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System analysis of membrane facilitated water generation from air humidity

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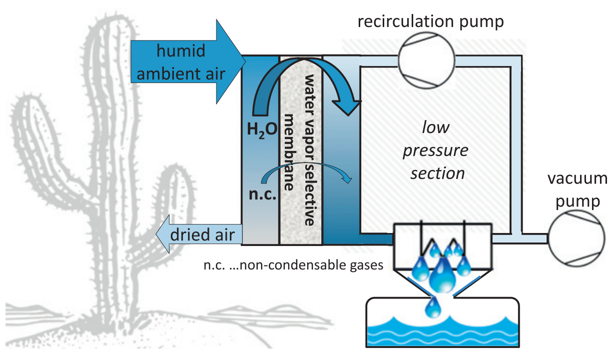
HIGHLIGHTS

- Membranes reduce the energy costs of atmospheric water generation by more than 50%.
- We propose a model system to concentrate water vapor with membranes prior to cooling.
- A system analysis is performed and ideal operational conditions determined.
- A low pressure sweep allows energy efficiency even in the presence of leak-ages.
- The quality of the condensed water improves by the use of membranes.

GRAPHICAL ABSTRACT



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ABSTRACT

The use of water vapor selective membranes can reduce the energy requirement for extracting water out of humid air by more than 50%. We performed a system analysis of a proposed unit, that uses membranes to separate water vapor from other atmospheric gases. This concentrated vapor can then be condensed specifically, rather than cooling the whole body of air. The driving force for the membrane permeation is maintained with a condenser and a vacuum pump. The pump regulates the total permeate side pressure by removing non-condensable gases that leak into the system. We show that by introducing a low-pressure, recirculated, sweep stream, the total permeate side pressure can be increased without impairing the water vapor permeation. This measure allows energy efficiency even in the presence of leakages, as it significantly lowers the power requirements of the vacuum pump.

Such a constructed atmospheric water generator with a power of 62 kW could produce 9.19 m^3/day of water (583 MJ/m^3) as compared to 4.45 m^3/day (1202 MJ/m^3) that can be condensed without membranes. Due to the physical barrier the membrane imposes, fresh water generated in this manner is also cleaner and of higher quality than water condensed directly out of the air.

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1. Introduction

The increasing water scarcity, due to ongoing desertification, salinization of fresh water sources and a still increasing global population poses a major challenge for society. Access to safe drinking water is so substantial that it was made one of the United Nations "Millennium Development Goals". Most approaches for generating new sources of

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fresh water focus on desalination techniques to make use of the seemingly unlimited water body of the oceans [1,2].

Another possibility, which has found less application up to now, is the extraction of water from the air humidity. The amount of water that can be present as vapor strongly depends on the temperature. Therefore, when a body of air is cooled down far enough, it will result in the condensation of the excess vapor which can then be collected. This cooling can either occur naturally (dew collection [3,4]) or it can be achieved by investing energy [5].

Due to the relatively high latent heat of water, the energy requirements to condense water are usually orders of magnitude larger than the energy required for water purification methods. Thus, atmospheric water vapor processing can only be remunerative in the presence of natural or existing heat sinks (radiative cooling [6,7], deep sea water [8,9], otherwise unused heat-sinks [10]) or in remote areas where the energy balance changes significantly when transportation is taken into account. In such locations a humidity harvesting unit may be driven by renewable energy, like solar [11–13] or wind [14] energy, so it could be a stand-alone application, independent of existing infrastructure.

Besides the energy required for the condensation, a significant part of the energy demand in humidity harvesting is needed for cooling the body of air in which the water vapor is embedded at atmospheric conditions. If a cubic meter of air of 30 °C with a relative humidity of 50% is cooled down to 2 °C, only 43.6% of the cooling power is used for condensing water (9.66 g), while the remaining 56.4% is almost entirely spent on cooling air. A way to circumvent this sensible heat requirement is to concentrate the water vapor by the use of desiccants [15–17]. However, even with the recent discovery of advanced desiccant materials [18] the main disadvantage of this process is that a desiccant system works in cycles, reducing the maximum water output as a continuous process is not possible. Another method that brings about the same advantages, but allows for a continuous process is the use of water vapor selective membranes to separate the water vapor from the other gases prior to the cooling process [19]. The driving force for the permeation is the partial pressure difference across the membrane. This force is maintained with a condenser and a vacuum pump that displaces the inflow of non-condensable gases. Due to the use of a dense polymer membrane that is highly selective for water vapor, no pollutants or pathogens can pass the membrane, making the condensed water very pure. Also the membrane maintenance should not pose a major challenge as only air and vapor (therefore no scaling) are used as a feed and the absence of sunlight and aqueous environment does not favor bacterial or algae growth, which poses the greatest challenges to other common membrane technologies.

In this paper we analyze the effects of operational and meteorological conditions (like temperature, humidity, permeate side pressure or water vapor pressure) on the water production and the energy efficiency of a system working with membrane separation. According to these and the membrane characteristics, such as permeability and selectivity, we suggested a system design and provide operational parameters, that can be used to significantly reduce the energy demand for the production of potable water.

2. Humidity harvesting with membranes

To extract humidity from the air with the use of water vapor selective membranes we propose an installation that is schematically depicted in Fig. 1.

A membrane module (I) exposed to a humid air stream (feed stream) is the centerpiece of that system. Due to its selective properties and an imposed driving force water vapor permeates through the membrane and the remaining dried air stream is discharged (retentate).

The driving force for the water vapor transport over the membrane is maintained by two main components: a vacuum pump (II) that controls the total pressure on the permeate side and a heat pump that cools down and condenses the permeated water vapor at the condenser

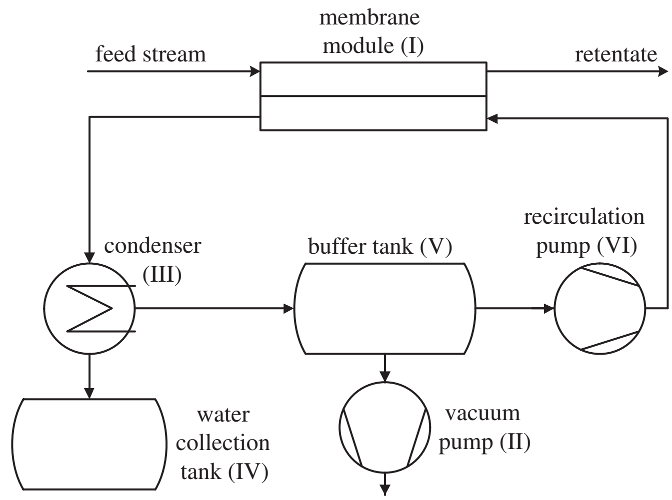

Fig. 1. Schematic representation of the membrane unit and the permeate side constituents of a humidity harvesting unit, working with water vapor selective membranes.

(III). Thus the water vapor pressure on the permeate side depends on the condenser temperature and the according water vapor saturation pressure. The condensed water is collected in the water collection tank (IV) from which the water can be pumped out.

A buffer tank (V) can be added to increase the permeate side volume making the system less susceptible to pressure changes. A recirculation pump (VI) is used to create a low-pressure recirculation sweep stream. This facilitates the uncoupling of the permeate side water vapor pressure from the total permeate side pressure as will be described later on.

3. System parts and analysis

3.1. The membrane unit

A water vapor selective membrane is a material that has permeability for water vapor much larger than that for any other gas. While gas separation membranes are often porous structures with pore sizes small enough to separate molecules due to their different free path lengths (Knudsen diffusion) [20], membranes for vapor permeation and pervaporation can make use of the polarity of the water molecule. Such membranes are dense, thin films (polymers) which, according to the solution–diffusion model [21], have high solubility for water (hydrophilic material) and a fast diffusive transport from one side to the other. Therefore, water vapor selective materials, like Pebax®[22] or PEO-PBT, can achieve permeances for water vapor (P_{H_2O}) much higher than for other gases (P_i), such as nitrogen (P_{H_2O}/P_{N_2}>40, 000 [23]), while maintaining a high permeability as well. To our knowledge the highest reported water vapor permeance has been achieved with an ultra-thin poly-dopamine layer, where a permeance of up to $3 \cdot 10^{-6}$ mol/(s Pa m^2) (≡9000 GPU) was measured [24].

The driving force for permeation is the chemical potential difference, which, under given circumstances, is equivalent to the partial pressure difference between the feed and the permeate side of the membrane [21]. The permeation of a species i is described by:

$$\dot{N}_i = A\,P_i\,\Delta p_i \tag{1}$$

with $\dot{N}_i$ being the molar flow rate of species i, A the membrane surface area, P_i the permeance of the membrane towards species i, and Δp_i the partial pressure difference of this species across the membrane.

As the vapor pressure in the feed stream cannot be modified (as function of temperature and relative humidity), the partial pressure difference for water vapor permeation can be induced by either reducing

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