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A low pressure recirculated sweep stream for energy efficient membrane facilitated humidity harvesting

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ABSTRACT

Water vapor in the atmosphere can be used as a source of fresh water by means of condensation. The use of selective membranes, that separate the water vapor from the other gases, allows a specific cooling of the concentrated vapor and makes the process more energy efficient. In this paper the different driving forces for the vapor permeation across the membrane are analyzed. The advantages and disadvantages of using vacuum and a sweep stream are assessed and a combination of these two is introduced, which provides an optimal condition for humidity harvesting. When air is recirculated from the condenser to serve as a sweep stream while the total system pressure is regulated with a vacuum pump, the driving force can be uncoupled from the permeate side pressure. It is demonstrated that with such a configuration substantial water production rates can be achieved, even at higher vacuum pressures, which reduces the work requirement of the vacuum pump. At the same time these moderate vacuum conditions reduce the energy demand for cooling the sweep stream so that the energy efficiency can be significantly improved compared to systems without membranes.

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1. Introduction

The access to safe drinking water is one of most important necessities for human beings. As aquifers are becoming increasingly depleted and ongoing desertification is reducing habitable spaces, while facing a tremendous population growth, the quest for new water sources is in full progress [1]. Even though great progress has been made in desalination techniques [2,3], which provide safe and relatively cheap water, this source becomes less appealing when areas are considered which are not close to saline water bodies. In such cases transportation costs make that water uneconomical. Especially for these remote areas, also other sources like the water vapor present in the atmosphere should be considered [4].

However, the production of drinking water from air humidity (humidity harvesting or atmospheric water generation) has previously not received a lot of attention. This might be attributed to the high energy requirement of the process. Apart from the high energy demand for the vapor condensation, also the fact that water vapor is embedded in air at atmospheric conditions substantially contributes to the energy balance. About 50% of the energy requirement of harvesting drinking water by cooling down humid ambient air is wasted on producing cold air, rather than water [5].

Therefore, many approaches that use the air as water source utilize the daily temperature cycle for cooling (dew collection [6,7]) or the presence of existing heat sinks (radiative cooling [8,9], deep sea water [10,11], or otherwise unused heat-sinks [12]) to avoid high energy investments.

A different approach to tapping the air's fresh water is to concentrate the water vapor before the cooling. This can be achieved by using desiccants that adsorb the vapor from the air, which can then be recovered in a separate step [13–15].

As shown in our earlier work [16], vapor concentration can also be achieved by using water vapor selective membranes. Such membranes allow the separation of water vapor from other molecules in air prior to the cooling process. This has already been successfully demonstrated for other applications like the dehydration of natural gas [17] or flue gas [18]. Yet, in atmospheric water generation the driving force for the vapor permeation is relatively small (as compared to flue gas applications) so that delicate process engineering is required to achieve an apt water output.

The driving force for the permeation through the membrane is the difference in partial pressure [19]. This can either be imposed by lowering the total permeate side pressure [20] or by introducing

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a dry sweep stream [21]. Another possibility is combining both methods to enhance the permeation across the membrane via a low pressure sweep stream [22–24]. In a low pressure environment, any sweep stream needs to be displaced by a vacuum pump, which requires energy. Lower pressures with little to no sweep are therefore energetically more appealing. Yet, as Vallieres and Favre [23] point out, pressures below 20 mbar are delicate to obtain in industrial applications. This reduces the applicability of the vacuum-only option for humidity harvesting, as the feed side vapor pressure is usually in that same pressure range of 20 mbar. This means that the driving force would be rather moderate and hardly any vapor permeation could be achieved.

Even if lower pressures were easy to obtain, with a condenser unit located on the permeate side (as depicted in i.e. Fig. 1), then the lower bounds of the permeate side pressure are set by the vapor saturation pressure of the condenser temperature. For practical reasons, this temperature should be above 0 °C. This is necessary to avoid additional energy requirement for the latent heat of freezing/deposition and because the heat transfer coefficient of a condenser suffers greatly from an isolating ice layer. For a cooling temperature of e.g. 2 °C (as used in this paper), the saturation pressure of water vapor is 7.1 mbar. This pressure also marks the potential minimum total pressure, as below the saturation pressure the evaporation rate exceeds the condensation rate and thus no water could be collected.

For low pressures above this limit, the saturation pressure of 7.1 mbar can lead to a considerable co-transport of vapor when the vacuum pump is removing gases to maintain a constant system pressure. Any non-condensable gases[1] that permeate or leak into the system can only be removed by pumping out humid air, and when the system pressure is close to the saturation pressure the vapor content of this air is significant. This vapor flow, that is thus lost to the condensation process, is therefore termed the vapor loss rate.

Obviously, a similar form of vapor loss also occurs for a (low pressure) sweep configuration, as the amount of the permeated water that has not been condensed (equivalent to the saturation pressure) is removed together with the sweep. Unless, the sweep stream is kept within the system.

This can be accomplished by generating the sweep stream via recirculating dried air from the outlet of the condenser back into the membrane unit with a pump [16]. The heat requirement for cooling this sweep to condense the water vapor depends on its mass-flow. However, this heat requirement can be reduced when an additional vacuum pump is used to lower the total permeate side pressure. This reduces the mass-flow of the sweep stream at constant volume-flow.

With such a low pressure recirculation sweep the system pressure can be controlled independently of the driving force for the vapor permeation (minimizing the vapor loss rate). With the right choice of parameters, the process can be optimized in a way that generates the most energy efficient water output [16] while making maximum use of the relatively small ambient vapor pressure to produce an apt water output. With such measures membrane separation can become a valuable addition to humidity harvesting technologies.

In this paper we provide the experimental verification of such an operational mode. We show how the water production rate of a humidity harvesting unit can be increased by different combinations of system pressure and recirculation speed.

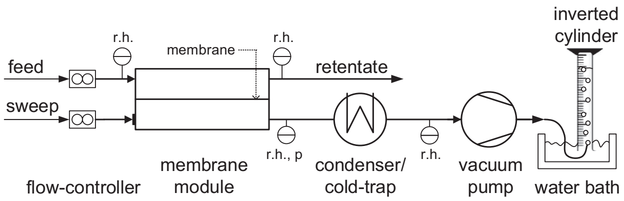

Fig. 1. Schematic setup to measure the water production rate by lowering the permeate side pressure (blocking the sweep inlet), or by an adjustable low pressure sweep stream. The vapor that permeates through the membrane module is condensed using a cold-trap or condenser. The outlet of the vacuum pump is collected in an inverted cylinder in a water bath to monitor the amount of non-condensable gases that have to be displaced. The process parameters are monitored by humidity (*r.h.*) and pressure (*p*) sensors.

2. Materials and methods

2.1. Theoretical framework

The theoretical framework for this study is laid by the solution-diffusion model. It describes the permeation flow-rate (Q_i) of a certain species i (i.e. water vapor), based on the membrane permeability (P_i) the membrane area (A) and thickness (z) and the partial pressure difference of species i across the membrane (Δp_i) [19]:

$$Q_i = \frac{P_i \cdot A}{z} \Delta p_i = \frac{P_i \cdot A}{z} (p_i^{\text{feed}} - p_i^{\text{permeate}}) \tag{1}$$

The amount of permeation therefore depends on the partial pressure of a certain component in the feed and its partial pressure on the downstream side.

2.2. Vacuum and low pressure sweep

To assess the water production rate at reduced permeate side pressures and when using a low pressure sweep stream, a setup was built that is schematically depicted in Fig. 1. An air stream coming from the local pressurized air distribution, regulated by a flow-controller (MV-304, Bronkhorst), is guided through a series of water filled bottles using diffusers to achieve a feed flow at 30 °C and a vapor pressure of approx. 33 mbar (≡77%*r.h.*). The temperature and water vapor content is measured and read out by digital humidity sensors (SHT 21 and SHT 75 + EK-H4, Sensirion). This humidified air stream is blown through the lumen side of a hollow fiber membrane module (inside feed), custom made by Parker Inc. ($\o_{\text{fiber,in}} = 0.7$ mm, $A = 0.47$ m^2, l = 30 cm), where the fibers have been coated with Sulfonated-poly-ether-ether-ketone (SPEEK) [18], at a flow-rate of 15 l(STP)/min(≡0.393 g_{H_2O}/ min). Also a commercially available polydimethylsiloxane (PDMS) module (PermSelect®, PDMSXA-2500, MedArray Inc.; $\o_{\text{fiber, in}} = 0.19$ mm, $A_{\text{in}} = 0.16$ m^2) is used at a feed flow-rate of 10 l(STP)/min (≡ 0.262 g_{H_2O}/ min). To keep the conditions constant, the saturation bottles as well as the membrane module are kept in a temperature controlled incubator (FC 222, MMM Medcenter Einrichtungen GmbH) at 30 °C. The flow-rates of the feed speed are chosen to suit the module surface areas.

To create vacuum-only conditions the permeate side sweep inlet can be blocked (see Fig. 1). To generate a dry sweep stream a flow-controller (EL-Flow 4000 ml(STP)/min, Bronkhorst) allows a well defined air stream (stemming from the local pressurized air distribution) to enter the system. To condense the water vapor, a liquid-nitrogen cooled cold-trap (KF 29-K, KGW Isotherm), that lowers the partial pressure of the water vapor to almost zero, or a condenser at 2 °C is used. The custom made condenser (LGSBV, The Netherlands) is cooled by a refrigerated circulating water bath

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[1] Non-condensable in this paper refers to the reference condenser temperature of 2 °C.

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