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Experimental and theoretical study of a lab scale permeate gap membrane distillation setup for desalination

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Abstract

Membrane distillation (MD) as a novel thermally-driven process with moderate operating temperatures is a known effective technology for salt-water desalination. In this research, a lab scale plate-and-frame permeate gap membrane distillation (PGMD) module with internal heat recovery characteristic is designed. The developed PGMD module performance is experimentally investigated for fresh and saline water feed in terms of permeate water flux rate, specific thermal energy consumption (STEC) and gained output ratio (GOR). The experimental results show that for a feed sample with 130 (g/kg: ppt) concentration (nearly four times seawater salinity), increasing the feed flow rate from approximately 0.4 to 1 L/min, led to increasing the distillate flux from 3 to 5 kg/m^2 h. However, increasing the feed flow rate in this range also led to approximately 40% increase in the STEC of the system. Furthermore, a single node theoretical model based on the PGMD module configuration is developed and the modelling results validated with experimental values at different feed water flow rate and salinity.

The comparison shows a good agreement between the developed model results and experimental outcomes. It is also concluded, optimization of the MD module performance to improve internal heat recovery and produce higher fresh water rate would be achievable by adjusting the effective membrane surface area and feed flow rate.

1. Introduction

The need for fresh water is considered to be a critical international problem and according to the World Water Council, 17% of the world population will be living in short of the fresh water supply by 2020 [5]. Consequently, the demand for alternative sustainable water sources including ground water, desalinated water and recycled water increased in recent years and as a result, the implementation of desalination plants is growing on a large scale. Fresh water can be derived from sea water by evaporation processes e.g., multi-stage flash (MSF), multi- effect distillation (MED) or membrane based processes such as reverse osmosis (RO), electro dialysis (ED) and membrane distillation (MD).

Membrane distillation is a separation process which involves phase change (liquid-vapour equilibrium) across a hydrophobic, highly porous membrane. In contrast to most membrane separation processes, which are isothermal and have driving forces as trans membrane hydrostatic pressures, concentrations, electrical or chemical potentials, MD is a non-isothermal process. If a temperature difference occurs across a non-wetting membrane, the created partial vapour pressure difference as a driving force, leads to water molecules evaporating at the hot side, crossing the membrane in the vapour phase and condensing at the cold side.

Commercially developed RO technology is associated with high electrical energy consumption in the range of (6–12) kwh/m^3 with the electricity currently being generated from non-renewable and polluting fossil fuels [3]. In contrast, MD is a thermal process using lower top temperature (80 °C or less) compared with the traditional thermal desalination processes such as MSF and MED, making it suitable for using waste heat or solar heat. Table 1 provides a comparison between the most developed current desalination technologies in terms of STEC, specific electrical energy consumption (SEEC) and operating temperature.

In addition, an advantage of the MD process [4] is that aqueous solutions of salts with higher concentrations than seawater can be treated by MD, reducing discharge volumes and increasing the water recovery factor up to 95% which considerably diminishes the environmental impact of the brine disposal.

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Nomenclature

Symbol

A_m	membrane surface area (m^2)
C_m	membrane mass transfer coefficient (kg/(Pam^2s))
C_{pC}	condenser channel specific heat capacity (J/kgK)
C_{pE}	evaporator channel specific heat capacity (J/kgK)
D_h	hydraulic diameter (m)
E_i	total power input (W)
f	friction factor (−)
GOR	gained output ratio (−)
h_{fg}	specific heat of vaporization (J/kg)
h_C	heat transfer coefficient at the condenser channel (W/m^2K)
h_E	heat transfer coefficient at the evaporator channel (W/m^2K)
h_F	heat transfer coefficient at the impermeable polymeric film (W/m^2K)
h_{PG}	heat transfer coefficient at the permeate gap (W/m^2K)
h_M	heat transfer coefficient at the membrane (W/m^2K)
J_p	permeate flux (kg/m^2s)
K_E	evaporator channel thermal conductivity (W/mK)
K_m	membrane thermal conductivity (W/mK)
K_{pg}	permeate gap thermal conductivity (W/mK)
L	module length (m)
l_s	orthogonal distance between net spacer filament (m)
$\dot{m}f$	feed flow rate (kg/s)
$\dot{m}_{Ci}$	condenser channel inlet mass flow rate (kg/s)
$\dot{m}_{Ei}$	evaporator channel inlet mass flow rate (kg/s)
$\dot{m}_{Eo}$	evaporator channel outlet mass flow rate (kg/s)
$\dot{m}_{PG}$	permeate output rate (kg/s)
$P_{v,w}$	pure water vapour pressure (Pa)
$P_{v,sw}$	saltwater vapour pressure (Pa)
Pr_E	Prandtl number in evaporator channel (−)
q_{STEC}	specific thermal energy consumption(kWh/m^3)
$\dot{q}_C$	convective heat flux from the condenser channel (W/m^2)
$\dot{q}_{cold}$	condenser channel heat flux (W/m^2)
$\dot{q}_E$	convective heat flux from the evaporator channel (W/m^2)
$\dot{q}_{hot}$	evaporator channel heat flux (W/m^2)
$\dot{q}_M$	convective heat flux from the membrane surface (W/m^2)
$\dot{q}_{M,C}$	specific conductive heat flux (W/m^2)
$\dot{q}_{M,L}$	specific latent heat flux (W/m^2)
Re_E	Reynolds number in evaporator channel (−)
S	salinity (g/kg)
S_{Ci}	condenser channel inlet feed water salinity (g/kg)
S_{Ei}	evaporator channel inlet feed water salinity (g/kg)
S_{Eo}	feed water salinity in the output of the evaporator channel (g/kg)
T_{Ci}	temperature at the condenser inlet (°C)
T_{Co}	temperature at the condenser outlet (°C)
T_{Ei}	temperature at the evaporator inlet (°C)
T_{Eo}	temperature at the evaporator outlet (°C)
T_{Me}	temperature at the membrane surface in the evaporator side (°C)
T_{Mp}	temperature at the membrane surface in the permeate gap side (°C)
T_{PG}	temperature in the permeate gap channel (°C)
u_m	feed velocity (m/s)
$\dot{V}_f$	feed flow rate (m^3/s)
$\dot{V}_p$	permeate flow rate (m^3/s)
α	Antoine equation coefficient (−)
β	Antoine equation coefficient (−)
$??$	Antoine equation coefficient (−)
$??_F$	impermeable film thickness (m)
δ_m	membrane thickness (m)
δ_{PG}	permeate gap thickness (m)
ΔP	pressure drop (Pa)
ρ	feed density (kg/m^3)

However, the MD process is still under study and the lack of experimental data has indicated that there is a need for more comprehensive research in this field, both experimentally and mathematically. The central issues are the external energy source for MD units, lack of MD membranes and fabrication of modules for each MD configuration. There are also uncertain energetic and economic costs as well as difficulties with long-term operation and the possibility of membrane pore wetting and membrane fouling. Overall, optimization of MD plants is required in order to reach higher MD performance and to decrease energy consumption [17]. The reported values for permeate flux are relatively low and to overcome this issue, an appropriate redesign of the MD module is demanded in order to achieve mass transfer improvement and to increase the membrane surface area per module volume.

In addition, with the exception of direct contact membrane distillation (DCMD), which has been more widely studied, other MD configurations have not been properly investigated, so more focus on other MD configurations is required [1]. Generally, there are four basic MD configurations, including: a) DCMD); b) air gap membrane distillation (AGMD); c) vacuum membrane distillation (VMD); d) sweeping gas membrane distillation (SGMD); PGMD or liquid gap membrane distillation (LGMD) is a recently introduced configuration of DCMD, which the permeate is extracted from the highest module position, so that the gap between the membrane and the impermeable film fills with permeate during the operation. Some recent research works studied around different MD configuration and compared the developed MD configuration in terms of main output factors.

Table 1
Comparison of most developed desalination technologies [15].

Technology	Plant capacity (m^3/day)	STEC (kWh/m^3)	SEEC (kWh/m^3)	Operation temperature (typical) (°C)
MSF	4000–450,000	55–220	4–6	90–120 (112)
MED	100–56,000	40–220	1.5–2.5	50–70 (70)
RO	0.01–360,000	–	2.8–12	< 40

Furthermore, the energy source of the MD process is an important issue for commercialization of this technology as a sustainable process. Membrane distillation associated with renewable energy is considered to be a highly promising process, especially for situations where low-temperature solar, waste or other heat is available. The STEC of MD systems varies based on the module configuration, setup scale and operating condition. A wide dispersion of reported values is observed in the literature for STEC based on different MD configurations, with the STEC varying in a range of (1–9000) kWh/m^3. Moreover, the energy consumption of a small scale installation is much higher than for pilot plants with higher effective membrane surface areas [14].

Concerning comparing different MD configuration, Cipollina et al. [6] also developed a lab scale plate-and-frame membrane distillation module for seawater desalination by applying PTFE membrane with the effective membrane surface area of 0.042 m^2. Three different channel configurations were investigated during this research, including free air gap, permeate-gap and partial vacuum air gap. As well, this study also investigated the effect of different operating conditions including variation of hot channel inlet feed flow rate and temperature on distillate