Lecture Notes in Mechanical Engineering

Ali Cemal Benim · Rachid Bennacer ·
Abdulmajeed A. Mohamad ·
Paweł Ocłoń · Sang-Ho Suh ·
Jan Taler *Editors*

Advances in Computational Heat and Mass Transfer

Proceedings of the 14th International Conference on Computational Heat and Mass Transfer (ICCHMT 2023), 4–8 September, 2023, Düsseldorf, Germany - Volume 1

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Preface

This volume of Lecture Notes in Mechanical Engineering contains selected papers presented at the 14th International Conference on Computational Heat and Mass Transfer (ICCHMT2023), held in Düsseldorf, Germany on September 4–8, 2023. The conference was organized by the Düsseldorf University of Applied Sciences (Hochschule Düsseldorf), in cooperation with the University of Calgary (Canada), École Normale Supérieure Paris-Saclay (France), Cracow University of Technology (Poland) and Soongsil University (South Korea).

The International Conference on Computational Heat and Mass Transfer (ICCHMT) conference series has been held regularly since 1999 and has established itself as a reference event in the field of heat and mass transfer. The conferences provide a platform for scientists and engineers to meet regularly and discuss new ideas and developments in the field of computational methods and their applications, as well as a good opportunity for young scientists and engineers to explore the art of computational methods and future perspectives. The conference series focuses on the research, development and application of computational methods in all areas of flow, heat and mass transfer, but without excluding experimental and theoretical approaches, especially as a means of validation and inspiration. The previous 13 conferences in this series have been held in various countries around the world, including Brazil, Canada, China, Cyprus, France, Italy, Korea, Poland and Turkey.

To the current, 14th conference, held from September 4-8, 2023, in Düsseldorf, Germany, a total of 304 abstracts from 47 countries were submitted, and a total of 239 of them were accepted for presentation at the conference. The full papers were submitted subsequent to the conference, and after a thorough peer-review process, 134 papers, written by authors from 36 countries, were accepted for publication in the proceedings. This first volume of the proceedings includes 67 of them.

We would like to take this opportunity to thank all committee members, session chairs as well as the invited external reviewers for their support and for their efforts and expertise in contribution to reviewing the papers. We also thank very much to the keynote speakers: Prof. Dr. Carol Eastwick (University of Nottingham, UK), Prof. Dr. Giancarlo Iaccarino (Stanford University, USA), Prof. Dr. Andreas Kempf (University of Duisburg-Essen, Germany), Prof. Dr. Sylvie Lorente (Villanova University, USA), Prof. Dr. Qiuwang Wang (Xi'an Jiaotong University, P. R. China), Prof. Dr. Jan Taler (Cracow University of Technology) for sharing their esteemed knowledge and experience at the conference. We highly appreciate the partnership with Springer and our sponsors for

their support. Our special thanks naturally goes to the authors and participants for their valuable contributions.

April 2024

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Numerical Modeling of an Air Gap Membrane Distillation Regenerator for Liquid Desiccant Air-Conditioning Applications

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Abstract. Liquid desiccant cooling is a promising alternative to vapor compression cycle due to its lower electricity consumption. Regeneration process is the principal source of the overall energy consumption which aims to concentrate the diluted desiccant. Conventional direct/indirect regenerators use flowing air to remove the moisture and yield a relatively low thermal efficiency. Based on this, this paper presents a liquid desiccant regenerator which uses air gap membrane distillation to simultaneously concentrate the weak desiccant and produce potable water. A heat and mass transfer model is developed and validated to explore the regenerator performance under various operation conditions as well as the effects of heat transfer enhancement. The simulation results show that the regeneration rate and thermal efficiency increase remarkably with the rise in both the temperature and flow rate of the desiccant. Decreasing both the temperature and flow rate of the coolant can obtain an obvious increase in the regeneration rate but slight fall in the thermal efficiency. In addition, it is found that the convection inside the desiccant channel plays a dominant role in the overall heat transfer performance. By contrast, enhancing condensation heat transfer on the cooling plate surface has a negligible influence on the regenerator performance. This study provides a guideline for the design and optimization of the air gap membrane distillation based liquid desiccant regenerator.

Keywords: Liquid desiccant regeneration · Air gap membrane distillation · Numerical modeling · Performance analysis

1 Introduction

Nowadays air-conditioning is responsible for a significant proportion of electricity use and carbon emissions associated with buildings especially in hot and humid regions. In addition to temperature control, air humidity is no doubt another concern that relates directly to occupiers' thermal comfort and health. Liquid desiccant cooling (LDC) technology has emerged as a cost-effective alternative to vapor compression method widely used at present due to its feature of independently handling sensible and latent heat loads and using low-grade thermal energy [1]. Regeneration is the major source of energy use in a LDC system, and therefore, developing highly efficient technologies to concentrate liquid desiccant has great significance in energy savings and carbon neutrality.

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The most common regenerators are based on thermal evaporation. The working principle is that air blows through regenerators where it comes into direct contact with liquid desiccant and then eliminate the water vapor from the desiccant. To overcome the issue of liquid droplets carryover, some researchers have applied semi-permeable membranes to separate regeneration air from liquid desiccant so that heat and mass exchange can happen without the direct contact between two working streams [2]. However, the performance of all the regenerators above is highly limited to outdoor air conditions and the another concern is the considerable energy losses [3]. Based on this, membrane distillation (MD) has been successfully applied to concentrate liquid desiccant accompanied with fresh water production [4]. Duong et al. [5] experimentally evaluated the regeneration capacity of direct contact membrane distillation (DCMD) for various brine solution. Lefers et al. [6] conducted a pilot-scale experiment to demonstrate the feasibility of using vacuum membrane distillation (VMD) to regenerate calcium chloride and magnesium chloride aqueous solution. Liu et al. [7] investigated the fouling in DCMD for lithium chloride (LiCl) solution regeneration. Zhou et al. [8] studied the regeneration performance of hollow fiber membrane-based VMD with LiCl solution. Air gap membrane distillation (AGMD) is also a potential MD technique for liquid desiccant regeneration due to its low heat losses, whereas, the relevant research is lacking.

This paper proposes a novel liquid desiccant cooling system in which an AGMD based regenerator is employed to concentrate the liquid desiccant from the dehumidifier and product fresh water at the same time. The main objective of this study is to assess the regeneration performance of the AGMD regenerator with flat-sheet membrane. Furthermore, this study is also aimed at seeking for the methods for performance improvement. Based on a developed heat and transfer model, the numerical analysis is carried out to investigate the effects of involved operation variables and enhancement factors for heat transfer. The modeling results are expected to promote the practical application of air gap membrane distillation in liquid desiccant regeneration.

2 Model Development

Figure 1 (a) shows the schematic diagram of the liquid desiccant cooling system with air gap membrane distillation regenerator. The diluted liquid desiccant exiting the dehumidifier is heated before flowing into the AGMD regenerator. Driven by the temperature between the desiccant and coolant, the water vapor removed from the desiccant is condensed and then is collected at the bottom, thereby concentrating the desiccant. Figure 1 (b) illustrates the working principle of the AGMD regenerator. The AGMD regeneration process consists of the following steps:

- Movement of the water molecules from the bulk desiccant feed towards the membrane surface
- Water evaporation at the feed-membrane interface
- Migration of water vapor molecules through the membrane and air gap
- Water condensation on the surface of the condensing plate

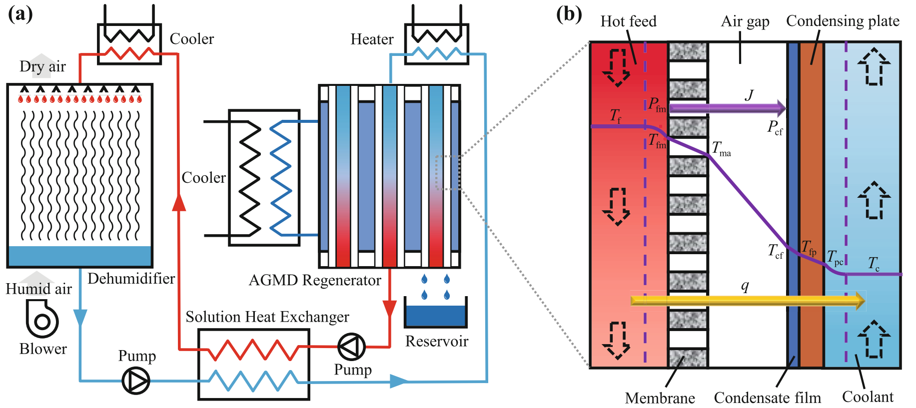

Fig. 1. The schematic diagram of (a) the liquid desiccant cooling system with air gap membrane distillation regenerator; and (b) the air gap membrane distillation regeneration process

Due to the presence of thermal resistance, the water evaporates at a temperature higher than that of the feed bulk and subsequently the vapor condenses at a temperature lower than that of the coolant bulk. This phenomenon is recognized as temperature polarization effect that is generally described by temperature polarization coefficient (*TPC*). Similarly, there exists a concentration gradient near the membrane surface, thereby reducing the vapor pressure on the interface between the desiccant and the membrane. This phenomenon is known as concentration polarization effect which can be neglected in treating highly saline water compared to temperature polarization effect [9]. The heat and mass transfer model as well as performance assessment indices will be established in the following sub-sections.

2.1 Heat and Mass Transfer Model

First of all, the following assumptions are made to simplify the modeling [10]:

- The membrane is straight and solid;
- Concentration polarization in the feed channel is negligible;
- The AGMD module works in steady state;
- The air in the air gap is stagnant and thus no convection heat transfer happens;
- Only water vapor is transported through membrane pores;
- Pressure drop and heat losses in the AGMD are negligible;

The governing equations of mass and energy conversation for hot feed and coolant is expressed as (hot feed flows in x direction):

$$\frac{\mathrm{d}m_\mathrm{f}}{\mathrm{d}x} = -WJ \tag{1}$$

$$\frac{\mathrm{d}(m_\mathrm{f}X)}{\mathrm{d}x} = 0 \tag{2}$$

$$\frac{dh_f}{dx} = -\frac{W\alpha_f(T_f - T_{fm})}{m_f} \tag{3}$$

$$\frac{dh_c}{dx} = -\frac{W\alpha_c\left(T_{pc} - T_c\right)}{m_c} \tag{4}$$

where m_f and m_c are the mass flow rates of hot feed and coolant. X represents the weight concentration of hot feed, J is the water flux through membrane and W is the width of membrane. α_f and α_c are the heat transfer coefficients within the hot feed and coolant channels respectively. The temperature distribution is shown in Fig. **1** (b).

For common commercial semi-permeable membrane, the Knudsen-Molecular transition diffusion dominates the mass transport process and the mass transfer across the can be expressed as [11]:

$$J_w = D(P_{fm} - P_{cf}) \tag{5}$$

$$D = \left[\frac{3\tau\delta_m}{2\varepsilon r}\sqrt{\frac{\pi RT}{8M_w}} + \frac{P_a RT\left(\tau\delta_m + \delta_{ag}\right)}{\varepsilon P_{atm} D M_w}\right]^{-1} \tag{6}$$

where δ_m and δ_{ag} are the membrane and air gap thicknesses. τ represents the tortuosity of membrane pores, r is the radius of the membrane pore, ε is membrane porosity, and M_w is the molecular weight of water. P_a and P_{atm} are the dry air pressure and atmospheric pressure respectively.

The heat flux from feed bulk to membrane surface by convection can be expressed as:

$$q = \alpha_f(T_f - T_{fm}) \tag{7}$$

The heat flux through membrane and air gap by conduction and vaporization can be expressed as:

$$q = \frac{k_m}{\delta_m}(T_{fm} - T_{ma}) + J_w\Delta h_{vap} \tag{8}$$

$$q = \frac{k_a}{\delta_{ag}}(T_{ma} - T_{cf}) + J_w\Delta h_{vap} \tag{9}$$

The heat flux through condensate film can be expressed as:

$$q = \alpha_{con}\left(T_{cf} - T_{fp}\right) \tag{10}$$

The heat flux through condensing plate can be expressed as:

$$q = \frac{k_{cp}}{\delta_{cp}}\left(T_{fp} - T_{pc}\right) \tag{11}$$

The heat flux through condensing plate can be expressed as:

$$q = \alpha_c\left(T_{pc} - T_c\right) \tag{12}$$

where Δh_{vap} is the enthalpy of vaporization of water, δ_{cp} is the condensing plate thickness, and α_{con} is the condensation heat transfer coefficient. k_m, k_{ag} and k_{cp} are the thermal conductivities of membrane, air and cooling plate respectively.

2.2 Performance Evaluation

To evaluate the water removal capacity of AGMD regenerator, the regeneration rate is defined as:

$$RR = \int_0^L JW \mathrm{d}x \tag{13}$$

where L is the membrane length.The thermal efficiency of AGMD regenerator can be expressed as:

$$TE = \frac{RR \times \Delta h_{\mathrm{vap}}}{RR \times \Delta h_{\mathrm{vap}} + Q_{\mathrm{loss}}} \tag{14}$$

where Q_{loss} represents the heat loss to the coolant by conduction.

The temperature polarization coefficient is expressed as:

$$TPC = \frac{T_{\mathrm{fm}} - T_{\mathrm{cf}}}{T_{\mathrm{f}} - T_{\mathrm{c}}} \tag{15}$$

3 Results and Discussion

Based on the above heat and mass transfer theory, a numerical model with differential equations is established in MATLAB and the equation group is solved by infinite difference method. The PTFE membrane used in this study has a pore size of 0.45μm, a thickness of 150μm as well as a porosity of 80% [12]. LiCl solution is adopted as the liquid desiccant. It should be noted that the rest of operation parameters are kept constant when one variable is investigated in parametric analysis unless otherwise specified. The AGMD module geometry dimension and the reference values of operation parameters are summarized in Table 1.

Table 1. AGMD module geometry dimension and reference values of operation parameters.

AGMD module geometry dimension		Reference values of operation parameters	
Channel length L (mm)	500	Solution flow rate m_{f} (kg/s)	0.02
Channel width W (mm)	300	Coolant flow rate m_{c} (kg/s)	0.02
Channel depth D (mm)	3	Solution inlet temperature $T_{\mathrm{f,in}}$ (°C)	60
Air layer thickness δ_{ag} (mm)	1	Coolant inlet temperature $T_{\mathrm{c,in}}$ (°C)	20
Condensing plate thickness δ_{cp} (mm)	0.5	Feed inlet concentration X_{in} (wt%)	20

3.1 Effects of Operation Temperatures

Temperatures of feed and coolant are associated with vapor pressures, thereby playing an important role in regenerator performance. Figure 2 shows the effects of operation temperatures on the regenerator performance. It can be seen that increasing the feed temperature can lead to a dramatic rise in both of the regeneration rate and the thermal efficiency. However, the temperature polarization effect is also found to be intensified. By contrast, reducing coolant temperature has a similar influence on the regeneration rate but results in an obvious decrease in the thermal efficiency. At the same time, a slight mitigation of the temperature polarization effect can be observed.

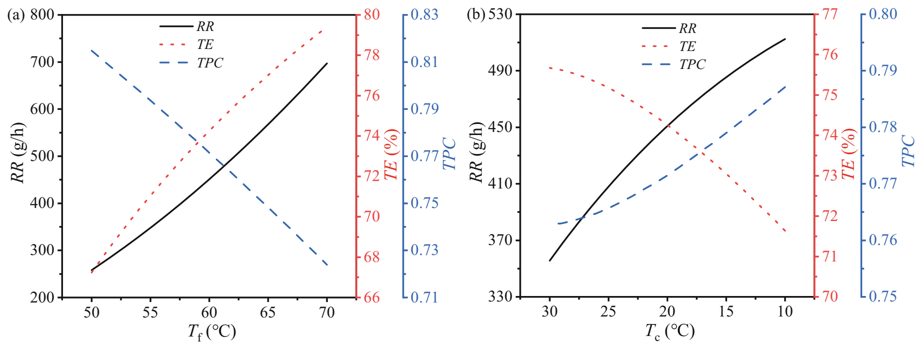

Fig. 2. Effects of operation temperatures on the regenerator performance

3.2 Effects of Flow Rates

The effects of desiccant and coolant flow rates on the regenerator performance are presented in Fig. 3. It can be seen from Fig. 3 (a) that both the regeneration rate and the thermal efficiency rise with the increase of the desiccant flow rate. Figure 3 (b) shows that increasing the coolant flow rate can also lead to a growth in the regeneration rate but whose impact is not as noticeable as increasing the desiccant flow rate. For example, increasing the desiccant flow rate from 0.015 kg/s to 0.035 kg/s causes 33.3% rise in the regeneration rate, while increasing the coolant flow rate by the same amount only achieves an 8.8% growth. In addition, increasing the coolant flow rate is observed to have a negligible effect in the thermal efficiency. It is worth noting that increasing both of the flow rates can effectively mitigate the temperature polarization effect.

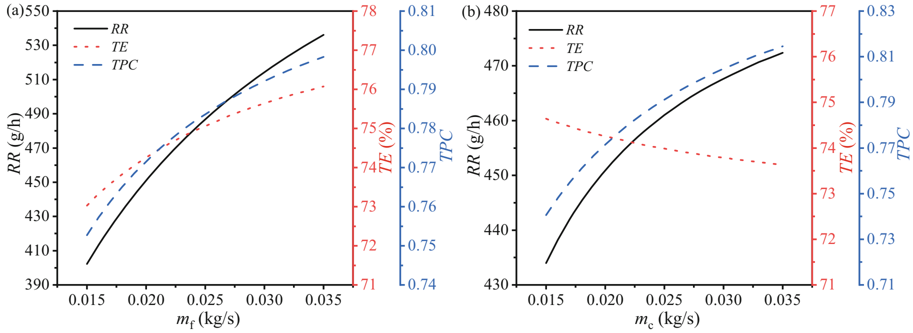

Fig. 3. Effects of flow rates on the regenerator performance

3.3 Effects of Enhancement Factors for Heat Transfer

Enhancing the heat transfer from the desiccant to the coolant can significantly reduce the temperature polarization effect and thus improve the regeneration performance. This subsection is aimed at revealing the effects of enhancement factors for heat transfer in various stages. Given that heat conduction is dominated by thickness and thermal properties of materials, only the convection in the desiccant/coolant channels and on the condensing plate surface is discussed.

As can be seen in Fig. 4, enhancing the heat convection inside the desiccant channel exerts a positive influence on the regeneration rate, the thermal efficiency as well as the temperature polarization coefficient. By comparison, enhancing the heat convection inside the coolant channel makes a minor contribution to the regeneration rate but leads to a slight reduction in the thermal efficiency. Besides, enhancing the heat convection inside both of the channels has a similar effect on the temperature polarization coefficient. With regard to enhancing the condensation heat transfer over the condensing plate, it has a negligible effect on the regeneration performance. The answer for this can be found from the distribution of thermal resistance as demonstrated in Fig. 5. The falling film only accounts for less than 0.2% of the total thermal resistance, indicating that enhancing the condensation heat transfer makes little sense to the overall regeneration performance.