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FULLY POLYMERIC DISTILLATION UNIT BASED ON POLYPROPYLENE HOLLOW FIBER MEMBRANES: THERMAL PERFORMANCE ANALYSIS

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Abstract: *Water scarcity is one of the current threats for many people around the globe. Desalination processes are a crucial solution for areas with access to sea water on the one hand and with the inadequacy of fresh water on the other. Used technology, membrane distillation, is a thermally driven separation process using a porous membrane to set liquid and gas phases apart. Water evaporates and its vapour crosses the membrane's pores. Polypropylene membrane modules and chaotic hollow fiber condenser were used to construct a (fully polymeric) sweep gas membrane distillation unit. Data of four membrane modules were measured to evaluate the unit thermal performance. Limitations lay in 1) the fiber (geometrical) separation of membrane modules, 2) proper utilization of the sweep gas velocity, and 3) improving condensation system. Still, the device shows a significant thermal efficiency (> 60 %) even at low operating temperatures. Moreover, further improvements are concrete and reachable.*

Keywords: Desalination, Heat transfer, Hollow fiber membranes, Sweep gas membrane distillation.

1. Introduction

In 2017, 71 % of the global population (5.3 billion people) used a safely managed drinking-water service, one located on-premises, available when needed, and free from contamination. It means that on Earth there were 2.2 billion people without safety managed services (WHO, 2021). The oceans represent the Earth's major water reservoir. About 97 % of the Earth's water is sea water, while another 2 % is locked in icecaps and glaciers. Thus, available fresh water accounts for less than 0.5 % of the Earth's total water supply (Khawaji, 2008). Moreover, conventional energy sources and fresh water reservoirs are quickly becoming in short supply. Therefore, new less energy-intensive and more environment-friendly water purification techniques are emerging. Membrane distillation (MD) is one of the recent promising separation processes. Contemporary, it has gained popularity due to some unique benefits. MD is a thermally driven process across a porous hydrophobic membrane. It possesses the potential to concentrate the solutions to their saturation point without any significant permeate flux decline. Furthermore, the process can be powered by waste heat such as solar energy, geothermal energy, and waste grade energy associated with low-temperature industrial streams. MD process allows only vapor to pass. Hence, the obtained product is theoretically 100 % pure from solid and nonvolatile contaminants (Drioli, 2015).

2. Methods

Sweep gas membrane distillation (SGMD) is a promising distillation method that achieves the desired balance between reducing conductive heat loss and improving membrane permeability using flowing gas instead of condensing water and static air gap in the permeate side (Li, 2020). In the experiment, the hot (60 °C) tap water modified with polyphosphate flows through the membrane module. It evaporates and its vapour leaves the membrane through pores. Then it is swept by air induced by a fan along the tunnel to the condenser, in which cold (20 °C) tap water flows. Air condensation occurs, and pure water is collected.

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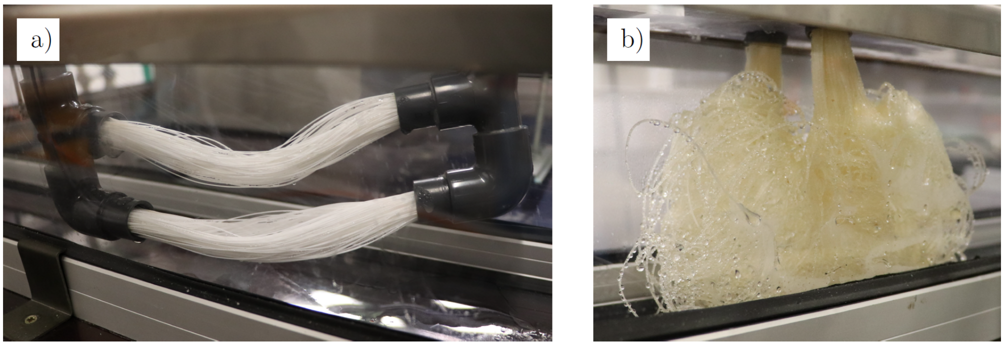

Figure 1: Detail in the distillation tunnel, a) double-bundle membrane module MM004 and b) condenser, chaotised polymeric hollow fiber heat exchanger is used to guarantee that all fibers are in direct contact with the moist sweeping gas. A method of separation of fibers is presented by (Raudenský, 2017).

The distillation unit consists of three main parts, the distillation tunnel containing the membrane module and the condenser. Four membrane modules (MM002, MM003, MM004 and MM006) with different amounts of fibers were prepared in the laboratory. Number X stands for hundreds of fibers in the module MM00X. Modules MM002 and MM003 are single-bundle modules and the others are double-bundle. Distillation tunnel forming rectangular 2000 mm $\times$ 1000 mm closed loop is made of transparent polycarbonate sheets so the process can be continuously observed. The tunnel's rectangular cross-section has 120 mm in height and 100 mm in width. Airflow in the tunnel is induced by a fan with a diameter of 100 mm with a supply voltage of 11 V. The speed of air inside the tunnel is 0.8 m·s^{-1}. The module membrane in figure 1 a) consists of two bundles of 200 polymeric hollow fibers (PHF) with a length of 140 mm. It is made of hydrophobic polypropylene fibers produced by (ZENA MEMBRANES, 2022) with an outer diameter of 0.53 mm, an inner diameter of 0.44 mm . Hence, the membrane thickness is equal to 0.045 mm. Mass transport area is equal to 0.08 m^2. The average pore size is 0.1 µm with a porosity of 50 %, and liquid entry pressure (LEP) is higher than 350 kPa. If the applied pressure exceeds value LEP, liquid penetrates the hydrophobic membrane. Thus MD can not be used. Previous experiments showed that fibers must be separated from each other to increase the permeate flux. It is done by pushing module terminals towards each other by 20 %, hydrophobicity is not affected, and no kinks are created by this method (Kůdelová, 2021). The hot medium flowing through the membrane is modified with polyphosphate (0.02 g·l^{-1}) to prevent fouling. Membrane input and output are placed on positions Tmi1 and Tmo1, respectively, (figure 2). The polymeric hollow fibers heat exchanger (PHFHE) takes place as a condenser in the unit, represented at figure 1 b). It is also made of hydrophobic polypropylene. 200 PHFs of length 600 mm, outer diameter, and inner diameter of 0.8 mm and 0.6 mm, respectively, create a chaotised bundle with a total heat transfer area of 0.3 m^2. The condenser input and output are located in positions Tci1 and Tco2, respectively (figure 2). Input and output temperature, pressure drops, and water flow rate for the membrane module and the condenser were measured, i.e. at spots Tmi1 and Tmo1 for the membrane module and Tci2, Tco2 for the condenser. The humidity and temperature of the moist sweep gas were measured inside the distillation tunnel on spots H1, H3, H4, and T1, T3, T4, respectively. Air speed was measured at H4.

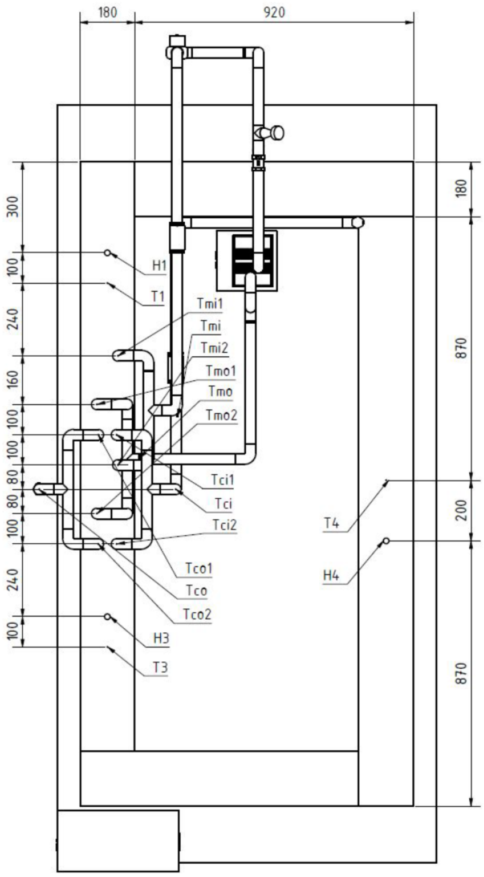

Figure 2: Scheme of the test rig, top view. Adapted by (Kůdelová, 2021).

Two main mechanisms occur in the MD system: conduction heat transfer $\dot{q}_c$ (across the membrane material and its gas-filled pores) and latent heat $\dot{q}_v$ (associated with the vaporized molecules). The influence of mass transfer on heat transfer can be ignored. We consider a steady-state operation. Both membrane and condenser are set up in the crossflow arrangement to the tunnel with the sweeping gas. Only latent heat contributes to the positive outcome of SGMD. Conduction provides just heat loss. We introduce thermal efficiency η_m naturally as fraction of $\dot{q}_v$ and the sum of both heat transfer rates.

One of the limiting factors of SGMD efficiency is the heat transfer through the boundary layers. To express whether the membrane is well designed, we introduce local (global one can be again taken as a mean value) polarization coefficient ψ as

$$\psi = \frac{T_{m,f} - T_{m,p}}{T_{b,f} - T_{b,p}}. \tag{1}$$

This coefficient reflects the reduction of the driving force (vapour pressure difference), which negatively influences the process productivity. In the ideal case, the value should be equal to one. Temperatures $T_{b,f}$, $T_{m,f}$ stand for the bulk temperatures of feed and permeate, $T_{m,f}$, and $T_{m,p}$ are the feed and permeate temperatures at the membrane surface, respectively.

3. Data Reduction

Firstly, the properties at atmospheric pressure of moist and dry air were interpolated from the appendix in (Borgnakke, 2013) and (Bergman, 2011), respectively. Properties of water (dynamical viscosity, specific heat capacity, thermal conductivity, density, and latent heat) were considered to be only temperature-dependent, whereas the temperature T in °C was taken as the average of temperatures on the input and output of the system (i.e. of the membrane module or the condenser). From the first law of thermodynamics, the heat transfer rate through the membrane q_m is given as

$$q_m = \dot{m}_m c_m \left(T_{m,i} - T_{m,o}\right), \tag{2}$$

where $\dot{m}_m$, c_m, $T_{m,i}$, and $T_{m,o}$ are mass flow rate of the water inside the membrane, specific heat capacity of the water at constant pressure inside the membrane, temperature of water inside the membrane at input and output of the module, respectively.

For evaluating the convective heat transfer coefficient of the membrane module in the experiment, we use the approach proposed by (Zarkadas, 2004). The membrane module can be interpreted as the PHFHE in the crossflow configuration. Suppose that the tube-side flow is fully developed laminar. Thus, the method can be used and the overall heat transfer coefficient is determined from the computed heat transfer rate q_m. Tube-side and air-side heat transfer coefficients have to be evaluated to calculate temperatures on the membrane module surface, which are necessary for evaluating polarization coefficient.

4. Results

Compilation of results is displayed in table 1. The heat transfer rate increased with increasing number of fibers in membrane modules. Condensation was measured in ml·h^{-1} and recomputed to permeate flux j. It is inverse proportional to the amount of fibers in membrane module. This is caused by overlapping fibres that reduce the module's active mass transfer area. Similarly, the membrane thermal efficiency of MM006 is the lowest (60 %) because of the highest loss due to the conduction of touching fibers. In all other cases, the efficiency is circa 80 %. Reynolds number in the membrane did not exceed value 500. Therefore, the flow is assumed to be fully developed laminar. The tube-side and air-side heat transfer coefficients were evaluated as proposed by (Zarkadas, 2004), from which necessary temperatures were determined to compute the polarization coefficient (1). In all cases, it was higher than 0.27. Thus, the distillation process was not limited by heat transfer. Moreover, temperatures $T_{m,f}$ and $T_{b,f}$ were very similar, i.e. at most 5 % relative difference, because the heat transfer through the feed is high. Therefore, the heat transfer resistance of the gas layer and the mass transfer resistance of the membrane control the process. In water-air application, such a small overall heat transfer coefficient of condenser might be expected (Bergman, 2011). The low thermal efficiency of the condenser means that the heat transfer area is too large. On the other hand, water vapour diffuses into a large sweep gas volume. Thus, it is necessary to use a large condenser leading to its low performance.

Table 1: Measured and evaluated data.

Module	A [m^2]	q_m [W]	j [kg·h^{-1}·m^{-2}]	η_m [%]	ψ [-]	U_c [W·K^{-1}·m^{-2}]	η_c [%]
MM002	0.05	106	2.81	79	0.40	48	3.38
MM003	0.07	135	2.33	83	0.46	78	5.46
MM004	0.08	166	2.14	79	0.27	64	3.88
MM006	0.15	202	1.26	60	0.59	60	4.30

5. Conclusions

Membrane distillation (MD), a relatively new process, is being investigated worldwide as a low cost and energy-saving alternative to conventional separation methods. Experiments performed in the Heat Transfer and Fluid Flow Laboratory study the sweep gas membrane distillation (SGMD) configuration with four different membrane modules, varying the mass transfer area from 0.05 to 0.15 m^2. A lower amount of fibers in a module brings proper fiber separation, thus high membrane thermal efficiency (circa 80 %) and great permeate flux, with the highest value of 2.81 kg·h^{-1}·m^{-2} for the smallest module. The polarization coefficient is higher than 0.27 in all cases. Hence, heat transfer is not limiting the distillation process, but heat transfer resistance of the gas layer and the mass transfer resistance of the membrane do limit the process. To improve the performance, we propose to study the effect of the speed of sweeping gas. A higher speed should decrease the resistance of the gas layer and increase the pressure drop. On the other hand, keeping the applied pressure below the liquid entry pressure for proper process operating is necessary. The design of the external condenser is one of the known SGMD issues. Used chaotised polymeric hollow fiber heat exchanger has too big heat transfer area, which is not effectively utilized and can be lowered. Further optimization can be performed by 1) increasing the sweep gas velocity, 2) keeping smaller membrane modules and add more of them to the unit, and 3) decreasing the condenser size.

Acknowledgments

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