate; PEGMEA, poly(ethylene glycol) methyl ether acrylate; PEGDMA, poly(ethylene glycol) dimethacrylate; PEO–PI, PEO–polyimide; PEO–PA, PEO–polyamide; PEO–PBT, PEO–poly(butylene terephthalate); PEO–PTT, PEO–poly(trimethylene terephthalate); T6T6T, tetra-amide; PEO–PSf, PEO–polysulfone; PEG-DME, polyethylene glycol dimethyl ether; GTA, glycerol triacetate; PEG-DBE, polyethylene glycol dibutylether; TMC, trimesoyl chloride; DGBAmE, diethylene glycol bis(3-aminopropyl) ether; DAmPEG, diaminopolyethylene glycol; RTILs, room temperature ionic liquids; PILs, poly(ionic liquid)s; TSILs, task-specific ionic liquids; PVAm, polyvinylamine; PAAm, polyallylamine; PAMAM, polyamidoamine; EDA, ethylenediamine; PIP, piperazine; MEA, monoethanolamine; MC, methylcarbamate; PANI, polyaniline; POSS, polyhedral oligomeric silsesquioxane; MWNTs, multi-walled carbon nanotubes; HT, hydrotalcite

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1. Introduction

Sustainable and clean energy development has become a major global issue in terms of the world's energy shortage and environmental problem. However, fossil fuels are still expected to be the predominant resource of energy by preference in the near term (next 5–20 years or even more) despite that an increasing number of renewable energies have received considerable attention over the several decades. Therefore, it is of great importance and impendency to develop more efficient ways to utilize these limited fossil fuels for sustainable development. Hydrogen has been widely considered to be an attractive energy carrier and storage medium with high efficiency for developing a cost-effective, environmental-benign and sustainable energy system, because it possesses distinct advantages of high gravimetric energy density (1.43×10^8 J/kg) and low greenhouse gas emission [1]. In addition, hydrogen is an important feedstock with increasing demands for the chemical industries. Hence, about 53 million metric tons of hydrogen worldwide was produced annually, and the hydrogen market valued at $88 billion in 2010 [2].

So far, hydrogen production is dominated by thermochemical processes, and about 96% hydrogen is generated from fossil fuels. In these hydrogen production processes, synthesis gas production is an intermediate step, and CO in synthesis gas could further react with water vapor via the water gas shift (WGS) reaction for enhancing H_2 yield. The shifted synthesis gas mainly consists of H_2 and CO_2, along with some minor contaminants such as CO, H_2S and CH_4. Generally, H_2 content in shifted synthesis gas varies from 60 vol% to 80 vol%, which depends on the quality of feedstock and process conditions. Moreover, biohydrogen production such as dark fermentation is a very promising alternative method to generate hydrogen, even if it contributes very limitedly to global hydrogen supply nowadays [3]. Similar to conventional thermochemical processes, the hydrogen product generated by biotechnological technique also contains some impurities (mainly CO_2). The produced H_2-rich gaseous mixture via various aforementioned production techniques is considered as raw H_2 product. However, it is difficult for raw H_2 product to meet the demands for purity in most cases [4]. For example, high-purity hydrogen ($>$ 99.99 vol%) supply is a prerequisite for the success of fuel cell technology. Therefore, hydrogen purification is essential to satisfy the purity requirements of various potential applications, and it is an important issue for efficient hydrogen supply. Moreover, H_2–CO_2 separation is a key process in pre-combustion CO_2 capture for integrated gasification combined cycle (IGCC) power plants, even though the required hydrogen purity for subsequent electricity generation is generally lower than that of aforementioned applications [2]. It should be noted that hydrogen possesses a very low volumetric energy density despite its aforementioned advantages over conventional liquid fuels. Hence, hydrogen storage is vital for the widespread utilization of hydrogen as well as hydrogen purification [5].

As a relatively new and rapidly developing technology, membrane technology exhibits inherent advantages of energy-efficiency, cost-effective and environmental compatibility compared to conventional separation techniques. Moreover, membrane technology can be facilely coupled with other separation techniques to enhance the efficiency and economics of separation process. Nowadays, membrane technology has been widely used in water treatment, meanwhile it has also commercialized for air separation, natural gas sweetening and hydrogen recovery from ammonia purge gas [6]. With the rapid development of hydrogen economy and membrane science, membrane-based gas separation technology shows great potential for the hydrogen purification market as well. Great demands for high-quality hydrogen products provide the driving force for research and development of advanced membrane materials and membranes for hydrogen purification. Benefited from the remarkable progress in materials science over the past several decades, some conventional membrane materials have exhibited notably improved performances via structural optimization. In addition, an increasing number of advanced materials, such as metal organic frameworks (MOFs), graphene-based materials, thermal