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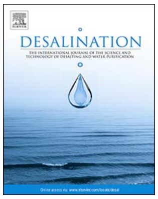

Techno-economic comparison of membrane distillation and MVC in a zero liquid discharge application

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ABSTRACT

Membrane distillation (MD) is a thermally driven membrane process for the separation of vapour from a liquid stream through a hydrophobic, microporous membrane. However, a commercial breakthrough on a large scale has not been achieved so far. Specific developments on MD technology are required to adapt the technology for applications in which its properties can potentially outshine state of the art technologies such as standard evaporation. In order to drive these developments in a focused manner, firstly it must be shown that MD can be economically attractive in comparison to state of the art systems. Thus, this work presents a technological design and economic analysis for AGMD and v-AGMD for application in a zero liquid discharge (ZLD) process chain and compares it to the costs of mechanical vapour compression (MVC) for the same application. The results show that MD can potentially be ~40% more cost effective than MVC for a system capacity of 100 m^3/day feed water, and up to ~75% more cost effective if the MD is driven with free waste heat.

1. Introduction

Membrane distillation is a thermal separation process which normally operates between 30 and 80 °C [1,2,3] and can distill fresh water from wastewater. As the name suggests, membrane distillation uses hydrophobic membranes and a driving force temperature gradient (even capable of using low grade waste heat) [4] to bring about the evaporation of water. Since the issuing of the first MD patent by Bodell in 1963 [5], the utilization of membrane distillation has been investigated for a large variety of applications such as food and beverage processing [6,7,8,9], concentration of sucrose solutions [10] textile industry effluent recycling [11,12], municipal waste water treatment [13,14], medical applications [15,16], removal of volatile organic compounds [17] or even treatment of radioactive wastewater solutions [18]. However, throughout the last 5 decades, the most common application has been desalination with a consensus amongst the community that *brine concentration* holds the highest potential within the scope of desalination for MD technology as presented in a systematic map review and survey by [19]. The potential of MD in desalination applications is shown in the progress of the more commercially orientated works targeted at MD module development and piloting [20,21,22].

However, a commercial breakthrough on a large scale has not been achieved so far. The barriers for entering into existing markets are high with state of the art reverse osmosis (RO) and evaporation technology to compete against, in regard to cost effectiveness and process reliability. Triggered by increasingly strict environmental policies regarding the management of liquid effluents from various kinds of industrial processes, technologies are needed that can concentrate liquid discharge up to a near saturation level. Here, state of the art technology runs into limitations (high pressure in RO and corrosion in evaporators) that MD does not encounter due to the vapour pressure driven nature of the process and the polymeric materials used, thus providing a unique market opportunity and driver for the commercialization of the technology as a process step in low or zero liquid discharge (ZLD) chains [1].

Zero liquid discharge (ZLD) is a term that has gained quite a lot of attention in the past decade; first in the United States of America, followed by China, India and the rest of the world. ZLD is an ideal process where no liquid discharge leaves the plant boundary eliminating any kind of wastewater discharge and meeting environmental regulations [23]. However, the conventional thermal ZLD schemes practiced all over the world are fairly expensive; sometimes more than the main processing plant which has urged many to look for alternatives. ZLD

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also should lead to recovery of water as water as a resource is becoming scarce on the one hand and its demand in the industrial sector is increasing on the other. In a constant struggle to reduce costs, minimizing use of resources and meeting environmental regulations in the process industry, installing a ZLD system might not seem like a correct choice to all industry owners; especially to those with smaller industries. Clearly there has to be a new strategy or technology to make this sustainable option economically viable. Membrane distillation (MD) is a currently trending and rapidly developing unique process that can be used to treat saline wastewater. It can concentrate wastewater until near saturation [24], utilize waste heat [20], is made of polymers and can recover water, which makes it a technology worth investigating, techno-economically.

The objective of this paper is to present a techno-economic analysis to determine if membrane distillation is a conceptually solid as well as an economical fit in the zero liquid discharge scheme of processing. Usually zero liquid discharge employs a brine concentrator (mechanical vapour compression evaporator) [23] to concentrate the wastewater to near saturation with the help of thermal/electrical energy before it can be sent to the final step of the process. Brine concentrators being robust, they are also notorious for being very expensive, usually because of the use of high grade metals and a compressor [23,25,26]. Undoubtedly, the brine concentrator recovers water (60–90%), but since a majority of them use electrical energy [3] (as opposed to steam driven), for a lower energy consumption, as their main source of energy to drive a compressor, it limits the application where waste energy such as waste heat could be utilized.

Membrane distillation (MD) certainly uses thermal energy but since it functions at not > 85 °C, and is made of polymers it holds great potential to fulfilling conditions of waste heat utilization while being economical. Although attempts on full scale cost analyses to compare MD and brine concentrators have been done before, they have not done enough justice to MD module and system design [25] one of the reasons being that the variant of MD (direct contact membrane distillation) mostly chosen in literature [25] is not always optimal for the application in the manner the research is conducted due to for example its higher sensitivity to the impact of driving force reduction through the impact of salt a topic well discussed by [27] along with other recommendations on selecting the appropriate channel configuration and membrane for different applications. Thus, this work aims at providing a techno-economic answer to whether choosing a ZLD scheme for an industrial wastewater treatment with MD as a component by substituting the brine concentrator is beneficial or not; which implies designing MD modules for such application with a full scale cost analysis for both technologies.

As energy in the form of heat or electricity and water are the most extensively used resources common to a majority of industries, reducing the use of water and energy at the source or, utilizing waste streams of energy such as waste heat in order to recover water would paint a better economic picture for any industry.

2. Methods

In order to make the analysis as realistic as possible a module design and subsequently a system design was simulated with a set-up which has been validated through various experimental, bench scale and field tests [28]. Within the module and system design, module types were simulated that are currently producible and have been tested in a lab environment as minimum requirement. Cost calculation methods were applied after the system design and are described in the following sections.

2.1. Cost calculation methods

To evaluate the costs and compare all systems, the total costs were divided into capital expenditure (CAPEX) and operating expenditure (OPEX) and then analyzed as total costs over fixed plant life times; to facilitate this, a cost calculation sheet was developed in Microsoft Excel. In order to obtain valid CAPEX and OPEX values for comparison, figures were obtained from literature and researched from various vendors and manufacturers of MVC systems. MD costing was conducted based on actual figures and realistically developed degression curves for upscaling. From this data CAPEX, OPEX and return on investment (ROI) values are derived for comparison of MD and MVC for three different capacities of wastewater to be treated per day. The cost figures are given in the currency EUROS.

Table 1
Description for the distribution of CAPEX costs.

No.	Type of cost	Description
1	Major process equipment	Includes major equipment, example MVC unit or MD modules
2	Piping and other equipment	Includes auxiliary equipment such as heat exchangers, pumps etc. as well as piping system
3	Electrical and instrumentation	Includes all measuring, controlling instruments, and electrical system
4	Engineering	Costs for performing engineering design
5	Installation	Costs for installation on site

2.1.1. Capital expenditure

The capital costs can be defined as the fixed, onetime expenses that incur through purchase of equipment, or construction, buildings etc. used in the production of goods. This capital or fixed cost (C_{CAP}) can be divided for both the technologies into categories shown in Table 1:

The total (or individual) capital costs will be calculated as an amortized capital expenditure with an assumed practical interest rate as follows:

$$Amortised\ CAPEX = C_{CAP}\left[\frac{i\,(1+i)^n}{(1+i)^n-1}\right] \tag{1}$$

where i is the interest rate and n is the expected plant life in years [29]. In this work, an effective interest rate of 4% and plant life expectancies of 2, 4, 7 and 20 years are assumed [30]. As real time vendor data is difficult to obtain, some of the sub costs in the list above are assumed as a fraction of the major equipment cost based on references available in literature for the specific systems. The estimation of major process equipment cost is decisive as it represents the major share of the CAPEX; these costs were evaluated/acquired based on literature as well as input from vendors. The capacity method was used to estimate costs wherever specific data for the required capacity was not. It is given by:

$$C = C_{ref}\left(\frac{K}{K_{ref}}\right)^m \tag{2}$$

where C and K are the cost and capacity respectively of your equipment; C_{ref} and K_{ref} are the reference cost and capacity values from a valid reference data and m is the degression coefficient (also known as cost capacity factor) which is used in order to accommodate the economy of scale. For example, the degression coefficient for a salt water resistant heat exchanger is assumed to be 0,8 and was adopted from [28]. Some reference costs for MVC units, in literature, have been estimated five to ten years ago which requires them to be updated to current year. This has been done by cost indexes (based on the availability of cost index for the latest year); the one used in this paper is the ‘chemical engineering plant cost index (CEPCI)’. It is given by:

$$C = C_{ref}\left(\frac{Cost\ index\ at\ present\ year}{Cost\ index\ when\ estimated}\right) \tag{3}$$

For cost evaluation of MD modules, the input was based on information provided by SolarSpring GmbH, Freiburg. Cost estimation for MD modules will be discussed in Section 5.1 Capital expenditure