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# Theoretical analysis of a liquid desiccant based indirect evaporative cooling system

X. Cui [a], M.R. Islam [b], B. Mohan [a], K.J. Chua [a, b, *]

[a] Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576, Singapore
[b] Engineering Science Programme, National University of Singapore, 9 Engineering Drive 1, Singapore 117575, Singapore

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ABSTRACT

A compact desiccant-evaporative HMX (heat and mass exchanger) has been proposed by combining the benefits of the regenerative indirect evaporative cooling and the liquid desiccant dehumidification. In this design, the compact HMX was able to cool and dehumidify the product air simultaneously in a single unit. A computational model has been developed and validated using experimental data. The model displayed good agreement with the experimental findings with maximum discrepancy of 8%. The heat and mass transfer behavior was theoretically investigated to illustrate the detailed air treatment performance of the HMX. Simulations were performed to study the effect of several key parameters on the HMX's performance. Due to the effect of pre-cooling and pre-dehumidification, the working air showed improved cooling potential in the working channel. Consequently, the temperature of the product air could be reduced below the dew-point temperature of intake air. Simulation results showed that the outlet temperature of the product air was affected by the working-to-intake air flow rate ratio and the dimensionless channel length, while the outlet humidity ratio of the product air was influenced by the length of the liquid desiccant film and the dimensionless channel length.



## 1. Introduction

Air-conditioning systems should fulfill their duties to meet the cooling requirements due to sensible and latent loads. In conventional vapor compression systems, the latent cooling load is handled by cooling the process air to below its dew-point temperature in order to condense water vapor. The dehumidified air may be reheated thereafter to meet the required indoor condition. The over-cooling and reheating processes are key disadvantages of a conventional vapor compression system due to its inefficient method to dehumidify air. To overcome the drawback of the conventional vapor compression system, novel energy-saving green air-conditioning techniques are imperative.

Indirect evaporative cooling is considered an effective and sustainable method for sensible cooling. Indirect evaporative cooling system produces cool air by taking the advantage of the large latent heat of water evaporation, therefore, it is suitable for hot and arid regions. As a potential alternative to the mechanical vapor compression system, it has been studied in numerous research works [1–3]. Possible improvements on the IEHX (indirect evaporative heat exchanger) have been proposed for better cooling effectiveness. Regenerative IEHX, based on M-cycle, is able to provide cool air with an outlet temperature approaching to its dew-point temperature [4–6]. In a regenerative IEHX, the working air employs the pre-cooled air which is redirected from the product channel [2]. As a result, the product air is cooled without absolute humidity change. Researchers have studied several types of the IEHX with counter-flow [7–10] and cross-flow arrangements [11,12]. It is reported in previous studies that the regenerative IEHX is able to achieve a dew-point effectiveness up to 0.9. The concept of evaporative cooling has been widely used in a variety of air-conditioning systems [13–16]. However, the IEHX is unable to effectively handle latent cooling load which limits its application in humid climates.

The use of LD (liquid desiccant) for dehumidification is one promising method to deal with latent cooling load [17–19]. A number of theoretical and experimental studies have been conducted to investigate liquid-desiccant's dehumidification performance. For example, Mesquita [20] et al. developed mathematical models for parallel-plate type liquid desiccant dehumidifiers. Dai and Zhang [21] numerically studied the simultaneous heat and mass transfer in a cross-flow liquid desiccant dehumidifier. Analytical models were developed based on the overall heat and mass transfer coefficients determined from using dimensionless

* Corresponding author. Tel.: +65 6516 2558; fax: +65 6779 1459.
*E-mail address:* mpeckje@nus.edu.sg (K.J. Chua).

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**Nomenclature**

| | |
|---|---|
| $\alpha$ | thermal diffusivity [$m^2/s$] |
| $c$ | molar concentration [$mol/m^3$] |
| $D$ | diffusivity [$m^2/s$] |
| $h_{fg}$ | specific latent heat of water evaporation [kJ/kg] |
| $H$ | height of the channel [m] |
| $k$ | thermal conductivity [W/(m °C)] |
| $L$ | length of the channel [m] |
| $m$ | mass flow [kg/s] |
| $M$ | molar mass [kg/mol] |
| $P$ | pressure [kPa] |
| $r$ | working-to-intake air flow rate ratio |
| $R$ | ideal gas constant [kJ/(K mol)] |
| $T$ | temperature [°C] |
| $u$ | velocity in $x$ direction[m/s] |
| $v$ | velocity in y direction [m/s] |
| $V$ | volume flow rate of air [$m^3/s$] |
| $\omega$ | humidity ratio [g moisture/kg dry air] |
| $\varepsilon$ | efficiency |
| $\mu$ | dynamic viscosity coefficient [Pa s] |
| $\nu$ | kinematic viscosity [$m^2/s$] |
| $\rho$ | density [$kg/m^3$] |
| $\delta$ | thickness [m] |
| $\Gamma$ | mass flow rate of liquid desiccant solution per unit width [kg/(m s)] |
| $\zeta_D$ | concentration (mass fraction) of desiccant in the solution |
| $\zeta_w$ | concentration (mass fraction) of water in the solution |

*Subscript*

| | |
|---|---|
| *a* | air |
| *D* | desiccant |
| *in* | inlet |
| *out* | outlet |
| *w* | water |
| *dew* | dew-point temperature |
| *s* | solution |
| *sat* | saturated |
| *equ* | equilibrium |

parameters [22,23]. In the dehumidifier, the liquid desiccant directly contacts the moist air. One of the commonly selected dehumidification equipment is packed towers [24,25]. Compared with a random packed configuration, the structured packing provides a smaller pressure drop on the air side [26,27]. Since the moisture removal process releases latent heat, the increased temperature may depreciate the capability of the liquid desiccant. Consequently, improvements were proposed by incorporating internal cooled elements such as cooling water [28–30].

Several studies have proposed combined systems in which the liquid desiccant dehumidifier is integrated with other cooling equipment. Saman and Alizadeh [31] investigated a dehumidifier which was indirectly cooled by a secondary air stream. It was also reported that the performance of the conventional vapor compression system could be improved by utilizing liquid desiccant dehumidification [32,33]. In some combined systems, the liquid desiccant dehumidifier could also be operated in tandem with IEC (indirect evaporative cooling) devices [34–37], and/or DEC (direct evaporative cooling) devices [38,39]. In such systems, the process air was first dehumidified by the liquid desiccant, and then cooled in the IEC or DEC devices.

The review of previous studies indicates that the indirect evaporative cooling system and the liquid desiccant dehumidification system have been extensively investigated as shown in Table 1. In most of the previous related works, the IEC device or the LD dehumidifier was examined as a stand-alone unit. Thus far, few works have focused on the development of a compact HMX (heat and mass exchanger) which incorporates liquid desiccant to realize a regenerative IEHX based on M-cycle.

The present study aims to investigate the thermal process in a novel compact HMX which is able to dehumidify and cool the product air simultaneously in one single unit by combining the benefits of regenerative indirect evaporative cooling and liquid desiccant dehumidification. The advantages of the HMX are as follows. (i) The compact unit can save space. (ii) The arrangement makes full use of the working air to cool the liquid desiccant before the working air is finally exhausted. Cooling of liquid desiccant using precooled working air enhances the moisture absorption potential of liquid desiccant from the product air. (iii) The air can be dehumidified and cooled simultaneously in one unit. (iv) The compact HMX could be a potential alternative to the conventional vapor compression air handling unit. Therefore, considering these aspects, we believe it is essential to conduct a study on this compact design. The key objectives of this work are as follows: (1) introduce a desiccant-evaporative cooling HMX design in which the product channel is partially covered with liquid desiccant; (2) present a mathematical model to theoretically study the performance of the HMX; (3) investigate the influence of several key parameters such as the working-to-intake air flow rate ratio ($r$), the liquid desiccant film length ($L_D$), the dimensionless channel length ($L/H$), and the inlet conditions ($T_{a,in}$, $\omega_{a,in}$). Table 1 also indicates the differences between the present study and selected representative studies from literature.

In this paper, we first describe the configuration of the desiccant-evaporative HMX, followed by the mathematical formulation of the heat and mass transfer phenomenon in the HMX. The mathematical model is then validated against two sets of experimental data. Finally, the theoretical performance of the HMX is analyzed via the validated mathematical model.

## 2. Description of the desiccant-evaporative HMX

The desiccant-evaporative cooling HMX combines the benefit of the regenerative IEHX with the liquid desiccant dehumidification process. Fig. 1 is a schematic of a one-unit channel pair of the desiccant-evaporative cooling HMX. The HMX comprises numerous channel pairs stacked together. In the working wet channel, similar to the regenerative IEHX, water is injected to maintain a wet condition. In the product channel, liquid desiccant is supplied and covers part of the active surface. The length of the liquid desiccant film ($L_D$) is one of the key parameters that impact dehumidification performance. At the end of the product channel, part of the product air is diverted into the working wet channel and is subsequently exhausted to the atmosphere. As shown in Fig. 1, the diverted product air is first dehumidified and pre-cooled before channeling to the wet channel. Therefore, the air at the starting point of the working channel has significant cooling potential. The product air usually experiences an increase in temperature due to the release of heat during the dehumidification process, and it is then gradually cooled by the indirect evaporative cooling. As a