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Membrane and spacer evaluation with respect to future module design in membrane distillation

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HIGHLIGHTS

- Membranes with a high pore size to thickness ratio showed the highest flux.
- Spacers with a high mean mesh size to thickness ratio showed good results in terms of pressure drop.
- Increasing the filament angle leads to an increase in the pressure drop.
- The thickness of a spacer is not important for the achievable heat transfer to the membrane.

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ABSTRACT

In the case of membrane distillation (MD), the membrane is the core component, but in a full-scale module a spacer is also required in the flow channel. It is increasing mixing and thus the heat and mass transport to the membrane. In this work commercially available membranes and spacers for full-scale module design are evaluated. Special attention is paid to the pressure drop and the heat transfer properties of different spacers. It is shown that MD modules need to be operated in a different flow regime than other membrane processes due to pressure drop limitations. Especially spacers with a high mean mesh size as well as spacers with a high mean mesh size to thickness ratio $\overline{l_m}/\delta_S$ show good results. Pressure drop and heat transfer characteristics are combined in order to assess the most suitable spacer. For the evaluation of the membranes, Liquid Entry Pressure (LEP) and flux are measured. It is confirmed that membranes with a low pore size show high LEP values. Furthermore, it can be shown that membranes with a high pore size d_M to thickness δ_M ratio showed the highest flux.

1. Introduction

Water can be considered as one of the most important resources on earth. Especially freshwater is needed for various reasons, e.g. as nutrient for humans and animals, in agriculture, for washing and cleaning, as heat exchanging medium in industry and as a resource for the production of various products.

Unfortunately, only a small amount of water on earth is freshwater and in addition easily accessible. Therefore, seawater is desalinated for >150 years already [1]. Energy efficiency plays an important role for desalination technologies. One way to meet energy requirements is to improve existing technologies; another way is to work on new technologies. Membrane distillation is a separation process that is well-known for several years already [2]. It's combining a thermal separation with membrane technology resulting in an efficient hybrid process.

Waste heat can be used to run the membrane distillation as long as a temperature difference can be guaranteed. So far only few practical implementations of MD for desalination on an industrial scale are known [3]. Its application is not only limited to desalination but could be extended to other industrial fields as well. In the context of an industrial research-cooperation the application of membrane distillation in the field of seawater desalination is widely investigated. So far, commercially available technologies for seawater desalination are either thermal or membrane processes. Both of these technologies have certain disadvantages. The membrane process reverse osmosis (RO) needs to overcome the osmotic pressure which is increasing with the

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salinity of the feed medium [4,5]. Known evaporators need to have a large number of stages and therefore a high space demand in order to run at a low thermal energy demand [6].

Membrane distillation modules have already been built and evaluated by some research groups [7–11]. However, only in few cases the selection of materials was done under the aspect of performance optimization. In existing MD modules normally membranes designed for other applications like microfiltration are used because their properties enable the use for MD as well. On laboratory scale membranes were especially produced for the needs of MD, e.g. [3,12], but these ones are not available in sufficient quantity for module fabrication and thus not considered here. Membranes are evaluated in terms of flux which is characterizing process performance and in terms of Liquid Entry Pressure (LEP) which is assessing its suitability in full-scale module design. These parameters are necessary to know in order to design the module and choose a spacer depending on the possible pressure drop. Therefore, for full-scale module design characteristics of both membrane and spacer have to be known and matched.

1.1. State of the art

In previously published works the pressure drop in spacer-filled channels for processes like reverse osmosis or ultrafiltration (UF) has been widely investigated [13–17]. Although findings from these applications can be applied to some extent to MD processes as well, in MD there are pressure drop limitations that one has to pay more attention to. Here, the LEP of a membrane plays an important role and besides the mechanical stability is limiting the acceptable pressure drop over the total channel length. The LEP is of no interest in the other membrane processes named above where pressure drop measurements were carried out. Pressure drop evaluations of spacer-filled channels in MD so far are only rarely published [18].

It was found that there are various publications on mass transport enhancement using spacer-filled channels in MD [19–22] but only some of these are taking a closer look into the influence of the spacer on the heat transfer coefficient which is causing the mass transport enhancement effect. In addition none of these publications is combining its results with pressure drop measurements. A spacer with a high mass transport enhancement while having an extraordinary pressure drop wouldn't be efficient. This is what makes it important to know both, the pressure drop and the mass transport enhancement effect of a spacer used in full-scale MD modules.

The generated pressure drop is dependent on the flow velocity and the channel length. As the channel length of a laboratory set up is usually short, the flow velocity can be increased without a noticeable pressure drop. Therefore, in laboratory scale flow velocities in a short channel set up are not as limited as in full-scale modules. In full-scale modules, the channel is usually significantly longer so the pressure drop can become noticeable already at low flow velocities. Therefore, in regards of the later module design appropriate flow velocities should be chosen carefully already in laboratory scale experiments when evaluating MD performance. Flow velocities that cannot be achieved in full-scale modules due to pressure drop limitations should only be considered conditionally for evaluation in a laboratory scale set up.

The objective of this study is to find a more suitable membrane and spacer than the ones that are used so far for full-scale spiral wound modules. The spacer should enable a higher heat transfer coefficient with a comparable or even lower pressure drop. Therefore, the authors propose to combine heat transfer investigations with a pressure drop evaluation. A membrane is considered as more suitable when a higher flux is achievable at a comparable LEP. Overall, the influence of parameters such as thickness, mesh size, hydraulic diameter and filament angle of spacers and membrane thickness and pore size shall be evaluated. Where possible, general rules will be derived.

Findings of this material evaluation will help to design new spiral wound MD modules which will be operated in a pilot plant installed on board a cargo ship. The pilot plant will desalinate seawater by means of membrane distillation using waste heat from the cooling water system of the diesel engine at temperatures below 90 °C.

1.2. Membrane distillation technologies

In MD the driving force is a partial pressure difference over the hydrophobic micro porous membrane which is induced by a temperature gradient. Different configurations of MD exist named direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), vacuum membrane distillation (VMD) and sweeping gas membrane distillation (SGMD). Publications describing different configurations of MD are given by Lloyd and Lawson [23–25] and Drioli [26].

DCMD is the simplest channel configuration of MD. An evaporator channel containing the hot feed water is separated by the membrane from the condenser channel containing the permeate. Due to the hydrophobic properties of the membrane, water is prevented from entering the membrane pores whereas the water vapor is able to pass the membrane. The principle is shown in Fig. 1. T_e and T_c are the bulk stream temperature of the evaporator and condenser channel, respectively. The surface temperatures at the membrane are T_1 and T_0 with the corresponding partial pressure $\hat{p}_1$ and $\hat{p}_0$ of the fluid.

1.3. Module design

Modules used for membrane distillation consist of either a flat sheet membrane or a hollow fibre membrane whereas the flat sheet membranes can be used in the form of plate-and-frame or spiral wound modules. Reviews [3,27] give an overview on MD technology and module configuration. In this study the focus is on the flat sheet membranes used in spiral wound MD modules. As a reference, membrane and spacer used in spiral wound modules built by Fraunhofer Institute for Solar Energy Systems (ISE) have been selected (membrane L-66-0.20 and spacer no. 01). The modules consist of membranes and spacers whereof good experiences for solar applications are reported in literature [8,28]. For future module developments having other requirements regarding the heat source, a membrane and spacer screening has been conducted in order to find a suitable material and determine the influences of the characteristic specifications. Hereby, the focus was placed on DCMD applications.

2. Theoretical approach

In membrane distillation water vapor permeates through the membrane due to the partial water vapor pressure difference (see Fig. 1). The temperature in the MD process is crucial as the partial pressure is dependent on it. Therefore, the heat transfer is very important and the characteristics of the membrane and the spacer that can influence it are of interest. Furthermore, the mass transport, especially through

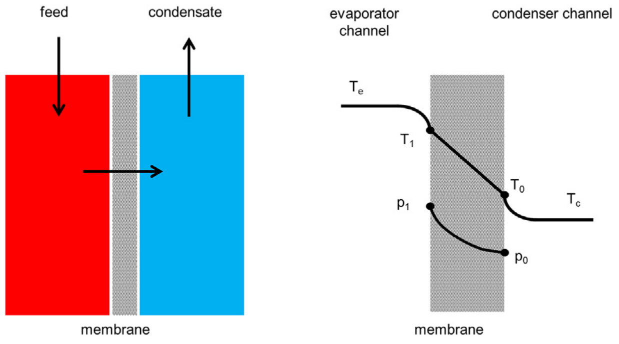

Fig. 1. Principle of DCMD (left); temperature and partial pressure profile for DCMD (right).