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NUMERICAL MODEL AND DEMONSTRATION OF A THERMAL BRINE CONCENTRATOR FOR CLEAN WATER PRODUCTION

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1. ABSTRACT

Desalination has emerged as a technology solution to meet the global demand for clean water by treating saline water sources. One of the major drawbacks of desalination is that it generates a hypersaline by-product or brine that must be managed. In this study, a thermal brine concentrator based on air gap diffusion distillation (AGDD) is presented that uses a counterflow heat exchanger design and plastic surfaces for high-salinity desalination. A numerical model is developed to predict the performance of AGDD under a range of operating conditions, and an experimental prototype is designed to demonstrate continuous operation. The results show that a multi-pass AGDD system can achieve an overall water recovery of ~70% and gain output ratio of 7 (corresponding to latent heat recovery of 88%) with an initial feed salinity of 70 g/kg. Overall, the system outperforms its thermodynamically similar counterpart, air gap membrane distillation (AGMD), by eliminating heat and mass transport resistances associated with the membrane.

2. INTRODUCTION

Excessive withdrawal and contamination of naturally occurring freshwater reserves have led to a global water crisis exacerbated by climate change. Desalination can augment freshwater supply by extracting clean water from saline sources (*e.g.*, brackish water, seawater, etc.), and technologies are classified into pressure-driven membrane-based reverse osmosis (RO) and thermally-driven evaporation-based multi-effect distillation (MED) [1]. While these treatment technologies are well established, they typically operate at 50% water recovery from seawater (salinity of 35 g/kg) owing to practical considerations such as pressure limits of the membrane and scaling of metal heat transfer surfaces. As a result, conventional desalination technologies generate large volume of a concentrated brine byproduct (salinity >70 g/kg) that must be managed [2].

This study discusses the development of air gap diffusion distillation (AGDD) as an emerging brine concentrator that is modular, operates at ambient pressure, utilizes low-cost materials of construction, and primarily consumes thermal energy. AGDD comprises a condenser channel and evaporator surface that are separated by an air gap, as shown in Figure 1 [3]. The inlet stream (cold stream) flows upward through the condenser channel, where it is preheated by water vapor that has condensed on the outer surface of the plate. Additional heat is provided by an external energy source (*e.g.*, solar collector) to increase the feed temperature to its desired value. The heated feed (hot stream) then flows down the evaporator surface causing water vapor

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to diffuse through the air gap to condense as permeate (freshwater). This counterflow design enables integration of latent heat recovery within the AGDD process, thereby minimizing the external energy required. This is critical for an evaporative process to be viable, since the latent heat of vaporization far exceeds the minimum energy required to separate salt from water. A coupled heat and mass transport model is developed to predict the system performance (water flux and gain output ratio) and to guide its optimal design.

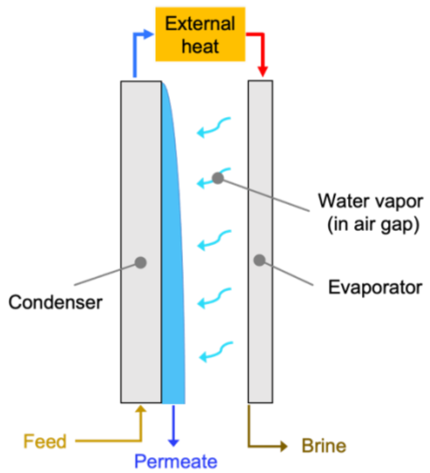

Fig. 1 Schematic of the AGDD brine concentrator that resembles a counterflow heat exchanger

3. METHDOLOGY

AGDD can be modeled by discretizing the system into nodes along the length of the evaporator and condenser. A simplifying set of assumptions is made to obtain a numerical solution without a loss in accuracy [3]. At each node, 1D steady-state heat and mass transport occur from the evaporator to condenser via conduction and vapor flow. The heat flux from the evaporator, $Q''_{evap,AGDD}$ can be described as:

$$Q''_{evap,AGDD} = \frac{k_{AG}}{\delta_{AG}}\left(T_h - T_{af}\right) + J_{v,AGDD} h_{fg} \tag{1}$$

where k_{AG} is the thermal conductivity of air δ_{AG} is the thickness of the air gap, T_h and T_{af} are the hot stream and air-permeate film interface temperatures, h_{fg} is the latent heat of vaporization, and J_v is the mass (permeate) flux. The mass flux, $J_{v,AGDD}$ can be modeled as:

$$J_{v,AGDD} = \frac{D_{WA} M_w}{\delta_{AG} R_u T_{avg,AG}}\left(P_h - P_{af}\right) \tag{2}$$

where (P_h - P_{af}) is the partial pressure difference between the evaporator and air-permeate film on the condenser side, which in turn varies with temperature and salinity. M_w is the molar mass of water, D_{WA} is the diffusion coefficient of water vapor in air, R_u is the universal gas constant, and $T_{avg,AG}$ is the average air gap temperature. Similar equations can also be obtained for the heat flux entering the condenser, Q''_{cond} and this is used to preheat the feed flowing within the channel.

$$Q''_{cond} = \frac{T_{af} - T_c}{R''_{cond}} \tag{3}$$

where T_c is the cold stream temperature and $R''_{cond}$is the total thermal series resistance comprising conduction through the permeate film, conduction through condensing plate, and convection in the cold feed stream flowing upward within the channel. Given that both the condenser and evaporator outlet temperatures are unknown, an iterative solving scheme is used to calculate these temperatures at each node [3].

4. RESULTS

There are two performance metrics of interest for the AGDD system: the gain output ratio or GOR, and the water recovery ratio (RR). The GOR is a dimensionless measure of the thermal energy consumed for permeate production (efficiency); a higher GOR corresponds to lower energy input per unit of permeate produced and indicates the extent of latent heat recovery [4]. The RR is a measure of the fraction of clean water recovered from the feed. Table 1 shows the input parameters used for the AGDD analysis, and Figure 2 shows the corresponding temperature profiles of the hot (evaporator) and cold (condenser) streams along the length of the system. This resembles a counterflow heat exchanger, which is expected given that this configuration is suitable for heat recovery. A parametric analysis was also performed, which showed that AGDD should be operated at low flowrates and high evaporator inlet temperatures to optimize both the RR and GOR in the system. Overall, an RR ~10% in a single AGDD pass can be achieved at a GOR ~15. By increasing the number of passes to 12, the AGDD system achieves a total water recovery of ~70% and GOR of 7. This corresponds to a permeate flux of 1.34 kg/m^2-h from a feed flowrate of 2 kg/h, with approximately 88% of the energy input coming from latent heat recovery.

For a range of system dimensions, flowrates, and temperatures, the AGMD heat and mass transport model developed herein shows excellent agreement (within 2-5%) with models in the literature and is experimentally validated to demonstrate its performance as a brine concentrator.

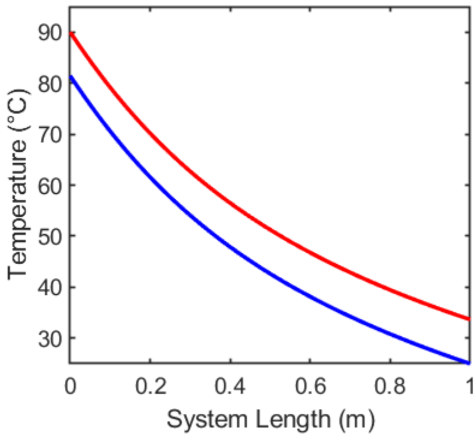

Fig. 2 Temperature profiles of the hot (red) and cold (blue) streams as a function of system length using input values in Table 1

Table 1. Input parameters for the AGDD heat and mass transfer model.

Fluid Parameters	Value	System Parameters	Value
Mass flowrate (kg/s)	2 –12	Evaporator/Condenser Length (m)	1
Evaporator Inlet Temperature (ºC)	60 - 90	Evaporator/Condenser Width (m)	0.2
Condenser Inlet Temperature (ºC)	25	Air Gap Width (mm)	3
Feed Salinity (g/kg)	70 - 160	Condenser Channel Thickness (mm)	2
		Condensing Plate thickness (mm)	1

5. CONCLUSIONS

The performance of a thermal brine concentrator based on air gap diffusion distillation (AGDD) is reported using a steady-state coupled heat and mass transport model. The energy efficiency (GOR) and water produced (recovery ratio) are the main outputs for brine concentration from a salinity of 70 to 200 g/kg. A parametric analysis that varied the system length, feed flowrate, salinity, and evaporator inlet temperature was performed that confirmed the viability of this technology for desalination of brines with an overall water recovery of ~70% and GOR of 7.

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