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How to select the optimal membrane distillation system for industrial applications

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ABSTRACT

Despite increasing academic interest in membrane distillation systems, industry adoption of the technology remains low. We propose a simple yet comprehensive method for selecting the optimal membrane distillation design for any industrial process. This flexible, system level analysis procedure yields a holistic view of the technology, which could help identify promising industries for commercial MD systems. The method consists of comparing membrane distillation designs on the basis of their total water production cost. Membrane distillation configuration, module type, heat exchange arrangement, operating conditions, and membrane properties all influence the total cost of the system. To illustrate our methodology, we apply the analysis procedure to a case study, optimizing the MD system design for an MD unit coupled to a condenser of a steam power plant. The total water production cost for the optimized system is \$2.11 per cubic meter of permeate with current commercial membranes or \$1.58/m^3 with improved membrane material.

1. Introduction

Membrane distillation technology has been proposed as a method to improve the performance of many diverse industrial processes, yet industry adoption remains low. On Web of Science (www.webofscience.com), over 1400 papers are listed which contain “membrane distillation” in the title. Of these, 55% were published in the last five years (2013–2017), with 400 articles from 2016 and 2017 alone. These publications propose a wide variety of applications of membrane distillation systems, including desalination, concentration of solutions (brines, fruit juices, acids, proteins, radioactive components, etc.), separation of mixtures, recovery of oil and gas produced water, removal of heavy metals and dyes, and wastewater treatment [1–5]. A review of the trends in recent membrane distillation publications (“growth phase”) classified MD applications into six main categories: desalination (48%), wastewater treatment (17%), non-food chemical processes applications (13%), brine concentration (11%), food industry (4%), and others (7%) [6]. The benefits of membrane distillation systems include 100% theoretical rejection of all non-volatile components, low operating pressures, and the ability to utilize low quality thermal energy [1]. Despite these advantages and the array of potential uses of membrane distillation systems, large-scale MD installations are limited to a handful of research projects funded by the European Commission: SMADES (2003), MEMDIS (2003), MEDESOL (2006), MEDINA (2006), MEDIRAS (2008), various pilot plants with a maximum capacity of 5 m^3/day, and a few demonstration or small commercial plants (10–400 m^3/day) [4,6,7]. Frequently cited barriers to commercialization include: low permeate flux, high thermal energy requirements, flux decay due to concentration and temperature polarization effects, uncertain economics and long term performance, and a lack of specifically designed membranes and modules for MD [3–5,8,9]. In order to gain industry acceptance, it is necessary to better understand the pros and cons of membrane distillation technology, and to quantify the value that an MD unit could provide when incorporated into an existing industrial process.

To quantify the value of a membrane distillation system in a specific industrial application, process engineers need to use a holistic approach. The highly specific nature of most recent MD publications does not facilitate easy comparison of the costs and benefits of different system designs. A majority of recent MD papers address one of the following five research areas: the development of novel MD membranes, MD process performance and optimization, process intensification or hybrid systems, fouling and wetting of MD membranes, or heat and mass transfer modeling in MD [6]. However, system performance in these focused analyses is not uniformly reported. A recent review article lists 40 different criteria which have been used to evaluate various aspects of membrane distillation systems [10]. While interesting from a scientific perspective, this lack of a unified evaluation

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standard renders comparisons between different membranes, module types, or operating conditions difficult. For major infrastructure projects, the European Commission recommends measuring all the benefits and costs of a project in “money terms” [11]. However, membrane distillation systems are rarely compared on the basis of their economics, and when cost values are reported, these are often only the cost of the MD unit itself and not the cost of the overall process. We propose a simple methodology for comparing different membrane distillation systems, whereby process engineers select the optimal MD design for an industrial process based on a comparison of the overall project economics.

2. Methodology

There are five principal criteria which affect the overall economics of a membrane distillation system: membrane material properties, MD configuration, module geometry, heat exchange arrangement, and operating conditions. Detailed descriptions of each of these factors are given in other books and reviews [1–5,7,12]. The objective of this paper is to show how the total water production cost (WPC) can be used to select the optimal combination of parameters for any industrial application of MD.

2.1. Overview

The method for selecting the optimal MD system design is illustrated in Fig. 1. We began by assuming constant membrane material properties, then iteratively calculating the system size and flow rates of different combinations of MD configurations, module types, heat exchange arrangements, and operating conditions. The total water production cost was calculated from these technical parameters, and the system with the lowest WPC was selected as the optimal design. The final water production cost was determined by optimizing the membrane material properties. The allowable range of operating conditions will vary for each specific process. All calculations were performed in Engineering Equation Solver (EES, see SI1 for details).

2.2. Performance model

The feed and coolant mass flow rates, permeate production rate, membrane area requirements, and pump work were calculated for each combination of MD configuration, module type, heat exchange arrangement, and transmembrane temperature difference. Simple thermodynamic relations are utilized to determine the temperature, pressure, enthalpy, and entropy of each node in the process. Steady state conditions are assumed for all models, and both the feed and coolant streams are recirculated. All properties of pure water were calculated using the built-in library of thermodynamic properties in EES. Properties of salt water were taken from the correlations developed by Nayar and Sharqawy [13,14]. The brine correlations are valid for a range of 0–120 g/kg salt concentration. Temperature polarization effects are estimated using standard Nusselt correlations (see SI2).

2.3. Cost model

The results of the performance model are used to estimate the water production cost of each MD system design. The WPC is defined as the total cost per cubic meter of permeate produced by the membrane distillation system. We estimate the water production cost, WPC ($\$/\mathrm{m}^3$ permeate water) by use of the annuity method, amortizing the capital expense into a fixed annual cost:

$$WPC = \frac{a(1+f_{ind})DC + AC}{\dot{V}_{p,year}}, \tag{1}$$

where DC is the sum of the total direct costs, AC is the sum of the total annual operating expenses, f_{ind} is the indirect cost fraction, $\dot{V}_{p,year}$ (m^3/year) is the total annual volume of permeate produced, and a is the capital recovery factor, estimated from the interest rate, i, and the life of the system, n (year) as follows:

$$a = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

The specific terms to be included in the calculation of the capital and operating costs will depend on the industrial process.

2.4. Membrane properties

As the objective of this method is to select the optimal MD system for large-scale applications, only commercially available membranes are considered. The properties of the commercial polymeric microfiltration membranes used for membrane distillation were compiled from the literature [1,5,7,15,16]. Two different structures of membranes have been used in membrane distillation: flat sheet and cylindrical. Cylindrical membranes are typically divided into three categories, differentiated by their internal diameter: “hollow fiber” membranes have internal diameters of less than 0.5 mm, “capillary” membranes have diameters in the range of 0.5–6 mm, and “tubular” membranes have diameters larger than 6 mm. Most commercial MD membranes may be classified as capillary membranes. Henceforth, all cylindrical membranes will be referred to as capillary membranes. Table 1 summarizes the range and average value of each membrane property. A full list of commercial membranes is included in SI3.

3. Case study

In order to demonstrate the application of the preceding methodology we optimized the design of a membrane distillation system coupled to the condenser of a steam power plant. This represents only one example of an integrated membrane distillation process; however, analysis of this scenario allows us to demonstrate the application of the proposed method.

3.1. Process description

A schematic of the proposed integrated system is shown in Fig. 2. The membrane distillation unit is inserted between the condenser and

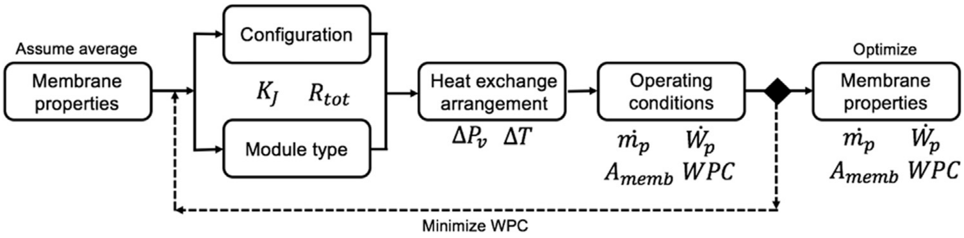

Fig. 1. Process flowchart for calculation of the WPC. The dotted line indicates an iterative procedure. The combination of MD configuration, module type, heat exchange arrangement and operating condition which yields the lowest WPC is selected as the optimal. Membrane properties are optimized separately.

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