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Energy performance of internally cooled desiccant enhanced evaporative cooling system in Hong Kong

Yanling Zhang*
the School of Professional Education and Executive Development
Renewable Energy Research Group, Department of Building Environment and Energy Engineering
The Hong Kong Polytechnic University
Hong Kong, China
yanling.zhang@connect.polyu.hk

Hao Zhang
the School of Professional Education and Executive Development
The Hong Kong Polytechnic University
Hong Kong, China
hao.zhang@cpce-polyu.edu.hk

Hongxing Yang
Renewable Energy Research Group, Department of Building Environment and Energy Engineering
The Hong Kong Polytechnic University
Hong Kong, China
hong-xing.yang@polyu.edu.hk

Yi Chen*
College of Marine Equipment and Mechanical Engineering
Jimei University
Xiamen, China
chenyi0511@jmu.edu.cn

Chun Wah Leung
the School of Professional Education and Executive Development
The Hong Kong Polytechnic University
Hong Kong, China
chunwah.leung@cpce-polyu.edu.hk

Abstract—The application of an internally cooled desiccant enhanced evaporative cooling system (ICDEVap) in Hong Kong is a promising scheme for energy saving and emission reduction. It consists of liquid desiccant dehumidification (LDD) and regenerative indirect evaporative cooling (RIEC) and can operate without a power-intensive compressor. The hot and humid air is first dehumidified by the internal cooling-*LDD*, and then sensibly cooled by the RIEC. To ensure efficient energy utilization and better indoor air quality simultaneously, the return air is indirectly utilized in the internal cooling of the LDD, which alleviates the efficiency deterioration of the desiccant. The influence of the return air ratio on the system performance is analyzed. The results show that the ICDEVap system operating at the optimal return air ratio saves 48% of the energy consumption compared to the mechanical vapor compressor refrigeration (MVCR) system in Hong Kong summer.

Keywords—liquid desiccant dehumidification; regenerative indirect evaporative cooling; energy saving; hot and humid

I. INTRODUCTION

Air conditioning systems are predicted to be the second-largest source of electricity consumption in the next three decades.[1] Especially in hot and humid area, like Hong Kong, buildings account for 60% of the total annual electricity consumption [2]. About 30-50% of the energy consumption is consumed by Air Conditioning (AC) systems [3]. In hot and humid areas, traditional MVCR systems coupled to handle heat and humidity loads can waste energy and have limited ability to accurately control temperature and humidity. Although better energy performance can be achieved by reapplying return air to the MVCR system, mixing return air with fresh air increases the risk of disease transmission in air-conditioned rooms. Therefore, indirect evaporative cooling (IEC) and liquid desiccant dehumidification (LDD) systems may be a safe and efficient alternative to MVCR air conditioning systems in hot and humid regions.

The liquid desiccant is considered a promising dehumidification method in air conditioning systems. However, the deterioration resulting from solution temperature increase during the dehumidification process is one major problem facing traditional LDD. Therefore, when considering the application of liquid desiccant for dehumidification in hot and humid areas, internal cooling is a promising measure to improve the vapor pressure difference and maintain the performance of dehumidification processes. Internal cooling LDD can effectively perform dehumidifying and preliminary ambient air cooling with high wet-bulb temperature. However, the sensible heat load of the air in hot and humid areas still requires a powerful cooling device.

Regenerative Indirect Evaporative Cooling (RIEC) utilizes cooled and dried air from the product air outlet to return to the secondary channel to be evaporatively cooled again, making the system efficient. This internally cooled desiccant enhanced evaporative cooling system (ICDEVap) will be a promising energy-saving solution for fresh air treatment in AC systems. The energy consumption of ICDEVap is expected to be much lower than that of conventional mechanical vapor compression refrigeration (MVCR) systems.

Previous studies on LDD-IEC [4-6] have amply demonstrated the excellent performance of this system in terms of energy efficiency and cooling effectiveness. However, the cooling methods of LDD are mostly based on external cooling facilities. The newly proposed system will fully apply the indoor return air as the air source for the internal cooling channels. The study will explore the impact of the return air ratio on system performance and evaluate the energy-saving with that of a conventional MVCR system in Hong Kong.

A	Heat and mass transfer surface area (m2/m)
cp	specific heat (kJ/kg·K）
H	channel height (m)
h	specific enthalpy (kJ/kg)
K	heat transfer coefficient (W/m2·K)
m	mass flow rate (kg/s)
NTU	Number of transfer units
RC	working to fresh air mass flow ratio in LDD (kg/kg)
Re	Reynolds number
re	Secondary to primary air mass flow ratio in RIEC
RH	Relative humidity %
t	Temperature (°C)
w	Humidity ratio (kg/kg)
a	air
ew	evaporation water
g	water vapor
w	water

II. Proposed System

The schematic diagram of the proposed ICDEVap system is shown in Figure 1. The outdoor air (33.7°C, 70% RH, Hong Kong weather conditions) first removes the latent heat and achieves initial cooling in an internally cooled LDD. RIEC is used to sensibly cool the air, a portion of the low-temperature dry fresh air is recycled and regenerated as the working air of

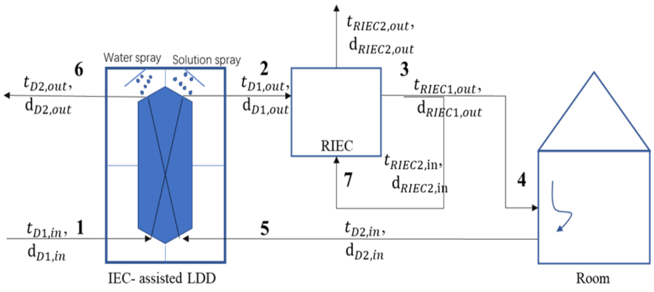

Figure 1 Schematic diagram of ICDEVap system

the RIEC, and the majority of the fresh air is sent to indoors. The return air (25°C, 55%) is supplied to the LDD cooling channels for internal cooling.

III. Methods

The model of each component of the system is established separately. Figure 2 shows the flow chart of the system model. The entire system is modeled with the following assumptions: 1) the system unit is adiabatic, no heat exchange with the outside, and no air leakage 2) the thermal properties of water are constant. 3) both the liquid desiccant and the water film are uniformly spread over the walls 4) heat and mass are transferred only vertically across the partitions 5) the Lewis number is uniform.

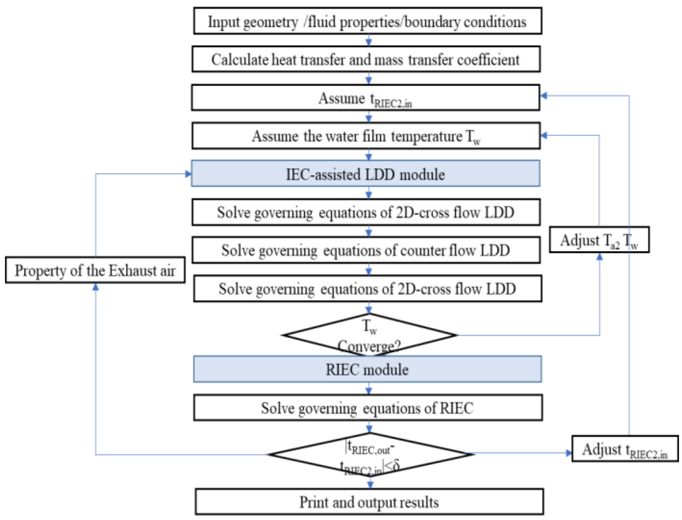

Figure 2 Simulation flow chart for solving the ICDEVap model

A. *LDD model*

A 2-dimensional finite model was created for the dehumidification channel and the internal cooling channel in the internal cooling LDD model. A hexagonal heat exchanger was used to obtain a better heat exchange between the dehumidification and cooling channel. The latent and sensible heat processes occurring in the microelements in the dehumidification channel can be expressed as Eq. (1) to (2).

$$dQ_{sen,s} = \alpha_s(t_s - t_{a1})2A\frac{d_x}{l} \quad (1)$$

$$dQ_{lat,s} = \frac{\alpha_s}{c_{p,a1}} \cdot r_w \cdot (w_s - w_{a1})2A\frac{d_x}{l} \quad (2)$$

The energy and mass conservation equations for dehumidification channels are shown as Eq.(3) to (4).

$$Qdx + m_{a1}dh_{a1} - dm_s c_{ps} t_s = 0 \quad (3)$$

$$m_{a1}dw_{a1} = dm_s \quad (4)$$

The energy and mass conservation equation for the internal cooling channel can be expressed as Eq.(5) to (6).

$$-Qdy + m_{a5}dh_{a5} - dm_w c_{pw} t_w = 0 \quad (5)$$

$$m_{a5}dw_{a5} = dm_w \quad (6)$$

The heat transfer between the two channels can be expressed as Eq. 7.

$$Q = K(t_s - t_w)d_x d_y \quad (7)$$

B. *RIEC MODEL*

For the RIEC model, a 2-dimensional finite model was developed. As the air undergoes a sufficient latent heat treatment before entering the RIEC. Therefore, there is no condensation in the primary channel of the RIEC, only sensible heat exchange. The heat and mass transfer processes and the mass-energy balance of the primary and secondary channels of the model will be solved.

The heat and mass balance are calculated in the secondary air as:

$$h_{a7}(t_{wall} - t_{a7})dA = c_{pa7}m_{a7}dt_{a7} \quad (8)$$

$$hm_{a7}(\omega_{twall} - \omega_{a7})dA = m_{a7}dw_{a7} \quad (9)$$

The heat balance equations of IEC without considering condensation from the primary air can be calculated as:

$$h_{a2}(t_{a2} - t_{wall})dA = cp_{a2}m_{a2}dt_{a2} \quad (10)$$

The mass balance of the evaporation film in the secondary channel:

$$dm_{ew} = m_{a2}dw_{a2} \quad (11)$$

Energy balance equation of the control volume:

$$m_{a2}dh_{a2} - cp_{a2}m_{a2}dt_{a2} = d(cp_{wall}t_{ew}m_{ew}) \quad (12)$$

The air mass flow rate relationship between the secondary channels of the RIEC, and the internal cooling channels of the LDD depends on the extraction air ratio of the RIEC re, $re = \frac{m_7}{m_3}$. The airflow ratio between the internal cooling channel and the dehumidification channel in the LDD is the return air ratio, expressed as RC, $RC = \frac{m_5}{m_1}$.

IV. RESULTS

A. *OPTIMIZATION OF THE RETURN AIR RATIO*

In the inner cooled LDD-RIEC, the secondary channel of the RIEC takes a portion of the fresh air from the primary channel outlet and uses it as secondary airflow. A larger extraction ratio helps to increase the cooling efficiency. However, sacrificing more produced air to return weakens the dehumidification and cooling effect of the internal cooling in the LDD. Therefore, it is important to optimize the return air ratio in the system.

A comparison of the influence of different RIEC return air ratios on the cooling and dehumidification effect of the LDD-RIEC system is shown in Figure 3. The temperature, moisture content and air supply volume entering the room are taken as the optimization targets. Considering a smaller return air ratio result in a larger supply air volume to ensure a uniform airflow distribution reaching the room. Overall, taking into account the interaction between the dehumidifier, the RIEC and the room return air, the optimum return air ratio for the RIEC is 0.3.

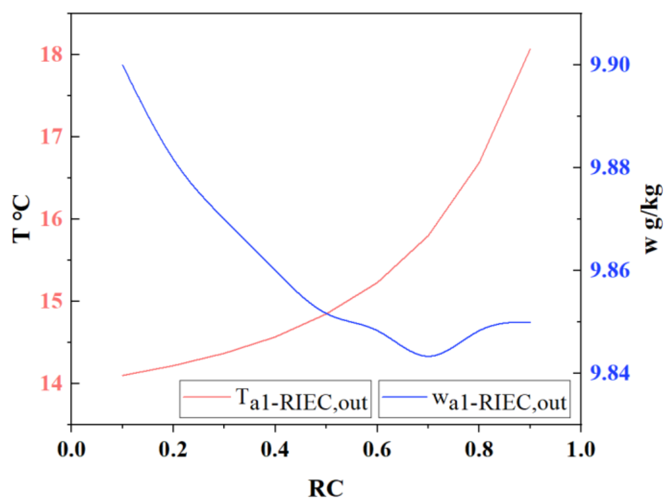

Figure 3 Influence of RC on outlet temperature and humidity ratio

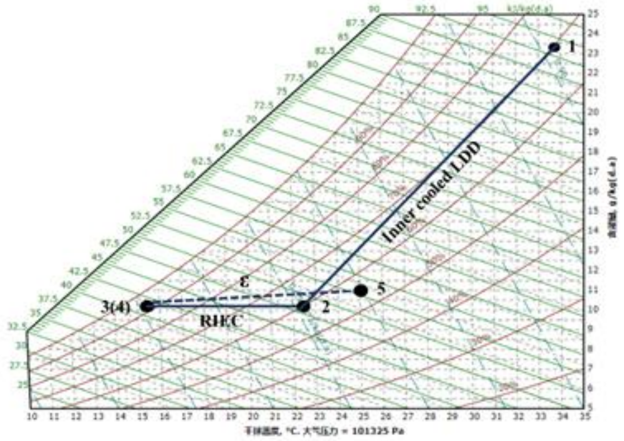

Figure 4 Air handling process psychometric chart of ICDEVap system

B. Air handling process

Using the model developed above, simulations were carried out at typical design air conditions in Hong Kong (outdoor: 33.7°C, 70%, indoor: 25°C, 55%). Based on the optimized return air ratio proposed in 4.1, the re in the RIEC is 30% and the RC in the LDD is 0.7.

Figure 4 gives the primary air treatment process of the ICDEVap system when the return air ratio is 0.7 in the form of a psychrometric chart. The ambient air is first dehumidified in the LDD unit to remove latent and partial sensible heat and then cooled by the RIEC for sensible load before entering the room. The air conditions of each point in the psychrometric diagram refer to table 1.

TABLE 1. AIR CONDITIONS OF EACH POINT (RC=0.7)

Point	Name	t(°C)	RH	ω(g/kg)	h(kj/kg)	m(kg/s)
1	D1,in	33.7	0.7	23.47	93.94	0.12
2	D1,out	21.86	0.602	9.89	47.113	0.12
3	RIEC1,out	16.69	0.83	9.89	41.82	0.084
5	D2,in	25	0.55	10.93	52.98	0.084
7	RIEC2,in	16.69	0.83	9.89	41.82	0.036

C. Energy performance of the system

The total cooling capacity of the IEDEVap system in terms of sensible and latent heat is calculated to be 7.76 kW. The current system widely achieves sufficient air supply and maximum energy savings at an optimized return air ratio of 0.3 (return air conditions: 25°C, RH=55%). The energy consumed by the IEC-assisted LDD and RIEC systems is mainly used for the electricity consumption of the circulation pumps, the solution pumps, and the fans. Based on the estimated energy consumption of 0.66 kW for the pumps and solution pumps and 0.24 kW for the fans, the coefficient of performance (COP) of the LDD-RIEC system can therefore be calculated as 8.6, which is much higher than the COP of the MVCR system (3.0-5.0). The energy consumption of the MVCR system is evaluated to be 1.94 kW (COP=4) when handling the same amount of cooling load. The newly developed ICDEVap system is therefore 48% more energy-efficient than a conventional MVCR system.

V. Conclusions

The internally cooled desiccant enhanced evaporative cooling system (ICDEVap) was explored by reusing the fresh air treated by regenerative indirect evaporative cooling (RIEC) as an indirect cooling source and using the return air in the room as an internal cooling air source for the liquid desiccant dehumidifier (LDD). The simulation results of the system show that the optimal ratio of regenerated fresh air ratio is 30%. The system operating under the optimal regeneration ratio can completely replace the traditional vapor compression air conditioner, and the energy-saving rate is 48%

Acknowledgments

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References

1. Allison, C.K. and N.A. Stanton, Eco-driving: the role of feedback in reducing emissions from everyday driving behaviours. Theoretical Issues in Ergonomics Science, 2019. 20(2): p. 85-104.
2. Department, C.a.S., Hong Kong Energy Statistics Annual Report. 2021, Census and Statistics Department.
3. Pérez-Lombard, L., J. Ortiz, and C. Pout, A review on buildings energy consumption information. Energy and Buildings, 2008. 40(3): p. 394-398.
4. Chen, Y., Y. Luo, and H. Yang, Energy Saving Potential of Hybrid Liquid Desiccant and Evaporative Cooling Air-conditioning System in Hong Kong. Energy Procedia, 2017. 105: p. 2125-2130.

5. Chen, Y., H. Yang, and Y. Luo, Investigation on solar assisted liquid desiccant dehumidifier and evaporative cooling system for fresh air treatment. Energy, 2018. 143: p. 114-127.

6. Kim, M.-H., J.-S. Park, and J.-W. Jeong, Energy saving potential of liquid desiccant in evaporative-cooling-assisted 100% outdoor air system. Energy, 2013. 59: p. 726-736.