Separation and Purification Technology 171 (2016) 191–196

Contents lists available at ScienceDirect

Separation and Purification Technology

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

Porous condenser for thermally driven membrane processes: Gravity-independent operation

A.V. Volkov *, E.G. Novitsky, I.L. Borisov, V.P. Vasilevsky, V.V. Volkov

A.V. Topchiev Institute of Petrochemical Synthesis, RAS, Moscow, Russian Federation

ARTICLE INFO

Article history:
Received 3 June 2016
Received in revised form 21 July 2016
Accepted 22 July 2016

Keywords:
Porous condenser
Membrane distillation
Thermopervaporation
Gravity-independent

ABSTRACT

New thermally driven processes configuration based on the porous condenser (instead of non-porous cooling plate) and using permeate as a coolant was suggested and successfully proven for two processes: (i) membrane distillation with porous condenser (MD-PC) tested for the desalination of model NaCl solutions of 5–40 g/l and (ii) thermopervaporation with porous condenser (TPV-PC) tested for the removal of *n*-butanol from its 1 wt.% aqueous solution. In both cases, the experiments were carried out at different orientations of the membrane module. No noticeable difference for MD-PC and TPV-PC performance, including the worst case scenario for conventional AGMD when the membrane was located horizontally under the air gap, was observed. In addition, in contrast to the conventional AGMD, stable MD-PC, and TPV-PC performance was demonstrated at extremely low air gap width of 0.1–1 mm. The water fluxes up to 21 kg/m^2 h and salt rejection higher than 99% were attained for MD-PC, and the total flux of 1 kg/m^2 h for TPV-PC separation of 1 wt.% butanol-water mixture was obtained which is comparable with the conventional vacuum PV. Potential applications for the new thermally driven processes such as space and marine can be identified.

1. Introduction

Temperature-driven membrane processes such as membrane distillation (MD), membrane crystallization (MC), pervaporation (PV) and thermopervaporation (TPV) gain increased attention during the last years since they are considered for some applications as a perspective and cost-effective alternative or preliminary stage for traditional separation processes [1–10]. The more volatile substances are separated from the initial solution by means of evaporation through the membrane followed by condensation of vapors on the other side of the membrane. The driving force for each component is determined by the partial pressure difference of the component due to the maintaining the process parameters in such a way that the initial solution (feed) is operated at higher temperatures, while the condensed liquid (permeate) is controlled at lower temperatures. Membrane distillation and membrane crystallization are realized by using porous membranes. The MD process selectivity is governed only by the vapor-liquid equilibrium resulted in the enrichment of the vapor phase by more volatile components (e.g. water). For aqueous media, to provide high vapor transport as well as the absence of the direct contact of feed and permeate solutions, the porous membranes should have sufficiently high porosity and hydrophobic surface properties. Typically, these are micro- or ultrafiltration membranes made of hydrophobic materials such as halogenated polymers or modified inorganic materials [1–3,11,12]. In pervaporation (PV) and thermopervaporation (TPV) processes, the additional selectivity to the vapor-liquid equilibrium is achieved by using the membranes with a dense selective layer, where the target component might have preferential sorption and/or diffusion through the membrane. PV and TPV processes can be utilized for separation of aqueous and organic mixtures, and, therefore, the membranes can be fabricated by using hydrophilic or hydrophobic polymers as well as inorganic materials [5–7,13,14].

Membrane distillation is mainly used for water desalination and waste water treatment. MD has a number of advantages over other membrane processes like nanofiltration, reverse osmosis or electrodialysis: (i) nearly 100% rejection for non-volatile compounds (e.g. inorganic salts) can be achieved, (ii) the water transport across the membrane is less affected by the salinity level, (iii) no additional chemicals are required for membrane cleaning. The most widely used configurations of MD are the direct contact membrane distillation (DCMD), where the both sides of membrane are in direct contact with the feed and permeate solutions, respectively, and the air gap membrane distillation (AGMD), where the

* Corresponding author.
E-mail address: avolkov@ips.ac.ru (A.V. Volkov).

http://dx.doi.org/10.1016/j.seppur.2016.07.038
1383-5866/

membrane inlet side is contacted with the hot feed solution and the cold surface of condenser is separated from the membrane outlet side by the air layer [1,2,15–20]. The highest water permeation can be achieved with DCMD due to the lowest mass-transfer resistance. However, this concept has some drawbacks like higher heat loss since the membrane cannot be considered as a good heat insulator, and risk of pores wetting during the operation resulted in the drop of the overall process selectivity. Since AGMD allows to overcome these problems, this concept is actively studied for further improvement of process efficiency [1,2,15,21,22].

Thermopervaporation method, first proposed by Aptel in 1976 [23], is still less investigated the mode of pervaporation separation. This process is similar to the AGMD method, but a non-porous membrane is used. Recently, the TPV process has attracted a keen interest as an effective energy-saving approach for the removal of bioalcohols from the fermentation broths [7,24–28]. Since the driving force is realized without applying of vacuum from the permeate side of the membrane, the non-condensable gasses dissolved in fermentation broth (namely, carbon dioxide and hydrogen) cannot negatively influence on the mass-transfer and operation cost in contrast to the conventional vacuum PV.

At the same time, thermally driven membrane processes with the air gap configuration such as AGMD and TPV have certain limitations in the module design and orientation. For example, the most studied membrane module configuration is the plate-and-frame one which has at least 5 inlet/outlet streams with a vertical orientation of membrane/condenser stacks that enables effective evacuation of the condensed liquid permeate from the cold surface of the condenser by gravity. In the 1980s, it was demonstrated [29,30] that the optimal thickness of air gap in AGMD should not exceed 1 mm to achieve a high water flux. However, such requirement is rather difficult to realize in the practice without the contact of the liquid permeate with the outlet side of the membrane. Analysis of the heat loss and heat transfer in the air gap during the removal of *n*-butanol from its aqueous solution by means of TPV indicated that the air gap width should not be lower than 2.5 mm to avoid partial filling of the air gap by the liquid permeate [7].

A certain progress in the increase of the vapor flux in AGMD mode can be achieved if the air gap is filled by porous media such as a mixture of the sand with deionized water [14]. Besides, the flat-sheet and hollow fiber porous membranes have been proposed as a porous condenser for different spacecraft applications such as the loop heat pump or gravity-independent porous membrane condensing heat exchanger for solid waste stabilization [31,32], and for the water vapor recovery from humidified waste gas streams [33,34]. Bearing these in mind and to overcome the problem of flooding of the air gap we have proposed in this study: (i) to introduce the porous condenser instead of a conventional non-porous cooling plate and (ii) to use liquid permeate as a coolant. The coolant/permeate pump is placed after the membrane module that provides a certain lowering of the pressure in the coolant circuit of the module and, hence, effective evacuation (soaking) of the condensed liquid permeate from porous condenser surface into the coolant circuit (see Fig. 1). The overpressure in the feed compartment is maintained by placing of the feed liquid pump before the membrane module.

This publication is devoted to the application of porous condenser for two temperature driven processes, namely, membrane distillation and thermopervaporation. Porous poly(tetrafluoroethylene) (PTFE) and non-porous poly[1-(trimethylsilyl)-1-propyne] (PTMSP) membranes were selected as widely used membranes for MD and PV/TPV applications, respectively. The performance of the new module design by using the porous condenser was evaluated for desalination of model NaCl solutions by MD and recovery of *n*-butanol from its aqueous solutions by TPV.

2. Experimental part

2.1. Membrane distillation with porous condenser (MD-PC)

MD-PC experiments were carried out by using the laboratory set-up represented in Fig. 2. The membrane module with an active surface area of 96 cm^2 was equipped with porous PTFE membrane (Gore & Associated Co) and porous condenser made of sintered stainless steel (supplied by VMZ-Techno, Russian Federation; thickness – 200 μm; porosity – 30%). The air gap width was varied in the range of 0.1–1 mm by using the polymeric spacer of appropriate thickness. To simulate the salinity of the brackish water, and Baltic and the Red Sea, three model solutions containing 5, 10 and 40 g/l of NaCl in distillate water, respectively, were used as the feed. The hot solution of NaCl (feed) with an initial volume of 1 l was circulated with the constant flow rate of 0.6 l/min through the membrane compartment of the module at the temperature of 50–80 °C. Distilled water of 1 l was initially taken as a coolant and circulated with the constant flow rate of 0.3 l/min through the porous condenser compartment of the module at the temperature of 25 °C. The salinity of liquid streams was controlled by measurement of specific electrical conductivity. The total flux across the membrane was calculated from the mass balance by weighing of the feed and permeate flasks.

2.2. Thermopervaporation with porous condenser (TPV-PC)

The same laboratory set-up described above (see Fig. 2) was used for TPV-PC experiments except that porous PTFE membrane was replaced by dense PTMSP membranes with the thickness of about 9 μm. The membranes were fabricated by casting of 1 wt.% of PTMSP (purchased from Gelest, USA) in chloroform onto cellophane at room temperature. The air gap width was set as 1 mm. The hot solution containing 1 wt.% of *n*-butanol in distillate water with an initial volume of 1 l was circulated with the constant flow-rate of 0.3 l/min through the membrane compartment of the module at the temperature of 60 °C. Equilibrium water-rich phase (approx. 7.5 wt.% of *n*-butanol in water) of 0.5 l was initially taken as a coolant and circulated with the constant flow-rate of 0.3 l/min through the porous condenser compartment of the module at the temperature of 10 °C. The total flux was measured by weighing of the feed and permeate flasks with checking the mass balance. Because of the phase separation, the permeate composition was analyzed by using gas chromatography (Crystallux-4000M, TCD detector) after prior dilution by the distillate water to achieve one phase mixture.

3. Results and discussion

3.1. Membrane distillation with porous condenser (MD-PC)

To verify the proper performance of the porous condenser, it was first placed in the membrane module made of transparent housing and the gas chamber (air gap) was filled with distillate water. As expected, the water was soaked through the porous condenser as soon as the liquid pump was turn on. Thus, the liquid which might appear in the air gap of MD-PC as a result of, for example, improper launching, operation or shut down of the system will be automatically removed to the coolant circuit without dissembling of the membrane module. The performance of porous condenser in membrane distillation process was examined by carrying out the identical experiments with different orientations of the membrane module.

The typical distance between the membrane and cooling plate in conventional AGMD cannot be lower than few millimeters in