Progress in Polymer Science 34 (2009) 62–98

Contents lists available at ScienceDirect

Progress in Polymer Science

journal homepage: www.elsevier.com/locate/ppolysci

Photo-irradiation for preparation, modification and stimulation of polymeric membranes

Dongming He[1], Heru Susanto[1,2], Mathias Ulbricht*,[1]

Lehrstuhl für Technische Chemie II, Universität Duisburg-Essen, 45117 Essen, Germany

ARTICLE INFO

Article history:
Received 7 December 2007
Received in revised form 17 August 2008
Accepted 22 August 2008
Available online 8 October 2008

Keywords:
Photo-irradiation
UV irradiation
Photo-polymerization
Photo-grafting
Polymeric membrane
Membrane preparation
Membrane modification
Stimuli-responsive membrane
Membrane separation

ABSTRACT

The recent developments in combining photo-irradiation-based and membrane technologies are analyzed in this review. It is emphasized that the effects of photo-initiated reactions onto properties of polymeric membranes will largely depend on the nature of the membrane's barrier (i.e., porous vs. non-porous, uncharged vs. charged, or involving affinity interactions). For *de novo* preparation of membranes from low molar mass or soluble precursors, photo-initiated polymerization and photo-cross-linking are the main pathways, while photo-degradation for pore formation is only rarely applied. Membrane functionalization (modification) is described with many examples, organized into photo-cross-linking of membranes and photo-grafting of membrane surfaces, either via "grafting-to" or via "grafting-from" routes. Photo-stimulation of barrier properties is an attractive concept to create stimuli-responsive membranes, and various ways to use photo-chromic moieties for that purpose are discussed. Overall, photo-irradiation-based methods can be very versatile enabling technologies to improve the performance of polymeric membranes in technical separations (e.g., in gas separation, pervaporation, ultra- and microfiltration or as membrane adsorbers) and other processes (e.g., for controlled release or in sensor systems), and they will definitely also contribute to the development of entirely novel membrane-based materials.

Abbreviations: AA, acrylic acid; AAm, acrylamide; ABMPEG, α-4-azidobenzoyl-ω-methoxy-PEG; AHBPE, aliphatic hyperbranched-polyester; BP, benzophenone; BSA, bovine serum albumin; BTDA, 3,3′,4,4′-benzophenone tetracarboxylic dianhydride; CB, Cibacron Blue F3GA; D, dialysis; DG, degree of grafting; DHB, dihydroxybenzophenone; DMFC, direct methanol fuel cell; EC, ethyl cellulose; ED, electrodialysis; EDMA, ethylene glycol dimethacrylate; EIPS, evaporation-induced phase separation; EO, ethyleneoxide; GMA, glycidyl methacrylate; GS, gas separation; HEMA, 2-hydroxyethyl methacrylate; HFP, hexafluoropropylene; LEDs, light-emitting diodes; MBAA, methylene bisacrylamide; MC, membrane contactor; MD, membrane distillation; MF, microfiltration; MIP, molecularly imprinted polymer; NF, nanofiltration; NIPAAm, *N*-isopropyl acrylamide; NIPS, non-solvent-induced phase separation; NVP, *N*-vinyl-2-pyrrolidone; PA, polyarylate; PAA, poly(acrylic acid); PAEK, poly(aryl ether ketone); PAN, polyacrylonitrile; PB, polybutadiene; PC, polycarbonate; PCEMA, poly(2-cinnamoylethyl methacrylate); PDMS, polydimetylsiloxanes; PDPO, poly(2,6-dimethyl-1,4-phenylene oxide); PE, polyethylene; PEC, poly(ethylenecarbonate); PEG, poly(ethylene glycol); PEGDA, poly(ethylene glycol) diacrylate; PEGMA, poly(ethylene glycol mathacrylate); PEO, poly(ethylene oxide); PEPP, poly[(4-ethylphenoxy)(phenoxy)phosphazene]; PES, poly(ether sulfone); PET, poly(ethylene terephthalate); PI, polyimide; PIs, polyisoprene; PMA, polymethacrylates; PP, polypropylene; PS, phase separation; PSf, polysulfone; PSt, polystyrene; P*t*BA, poly(*tert*-butyl acrylate); P*t*BMA, poly(*tert*-butyl methacrylate); PTFE, polytetrafluoroethylene; PV, pervaporation; PVA, poly(vinyl alcohol); PVC, poly(vinyl chloride); PVCin, poly(vinyl cinnamate); PVDF, poly(vinylidene fluoride); PVP, poly(2-vinyl pyridine); RO, reverse osmosis; SB, sodium benzoate; SPEEK, sulfonated poly(ether ether ketone); SPMMA, 1-[β-(methacryloyl)ethyl]-3,3′-dimethyl-6-nitro-spiro(indoline-2,2′-[2H-1]benzopyran); TIPS, thermally induced phase separation; *t*BIA, *tertiary*-butyl isophthalic acid dichloride; THO, theophylline; TMBPA, tetramethyl bisphenol-A; TMPD, trimethyl-1,3-phenylenediamine; TPMLH, bis-[4-(dimethylamino)phenyl] (4-vinyl-phenyl)methyl leucohydroxide; UF, ultrafiltration; VIPS, vapour-induced phase separation.

* Corresponding author. Fax: +49 201 183 3147.
E-mail address: mathias.ulbricht@uni-due.de (M. Ulbricht).

[1] These authors have contributed equally to this paper.

[2] On leave from: Department of Chemical Engineering, Universitas Diponegoro, Indonesia.

0079-6700/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.progpolymsci.2008.08.004

Contents

1. Introduction 63
2. Photo-irradiation and technologies based thereon 63
   2.1. General characteristics of photo-reactions 63
   2.2. Photo-reactions of/with polymers 65
3. Polymer membranes—state-of-the-art, needs and options for further improvements 66
   3.1. Membranes with non-porous barrier 68
   3.2. Membranes with porous barrier 68
   3.3. Porous membrane adsorbers 69
   3.4. Stimuli-responsive membranes 69
   3.5. Special membranes for integrated processes 69
4. Improved or novel polymer membranes by photo-irradiation-based methods or technologies 69
   4.1. Membrane preparation 70
      4.1.1. Photo-initiated polymerization 70
      4.1.2. Photo-cross-linking 73
      4.1.3. Photo-degradation 74
   4.2. Membrane modification (functionalization) 75
      4.2.1. Photo-cross-linking 76
      4.2.2. Photo-functionalization (“grafting-to”) 78
      4.2.3. Heterogeneous photo-initiated graft copolymerization (“grafting-from”) 81
   4.3. Membrane stimulation (switching barrier properties) 89
5. Conclusion and outlook 92
   References 93

1. Introduction

Photo-irradiation has a special role for life on earth because it serves as an important source of energy; photosynthesis is of crucial relevance for the global ecosystem. A more efficient use of solar energy is considered one of the key issues for sustainable development of mankind. Artificial sources of light have been used by men since very early days, and many more or less sophisticated versions are established nowadays. Light is used in information technologies for data transmission and storage. In many other technical applications, selective excitation with UV–vis irradiation is used to initiate chemical reactions which would not be possible via other pathways or which would be less efficient due to unwanted side reactions or effects. The synthesis, modification and controlled degradation of natural and synthetic polymers using photochemical methods are an important area.

Membranes are also essential for life; biological membranes form and define individual compartments on the cellular and sub-cellular levels. Any membrane is an interphase between two adjacent phases acting as a selective barrier and regulating the exchange of substances between the two compartments. Synthetic membranes are nowadays established for a large variety of applications, and many more are targets of intense research and development. The main advantages of membrane technology as compared with other unit operations in (bio)chemical engineering are related to the unique separation principle, i.e., the transport selectivity of the membrane. Separations with membranes do not require additives, and they can be performed isothermally at low temperatures and – compared to other thermal separations – at low energy consumption. Also, upscaling and downscaling of membrane processes as well as their integration into other separations or reaction schemes are easy. Membrane technologies are considered as key technologies for process intensification. The majority of technical membranes are made from polymers because a very wide variety of barrier structures can be realized with this group of materials.

It is the aim of this review to give an overview on the recent developments in combining photo-irradiation-based and membrane technologies. Because the rapid growth of membrane technologies has started only in the 1980s, there are only occasional papers on that topic in the earlier literature (and if so, more in side areas of membrane technology such as materials for coating, packaging or sensing). In agreement with the scope of this journal, we will focus on the work in the last decade. However, to our knowledge, such a comprehensive review on the topic has not yet been prepared before. Therefore, we will also include important examples from the earlier period. Brief introductions are given into the fields of photo-irradiation-based technologies (with focus on polymers; Section 2) and of polymeric membranes (with focus on concepts, preparation methods and functions of membrane systems; Section 3). The main part of this review is organized according to the three different ways, photo-irradiation can be used to create novel or improved membrane systems based on polymers (as already indicated in the title of this paper; Section 4). The conclusions part will also involve a brief outlook towards possible new developments in this interesting area (Section 5).

2. Photo-irradiation and technologies based thereon

2.1. General characteristics of photo-reactions

Photo-chemical reactions in the most general sense are reactions induced by ultraviolet ((= 100–400 nm), visible ((= 400–760 nm) and infrared ((= 780–20,000 nm) radiation [1]. In this review we will focus on photo-chemistry based on excitation with light of wavelengths in the range