Conference Proceedings

EuroSun 2014

Aix-les-Bains (France), 16 – 19 September 2014

Two-Stage Air-Dehumidification System for the Tropics – Assessment of Conceptual System Configurations

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Abstract

Under tropical climate conditions, conventional air-conditioning systems consume a considerable amount of electricity in order to get rid of the high latent load (humidity) of the ambient air. This is due to the applied simultaneous dehumidification and cooling processes. Therefore, an idea of a separate handling of the latent and the sensible loads is investigated by applying series connected heat powered dehumidification and electricity powered cooling systems. A two-stage dehumidification system including a membrane-based heat and mass exchanger and an Evaporatively COoled Sorptive dehumidification system (ECOS system) is proposed to dehumidify the ambient air; the sensible load (cooling of dehumidified air) is handled by an efficient conventional cooling process operating at relatively high evaporation temperatures ($14-20\ ^\circ\mathrm{C}$).

The aim of this study is to evaluate different conceptual system configurations and to find optimized systems for tropical climate conditions (air humidity and temperature are in the order of $20\ \mathrm{g_v/kg_{air}}$ and $32\ ^\circ\mathrm{C}$, respectively) by means of simulation calculations. The dehumidification capacity, the total specific removed enthalpy and the thermal coefficient of performance (COP) of the system are used as criteria for an assessment of the proposed concepts. The dehumidification system is mathematically modelled in MATLAB and linked with TRNSYS-17.1. Experimental data are used to validate the components models. Design and performance data of simulated air-dehumidification systems that are based on the concepts are presented.

Results of the performance assessment show that using additional ambient air flow for the evaporative cooling process in the ECOS system can improve the dehumidification performance of the system and can reduce the cooling load of the cooling system significantly.

Keywords: Two-stage air-dehumidification; membrane-based heat and mass exchanger; ECOS system; adsorption system; tropical climate.

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1. Introduction

In tropical cities, air-conditioning systems are challenged to counteract a high latent load (humidity) of the ambient air. In the conventional air-conditioning systems the dehumidification is generally reached by cooling the ambient air below its dew-point temperature (6-8°C) which normally results in high electricity consumption.

Membrane and a desiccant based air-dehumidification technologies have been exploited intensively in innovative air-conditioning systems in order to counteract the latent load while the cooling systems only handles the sensible load (Dai et al., 2002; Finocchiaro et al., 2012; Liang et al., 2010). A combination of a membrane unit and an evaporatively cooled sorptive dehumidification system (ECOS system) as a two-stage dehumidification system has been developed by the Solar Energy Research Institute of Singapore (SERIS) in collaboration with the Fraunhofer ISE. Dehumidification performance of the proposed two-stage dehumidification system under different operation conditions such as the regeneration temperatures and the air flow rates was evaluated in a recently published paper (Safizadeh et al., 2014).

In the current study, four different conceptual design configurations are analyzed. The conceptual

Selection and/or peer review under responsibility of EuroSun2014 Scientific Committee
doi:10.18086/eurosun.2014.07.14 Available at http://proceedings.ises.org

configurations are proposed as modifications of the reference system shown in Fig. 1. The modifications (Fig. 2) consist of (i) an air bypass configuration to supply a fraction of the return air flow to the membrane unit only, (ii) of an indirect evaporative cooling unit before the membrane unit, (iii) of an indirect evaporative cooling unit after the membrane unit and before the ECOS system, and (iv) of a mixing of ambient air and return air leading to a higher flow rate into the ECOS system.

An assessment of the proposed concepts (Fig. 2) provides valuable information for designing air-dehumidification systems (following the basic concept shown in Fig. 1) for practical application in the tropics.

Nomenclature		**Subscripts**	
$\dot{Q}$	Heat flow rate (kW)	*Ave*	Average
$\dot{m}$	Mass flow rate (kg s^{-1})	*removed enthalpy*	Removed enthalpy
h	Specific enthalpy (kJ kg^{-1})	*regeneration*	Regeneration air/process
COP	Coefficient of performance (-)	*ambient*	Ambient air
n	Number of data	*Supply*	Supply air
t_0	Start time for a process	*Process*	Process air
t_{end}	End time for a process	*v*	Vapour
		air	Air

2. System description

2.1 Description of the two-stage dehumidification system

Fig. 1 presents a schematic diagram of the analyzed two-stage dehumidification system. In the first stage, the warm and humid ambient air is pre-dehumidified and pre-cooled by the membrane unit. Thereafter, in the second stage, the pre-dehumidified process air is supplied to the ECOS system to be dehumidified to the desired humidity set-point. The dehumidification and cooling processes in the membrane unit are driven by the humidity and temperature gradient between the warm and humid ambient air (primary air) and the relatively dry and cool return air (secondary air) from the conditioned room. The cooling air leaving the membrane unit is discharged to the ECOS system to allow for an evaporative cooling process inside the ECOS system. Solar thermal energy or waste heat is used for the regeneration of the adsorption material of the ECOS system. The working principles of the membrane unit and the ECOS system are described by the previous studies (Bongs, 2013; Bongs et al., 2014; Niu and Zhang, 2001; Safizadeh et al., 2014).

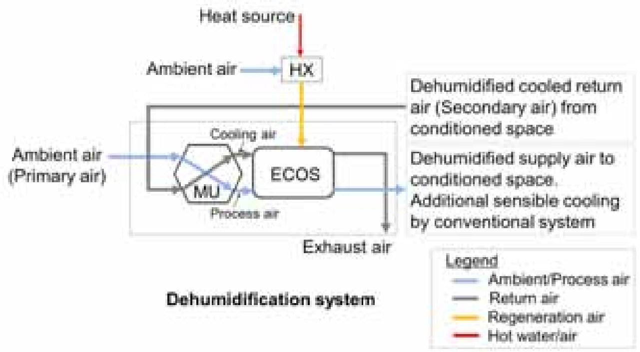


Fig. 1: Schematic diagram of a two stage-dehumidification system. MU stands for the membrane unit, ECOS stands for the Evaporatively COoled Sorption dehumidification system and HX stands for the heat exchanger. As the heat source, solar thermal energy or waste heat is considered. Electric energy is used for air transport.

2.2 Description of the conceptual system configurations

In this paper, the performance of four conceptual system configurations for a two-stage dehumidification system is assessed. The underlying idea is that the conceptual configurations may improve the performance of the two-stage dehumidification system.

I. System configuration-1:

Introducing an air bypass around the membrane unit for the return air flow in order to provide cooling air with a lower humidity ratio to the ECOS system (see Fig. 2-1). This decreases the wet-bulb temperature of the cooling air due to the lower humidity content and may increase the evaporative cooling efficiency for handling the adsorption heat in the ECOS system.

II. System configuration-2:

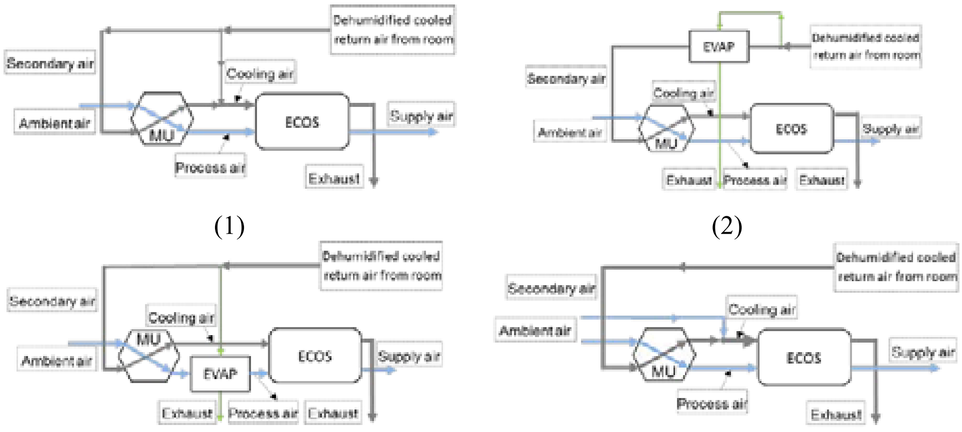
Introducing an indirect evaporative cooling unit before the membrane unit in order to further reduce the secondary air temperature to increase the cooling performance of the membrane unit (see Fig. 2-2). A fraction of the return air is used for the evaporative cooling of the secondary air flow. The adsorption performance of the ECOS system may be enhanced due to the improved pre-cooling process of the process air.

III. System configuration-3:

Introducing an indirect evaporative cooling unit after the membrane unit and before the ECOS system in order to cool down the process air temperature before entering the ECOS system (see Fig. 2-3). A fraction of the return air is used for evaporative cooling of the process air. Consequently, the ECOS system operates at lower temperatures (compared to the reference system, Fig. 1) which may result in a better water adsorption and a lower supply air temperature.

IV. System configuration-4:

Using a mixture of additional ambient air and secondary air (which has already been used for the dehumidification process in the membrane unit) resulting in a higher flow rate after the membrane unit and before the ECOS system (see Fig. 2-4). It may counteract the adsorption heat efficiently and increases the performance of the ECOS system due to higher cooling air flow rate and a better heat rejection process compared to the reference system shown in Fig. 1.



(1) (2)

(3) (4)

Fig. 2: Schematic diagrams of the conceptual system configurations 1 to 4 for the two-stage dehumidification systems described above. MU stands for the membrane unit, ECOS stands for the Evaporatively COoled Sorption dehumidification system, and EVAP stands for the evaporative cooling unit.

3. Model validation

Detailed conjugate transient heat and mass transfer equations for the ECOS unit (Barlow, 1982; Bongs, 2013; Pesaran and Mills, 1987) and the membrane unit (Min and Hu, 2011; Niu and Zhang, 2001) are numerically programmed in MATLAB and linked with other components (e.g. an indirect evaporative cooling unit) in TRNSYS in order to simulate and evaluate the performance of the four different conceptual system configurations under tropical climate conditions.

Simulation runs are performed using measured experimental air inlet conditions. The humidity and temperature of the simulated dehumidified air are compared with the experimental data. The dimensions of the ECOS and membrane units of the experimental system are summarized in Table 1 and Table 2.

Table 1: Dimensions of each ECOS unit

Parameter	Unit	Value
ECOS Height/ Length/ Width	m	0.4/0.4/0.4
Number of process/cooling channels	-	35/34
ECOS heat exchanger area	m^2	10.6

Table 2. Parameters of the membrane unit

Parameter	Unit	Value
Membrane Height/ Length/ Width	m	0.37/0.34/0.34
Number of membranes	–	77
Area of each membrane	m^2	0.13

Thickness sorption material	*mm*	1.0 - 1.20
Height of process/cooling channel	*mm*	3.6 - 4.0/5.0
Mass of silica gel	*kg*	7.3

barrier		
Total area of membranes	m^2	10.0
Height of each air channel	mm	2

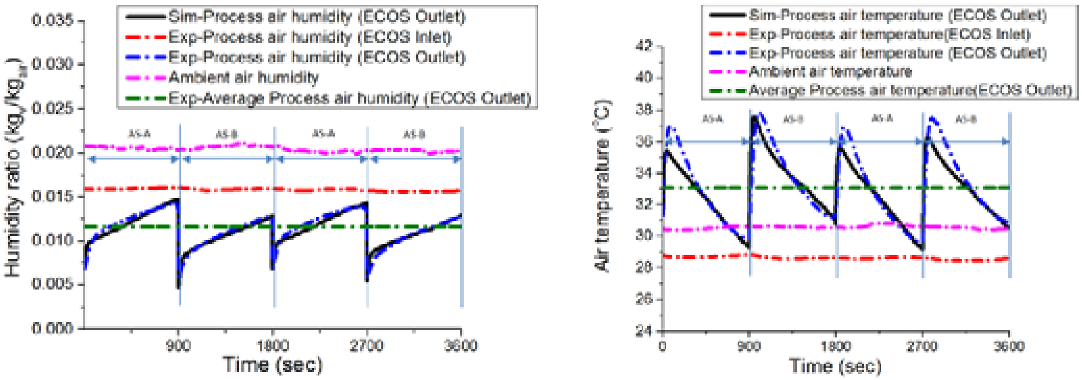
The experimental operating conditions of the ECOS system are listed in Table 3. The air flows for all three air streams including the supply air, the return air and the regeneration air are set to 0.055 *kg/s* (200m^3/h) and the regeneration air temperature is set to 85^oC. The system operates with an adsorption time of 15 *min*, a regeneration time of 13 *min* and 2 *min* for the pre-cooling stage.

Table 3. Experimental operating conditions

Parameter	**Value**
Cycle time	Adsorption: 15 min / Regeneration: 13 min / Pre-cooling: 2 min
supply/return/regeneration air flows	0.055 kg/s (200 m^3/h)
Regeneration air temperature	85^oC

Fig. 3 illustrates the comparison between the simulated and experimental values of the dehumidified process air at the outlet of the ECOS system. As observed from Fig. 3-a and Fig. 3-b, there is a reasonable agreement between simulation results in black color and experimental data in dashed blue color.

The dehumidification and cooling performance of the two-stage dehumidification system is explained as follows. As shown in Fig. 3-a, in the first stage, the humidity content of the ambient air in the order of 20 $\mathrm{g_v/kg_{air}}$ (in pink color) is removed by the pre-dehumidification process in the membrane unit in the average order of 5 $\mathrm{g_{va}/kg_{air}}$. In the next step, the pre-dehumidified process air (in red) is further dehumidified in the ECOS system in the average order of 4.5 $\mathrm{g_v/kg_{air}}$ to the green line. The properties of the dehumidified air (temperature and humidity) in each cycle are shown in blue color. Additionally, as can be seen from Fig. 3-b, the ambient air temperature in the order of 32°C (in pink color) decrease by 2°C in the membrane unit to the red line. During the adsorption process in the ECOS system, although the process air temperature (in blue color) is increased by the released adsorption heat, the average supply air temperature (green line) is still not much higher than the ambient air temperature due to the evaporative cooling effect in the ECOS system.



(a) (b)

Fig. 3: Comparison between the simulation and experimental values for the supply air at the system's outlet after the dehumidification process. The comparison of the humidity ratio is shown in (a) and the air temperature in (b). The regeneration temperature is 85℃ and the air flow rate is 200 $\mathbf{m^3/h}$. The adsorption time is 15 min, the regeneration time is 13 min and the pre-cooling time is 2 min.

4. Results and discussion

4.1 Performance assessment of the ECOS system under different ambient air temperatures

A need to have a pre-dehumidification process before a dehumidification process in a desiccant dehumidification system was assessed by previous studies (Finocchiaro et al., 2012; Safizadeh et al., 2014) (e.g. see Fig. 1).

They revealed that supplying pre-dehumidified process air to a desiccant dehumidification system has a positive effect on the performance of a complete dehumidification system. However, the effect of the process air temperature (see Fig. 1) was not assessed. Fig. 4 shows the dehumidification performance of the ECOS system under the experimental operating conditions listed in Table 3 and three different ambient air (process air) temperatures including the reference ambient condition in Singapore (in average order of 20 $\mathrm{g_v/kg_{air}}$

and 32 °C), the lower (-5K) and higher (+5K) temperatures are compared to the reference temperature. The dehumidification performance of the system increases with decreasing the process air temperature. It is due to the fact that the process air with a low temperature directly cools the desiccant material and partially handles the released adsorption heat. Consequently, the adsorption capacity of the cooled adsorbent material and the dehumidification capacity of the ECOS system are elevated. The positive pre-cooling effect on the desiccant dehumidification system encourages us to propose the second and third conceptual design. The aim of this configuration is to cool down the process air before entering the ECOS system leading to an improved dehumidification performance.

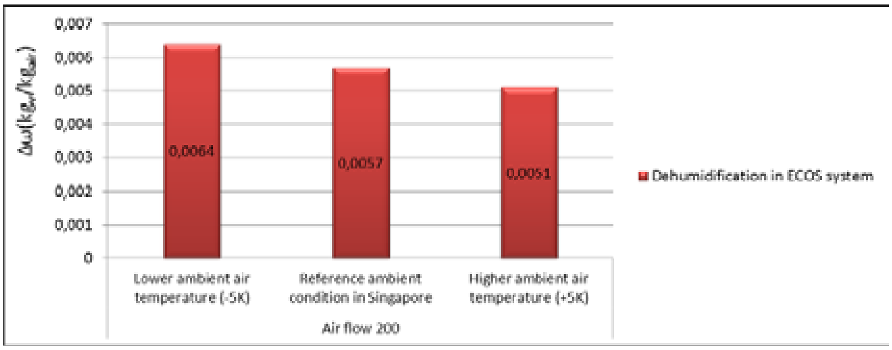


Fig. 4: Assessment of the ambient air (process air) temperature on the dehumidification performance of the ECOS system

4.2 Assessment of conceptual system configurations

In the current section, the evaluation of the four conceptual configurations (see Fig. 2) is carried out by choosing two different flow rates for each concept. Thereafter, the performances of these configurations are compared to the reference system. The simulation runs are performed based on the experimental operating conditions listed in Table 3 and dynamic Singapore climate conditions (ambient air humidity and temperature are in average order of 20 $\mathrm{g_v/kg_{air}}$ and 32 °C, respectively). An argument is later developed to recognize the optimal configuration among the proposed concept and the reference system.

The performance of the dehumidification system is characterized by the dehumidification capacity, the specific removed enthalpy (eq. 1) and the thermal coefficient of performance (COP, (eq. 4)). The mean specific removed enthalpy of the system is defined as the difference between the enthalpy of the ambient air entering a system and the enthalpy of the dehumidified process air (supply air) leaving the system (eq. 1). The removed enthalpy flow is calculated by (eq. 2). Both dehumidification as well as the temperature reduction (sensible cooling) of the ambient air determines the removed enthalpy. Additionally, the average thermal coefficient of performance (COP) of the dehumidification system is calculated by (eq. 4). The required heat for the regeneration process is calculated based on the enthalpy difference between the regeneration air after the heat exchanger (shown in Fig. 1) and the ambient air (eq. 3). Analyses of simulation or experimental data are carried out in a specified period of time (Δt) calculated by ($t_{end} - t_0$).

$$\Delta\mathrm{h}_{\mathrm{Ave,process}} = \left(\int_{t_0}^{t_{end}} \left(\mathrm{h}_{\mathrm{ambient}}(t) - \mathrm{h}_{\mathrm{supply}}(t) \right) dt \right) \Big/ \Delta t \qquad \text{(eq. 1)}$$

$$\dot{\mathrm{Q}}_{\mathrm{Ave,removed\ enthalpy}} = \dot{\mathrm{m}}\Delta\mathrm{h}_{\mathrm{Ave,process}} \qquad \text{(eq. 2)}$$

$$\dot{\mathrm{Q}}_{\mathrm{Ave,Regeneration}} = \dot{\mathrm{m}} \left(\int_{t_0}^{t_{end}} \left(\mathrm{h}_{\mathrm{regeneration}}(t) - \mathrm{h}_{\mathrm{ambient}}(t) \right) dt \right) \Big/ \Delta t \qquad \text{(eq. 3)}$$

$$\mathrm{COP}_{\mathrm{Ave,thermal}} = \frac{\dot{\mathrm{Q}}_{\mathrm{Ave,removed\ enthalpy}}(\Delta t)}{\dot{\mathrm{Q}}_{\mathrm{Ave,Regeneration}}(\Delta t)} \qquad \text{(eq. 4)}$$

Fig. 5 illustrates the dehumidification capacity of each configuration under two operation conditions and compares their dehumidification performance with the reference system shown in Fig. 1. The blue and the red bars present the dehumidification capacity of the membrane unit and the ECOS system, respectively. Fig. 6 shows the total specific removed enthalpy as the sum of the specific latent and sensible loads by the two-stage dehumidification system. Additionally, Fig. 7 shows the comparison between the thermal COPs calculated for the proposed conceptual configurations and the reference system. The comparison analyses between each configuration and the reference system are discussed in the following sections.

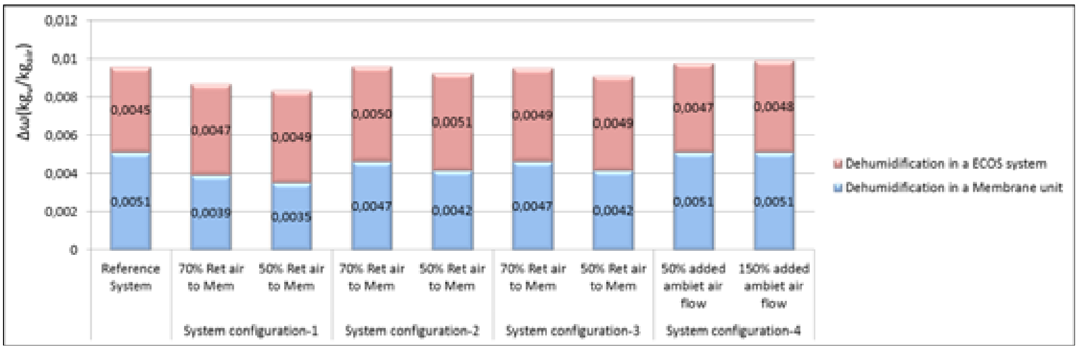


Fig. 5: Comparison between the dehumidification performances of the four proposed conceptual configurations and the reference system. The dehumidification capacities of the membrane unit and the ECOS system are shown in the blue and red bars, respectively. “Ret air to Mem” stands for the fraction of the return air to the membrane unit as a secondary air stream.

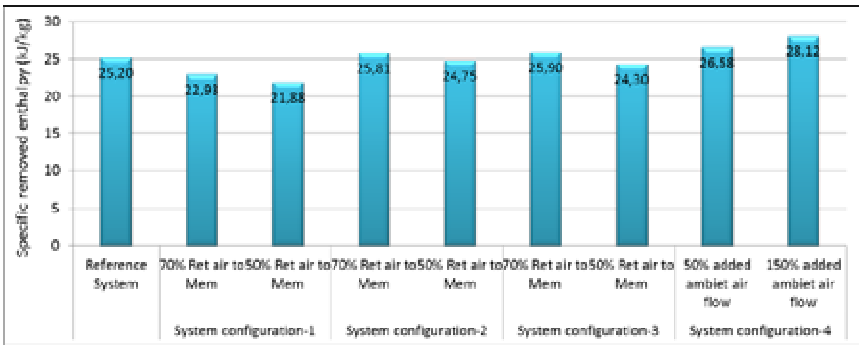


Fig. 6: Comparison between the total specific removed enthalpy (latent and cooling loads) by the four proposed conceptual configuration and the reference system. The mass flow rate is 0.055 *kg/s* (200 m^3/h). “Ret air to Mem” stands for the fraction of the return air to the membrane unit as a secondary air stream.

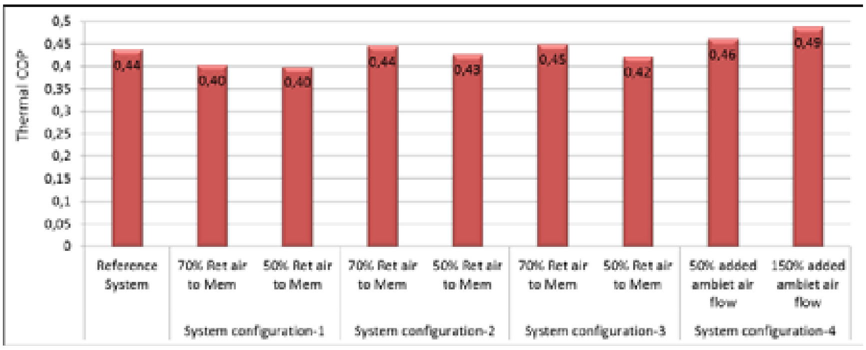


Fig. 7: Comparison between the thermal COP of the four proposed conceptual configuration and the reference system. “Ret air to Mem” stands for a fraction of the return air to the membrane unit as a secondary air stream.

4.3.1. System configuration-1: Air bypass configuration for the return air (around the membrane unit)

As can be seen from Fig. 5, the dehumidification capacity of the membrane unit is reduced by decreasing the return air flow to the membrane unit. At the same time, the dehumidification performance of the ECOS system increases; however, the total dehumidification performance decreases by decreasing the fraction of return air flow to the membrane and it is less than the dehumidification performance of the reference system. The variation of the dehumidification performance in the membrane unit and the ECOS system can be explained by the following facts. The dehumidification and the cooling processes in the membrane unit are driven by the humidity and temperature difference between the primary and secondary air streams. The temperature and the humidity of the secondary air at low air flow rates easily reach the level of the warm and humid air. Thus, using the bypass configuration decreases the performance of the membrane unit considerably. Furthermore, the improvement of the dehumidification performance in the ECOS system obtained by reducing the fraction of the return air to the membrane can be explained by two facts: (i) At a lower fraction of the return air flow through the membrane, a higher amount of relatively dry return air is supplied to the ECOS system as the cooling air for the evaporative cooling process. As a result, the wet-bulb temperature of the cooling air decreases and helps to counteract the adsorption heat effectively; thus, the dehumidification performance increases. (ii) As discussed, lowering the return air flow rate through the membrane unit reduces the performance of the membrane unit. Consequently, the process air enters to the ECOS system with a high humidity; therefore, the dehumidification load on the ECOS system increases. As a result of the analysis it can be concluded that the integration of the two-stage dehumidification system with the bypass configuration cannot improve the performance of the system analyzed.

4.3.2. System configuration-2: Using an indirect evaporative cooling unit before the membrane unit

As shown in Fig. 5, the performance of the membrane unit decreases by decreasing the fraction of return air to the membrane unit (the reason was discussed in section 4.3.1). In contrast, the performance of the ECOS system increases slightly by increasing the fraction of the evaporative cooling air (decreasing the air flow to the membrane unit). The total dehumidification performance of the two-stage system increases slightly at the operation condition with a fraction of 70% of the return air flow through the membrane unit. However, in general, using the evaporative cooling unit and a low secondary air flow through the membrane unit decreases the total performance of the system compared to the reference system. The performance improvement of the ECOS system can be explained by two facts: firstly, the dehumidification capacity of the membrane unit is reduced by decreasing the fraction of the return air flow to the membrane. Consequently, the dehumidification load on the ECOS system increases. Secondly, a higher fraction of the return air in the evaporative cooling unit decreases the temperature of the secondary air before entering to the membrane unit. This increases the cooling performance of the membrane unit and reduces the temperature of the process air further compared to the reference system. Process air with low temperature increases the dehumidification performance of the ECOS system due to the handling of a fraction of the adsorption heat (as presented in section 4.1).

Fig. 6 and Fig. 7 also show the comparison between the obtained results for the second system configuration under two operation conditions (70% and 50% fraction of return air to the membrane unit) and the experimental values for the reference system based on the specific removed enthalpy and thermal COP, respectively. As can be seen, this configuration can improve the total performance of the system analyzed to some extent under the first operation condition. However, using this kind of configuration is not suggested due to the additional complexity of system, the investment cost and the higher operational cost due to water consumption.

4.3.3. System configuration-3: Using an indirect evaporative cooling unit after the membrane unit and before the ECOS system

The operation results of the system configuration 3 are also illustrated in Fig. 5. While the dehumidification performance of the membrane unit decreases with decreasing the secondary air flow through the membrane unit, the dehumidification capacity of the ECOS system increases. Although the total dehumidification performance of the system is improved slightly at the operation condition with a fraction of 70%, the total dehumidification performance is lower compared to the reference system shown in Fig. 1.

The reason for the lower dehumidification capacity in the membrane unit compared to the reference system is already explained in section 4.3.1. The increment of the dehumidification capacity of the ECOS system is explained similarly by section 4.3.2. Indeed, the temperature of the pre-dehumidified process air is directly reduced by the evaporative cooling unit. The cooler process air is able to cool down the desiccant material directly and to handle a fraction of the adsorption heat. As presented in section 4.1, the cooled desiccant material increases the adsorption capacity of the material and the dehumidification capacity of the ECOS system.

The comparison between the results for the total specific removed enthalpy and the thermal COP for the presented configuration are shown in Fig. 6 and Fig. 7. Similar to the previous configuration, the comparison of the analyses indicates that the proposed concept can improve the total performance of the system analyzed slightly under some control conditions. However, exploiting this configuration for a two-stage dehumidification system is not recommended due to the increased complexity resulting only in a low performance improvement.

4.3.4. System configuration-4: Using an additional ambient air to be mixed with the return air from the membrane unit

The last two bars in Fig. 5 show the dehumidification performance of the two-stage dehumidification system using additional ambient air supplied to the ECOS system (additional 50% and 150% of the ambient air flow). In this configuration, since the modification is done after the membrane unit, the dehumidification performance of the membrane unit is equal to the one in the reference system. However, the performance of the ECOS system and the total dehumidification of the two-stage dehumidification system increase. Using a higher flow rate of the cooling air for the evaporative cooling process helps to counteract the adsorption heat considerably. Adding the humid ambient air to the cooling air increases the humidity content of the cooling air and therewith increases the wet-bulb temperature slightly. However, the higher cooling air flow rate and the lower temperature of mixed air compared to the ambient air can increase the efficiency of the evaporative cooling process in the ECOS system without significant additional cost for investments.

Fig. 6 interestingly shows that using an additional flow of ambient air can not only increase the dehumidification performance (Fig. 5), but also increases the total specific removed enthalpy. This is due to the fact that the improved evaporative cooling process in the ECOS system using additional ambient air and a higher flow rate can handle a higher sensible load of the process air compared to the reference system. The total specific removed enthalpy using the presented configuration under two operational conditions, additional 50% and 150% of the ambient air flow, is improved by 1.4 and 2.9 *kJ/kg* (*60W* and *150W* for the process air flow rate of *0.05 kg/s*), respectively. However, the electricity used for transporting the additional air increases about *7W* and *20W*, respectively. As shown in Fig. 7, the thermal COP of the fourth modification of the two-stage dehumidification system analyzed is improved as well.

5. Conclusion

In this study, conceptual system configurations were analyzed to provide useful information towards the performance improvement of two-stage dehumidification systems consisting of a membrane unit and an ECOS system. The analyses showed that although the application of an indirect evaporative cooling unit, proposed in many studies, has positive influences on the total performance of the air-conditioning systems, this configuration is not recommended for the two-stage dehumidification system under investigation. The best performance of the two-stage dehumidification system is achieved if the maximum performance of the membrane unit is realized. Therefore, the return air flow should be fully supplied to the membrane for the best possible dehumidification and cooling performance. An additional ambient air flow through the ECOS system improves the heat rejection process from the adsorbent material significantly. This results in an improved dehumidification performance of the ECOS system and the two-stage dehumidification system.

6. Acknowledgements

SERIS is sponsored by the National University of Singapore (NUS) and Singapore's National Research Foundation (NRF) through the Singapore Economic Development Board (EDB). The author, Safizadeh, is grateful for the PhD scholarship from the NUS Graduate School for Integrative Sciences and Engineering. The authors also extend their thanks to colleagues at department of Thermally Active Materials and Solar Cooling in Fraunhofer ISE for their valuable advices in course of this research work.

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