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Review

Vacuum membrane distillation processes for aqueous solution treatment—A review

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ABSTRACT

The current applications of vacuum membrane distillation (VMD) process for various industrial aqueous solutions have been thoroughly reviewed. The applications of VMD can be grouped into three major processes: the single component transport process, the binary component transport process and the multicomponent transport process. The porous and hydrophobic membrane in the VMD system serves as a physical support for the liquid–gas interface and does not allow one of the phases to disperse into the other. The membrane provides an efficient separator for the phase-change process. The use of the correct membrane can offer a high production rate and a high separation factor at low temperatures. VMD, an alternative separation technology with applications in desalination, concentration, organic extraction and dissolved gas removal, can compete with conventional liquid–gas separation systems. The present paper critically reviewed VMD technology; the important components of the scope of this review included applications and processes, membrane modules, heat and mass transfer, model development, membrane, process conditions, fouling, energy consumption and production cost. Finally, the potential for future research as a requisite for VMD industrialisation was suggested.

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1. Introduction

An aqueous solution system can be found in surface water, groundwater and wastewater. Both hydrophilic and hydrophobic substances such as salts, acids, bases, organics, inorganics and gases dissolved in water to form the aqueous solutions. For the purpose of sustainable development, many treatment technologies have been invented to separate the water or the valuable substances from the solutions for reuse. The treatment technologies include thermal techniques (e.g., multistage flash distillation, multi-effect distillation, vapour compression, etc.), adsorption, biological process, coagulation and flocculation, oxidation by ozone, chlorination and aeration. However, these technologies possess a lot of environmental, economical and operational problems such as high energy consumption and cost, high demand on mechanical parts and chemicals, complexity of the systems, treatment efficiency depends on the quality of the feed solution and spoilage of valuable substances under high temperature treatments.

Recently, membrane distillation (MD) has gained an increase attention in the aqueous solution treatments because the MD has fulfilled the requirements of process intensification [1,2]. The process intensification is defined as an approach to develop novel apparatuses and techniques that, compared to the traditional ones, leads to a substantially shrinking equipment size, reducing energy consumption, boosting plant efficiency, or minimising waste production, which eventually resulting in smaller, cleaner, more energy efficient and higher productive technologies [2,3]. As compared with the pressure-driven membrane processes (i.e., microfiltration, ultrafiltration, nanofiltration and reverse osmosis), the MD is safer, more efficient process in removing non-volatile components and requires lower operating pressure which interprets to lower equipment costs and increased process safety [4].

The MD process is a separation process where vapour(s) are thermally driven through a porous hydrophobic membrane. The MD can be divided into four types of configurations: (i) direct contact MD (DCMD), with the downstream side of the membrane in contact with cold water; (ii) air gap MD (AGMD), with the downstream side of the membrane in contact with stagnant air associated with a cold plate; (iii) sweeping gas MD (SGMD), with the downstream side of the membrane swept by an inert gas; and (iv) vacuum MD (VMD), with the downstream side of the membrane maintained under vacuum conditions or under low pressure. The four types of MD have a similar way of feeding the solution to the upstream side of the membrane, but the MDs have different ways of condensing the vapour(s) on the downstream side of the membrane.

The objective of this paper is to review the performance of the VMD technology in treating various aqueous solutions. The important scopes including the applications, membrane modules, heat and mass transfer, mathematical modelling, membranes, process conditions, fouling, energy consumption and production cost. The discussion concludes with consideration of the future directions of VMD.

2. VMD process for various aqueous solutions

The fundamental idea of the VMD separation process can be understood from Fig. 1. An aqueous feed solution is brought into direct contact with the upstream side of the porous hydrophobic membrane. The downstream side of the membrane is maintained under vacuum conditions. The hydrostatic pressure of the feed solution must not exceed the ‘liquid entry pressure of water (LEP_w)’ of the membrane and vapour–liquid (V-L) interfaces are formed at the entrances of membrane pores. Warming the feed solution allows the water evaporates at the V-L interfaces due to the heat of vaporisation. Such process configuration creates a driving force, i.e., the vapour pressure difference between the upstream side and the downstream side of the membrane.

The parameters to assess the VMD separation performance can be expressed in several ways. The most important parameter is the flux. The experimental flux (J) can be expressed as follows:

$$J = \frac{m_p}{A_m t} \tag{1}$$

where m_p, A_m and t are the mass of the permeate, membrane area and operation time, respectively.

For non-volatile solutes dissolved in the aqueous solutions, the solutes are possible to be rejected during the separation process. The rejection (R) of the non-volatile solutes can be obtained as follows:

$$R = \frac{c_f - c_p}{c_f} \times 100 \tag{2}$$

where c_f and c_p are the concentration solute in the feed solution and the permeate, respectively.

When volatile components such as volatile organic compounds (VOCs) dissolved in the aqueous solutions, the effectiveness of the