

2008

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Aynur, Tolga N.; Hwang, Yunho; and Radermacher, Reinhard, "A Heat Pump Desiccant Unit for Dehumidification and Humidification" (2008). *International Refrigeration and Air Conditioning Conference*. Paper 860.
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A Heat Pump Desiccant Unit for Dehumidification and Humidification

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ABSTRACT

A novel self-regenerating electric vapor compression heat pump desiccant (HPD) unit is introduced. The HPD unit dehumidifies the outdoor air during ventilation while cooling is needed, and uses only the moisture in the outdoor and return air to humidify the indoors during ventilation when heating is needed, and does not require additional water sources like the conventional humidifiers. It is found that the HPD unit provides and maintains the target indoor humidity ratio of 10 g/kg during the dehumidification mode, and for the humidification mode, it is obtained that, the HPD unit can trap significant amount of return air humidity and add it to the outdoor air.

1. INTRODUCTION

Indoor temperature control often receives far more attention than the indoor humidity control in commercial buildings. Historically, mechanical HVAC systems have focused on controlling the temperature, and space humidity has not been directly controlled and has often been described as coincidental (Murphy, 2003). However, moisture-related problems such as occupant comfort, building durability, storage purposes and operating costs of the air conditioning systems do occur in hot-humid climates in the cooling season and in dry climates in the winter seasons. Providing proper humidity levels has the potential to reduce the operation and maintenance costs of buildings and to provide a comfortable working environment. For these reasons, the performance of desiccant-based dehumidifiers, conventional humidification systems and their interactions with the air conditioning systems have been widely investigated both experimentally and numerically.

Lazzarin and Castellotti (2007) introduced a self-regenerating liquid heat pump desiccant dehumidifier that can dehumidify, heat, or cool the ambient air by an electric vapor compression heat pump system. The performance of the desiccant unit was investigated numerically in a supermarket application. It was found that the total energy requirement of the supermarket could be lowered by 5% to 22% by adding the desiccant dehumidifier to the existing air handling unit. Subramanyam *et al.* (2004) tested a desiccant assisted air conditioner to study the influence of design parameters such as supply airflow rate, compressor speed and desiccant wheel speed on the performance. Increasing airflow rate over the cooling coil from 263.4 m³/h to 732.9 m³/h was found to improve the system performance in terms of moisture removal capacity and COP, which were increased from 2.68 kg/h and 1.70 to 4.27 kg/h and 2.42, respectively. However, increasing the compressor speed was found to increase the total moisture removal capacity only. Henderson *et al.* (2002) tested a desiccant-based dehumidification system to improve indoor air quality. The solid desiccant system was used to pretreat the fresh air. It was found that the system provided more stable humidity levels while providing the ventilation during the occupied period. Saman and Johnstone (1994) studied two different humidity control; isothermal humidification with steam generator and adiabatic humidification with ultrasonic, in spaces where there is minimum or no humidity generation. It was found that the use of a steam humidifier resulted in more energy consumption. The result matches with other works by Turpin (2003), Mumma *et al.* (1997), and Kjelgaard (2002). Hao *et al.* (2006) proposed a three-rotary wheel (total heat, desiccant and sensible heat wheels) fresh air handling unit to increase the ventilation rate without increasing the energy consumption for summer and winter conditions. For the winter condition, only the total heat wheel was operated. The cold, dry outdoor air was preheated and prehumidified by the building exhaust air through the total heat wheel, and then heated by a heating coil and humidified by a steam generator and supplied to the indoors. It was found that the proposed air handling unit could achieve almost 50% energy savings compared to a conventional air handling unit.

In this study, a novel self-regenerating electric vapor compression heat pump desiccant (HPD) unit is introduced. The HPD unit dehumidifies the outdoor air during the ventilation in the cooling season, and uses only the moisture in the outdoor and return air to humidify the indoors during the ventilation in the winter season, and does not require additional water sources like the conventional humidifiers. The HPD unit was field-tested under varying outdoor conditions in an office suite.

2. SYSTEM DESCRIPTION

The HPD unit can be operated in both dehumidification and humidification modes.

2.1 Dehumidification Mode

The operation of the HPD unit in the dehumidification mode is illustrated in Figure 1. As can be seen, the HPD unit consists of outdoor air (OA) inlet, supply air (SA) outlet, return air (RA) inlet and exhaust air (EA) outlet, one supply fan at the SA outlet and one exhaust fan at the EA outlet. Furthermore, there is a hermetic compressor; two heat exchangers covered with adsorption material (AHX), an expansion valve, and a four-way valve on the refrigerant side. A similar AHX design can be found from Yabu and Ikegami (2007), and a similar system can be found from Ikegami and Yabu (2007), respectively.

During the first cycle, as shown in Figure 1a, the discharged refrigerant flows into an AHX (located on the top) which is used as a condenser and rejects heat. After the expansion device, the throttled refrigerant enters the second AHX; which is used as an evaporator at a much lower temperature than the condenser. The refrigerant, R410A, then returns to the compressor. The air dampers (not shown in the Figure 1) control the air stream direction adjusted such that the OA flows through the evaporator with the help of the supply fan, and the RA flows through the condenser with the help of the exhaust fan. Since the evaporator surfaces are covered with the adsorption material and the temperature is low due to the vapor compression cycle, the OA humidity can be trapped effectively on the evaporator, and in addition, the OA temperature decreases. Consequently, the dehumidified OA is supplied to the indoors as the SA.

During the dehumidification process, the surface partial pressure of water on the adsorption material on the evaporator rises until the vapor pressure of the air and adsorption material are the same. Since the driving force of the pressure difference decreases, the rate of the dehumidification decreases. This is why the adsorption material is regenerated periodically. Since hot refrigerant is flowing inside the condenser, it raises the water vapor pressure at the surface of the adsorption material above the partial pressure in the RA. This causes the regeneration of the adsorption material on the condenser surfaces, which was used as an evaporator in the previous cycle to dehumidify the OA. Since the RA flows through the condenser with the help of the exhaust fan according to the position of the air dampers, the moisture released by the regeneration process is removed from the HPD unit and exhausted to the ambient as the EA. When the evaporator needs to be regenerated, the HPD unit changes the position of the 4-way valve. Thus, it operates according to the second cycle, provided in Figure 1b, where the evaporator used for the dehumidification process in the first cycle becomes the new condenser and the condenser regenerated in the first cycle becomes the new evaporator. The air dampers adjust the new air paths in order to direct the OA through the new evaporator and the RA through the new condenser. Thus, continuous dehumidification can be maintained. When the new evaporator needs to be regenerated, the position of the 4-way valve and the positions of the air dampers are changed to their original positions, and thus the HPD unit reverts to the first cycle.

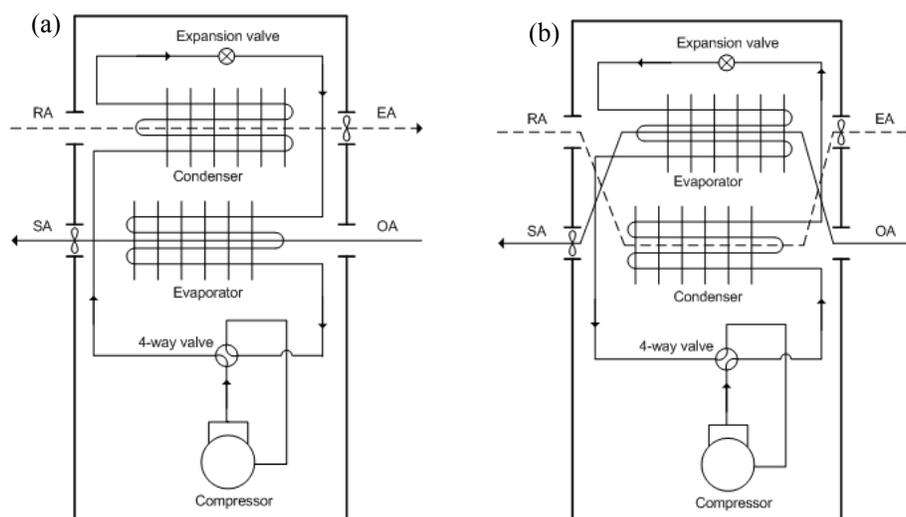


Figure 1: Operation of the HPD unit in the dehumidification mode, (a) first cycle, (b) second cycle

2.2 Humidification Mode

The operation of the HPD unit in the humidification mode is illustrated in Figure 2. The only difference between the dehumidification and humidification modes is that in the dehumidification mode, the OA flows over the evaporator, on the other hand, in the humidification mode, the OA flows over the condenser. As seen from Figure 2a, during the first cycle, since the operation mode of the HPD unit changes from the dehumidification mode to the humidification mode with the help of the 4-way valve, the discharged refrigerant goes into the AHX located on the bottom which is used as a condenser and raises its temperature. After the expansion device, the throttled refrigerant enters the second AHX which is used as an evaporator at a much lower temperature. Since the RA flows over the evaporator, the RA humidity can be trapped on the evaporator. Consequently, the dehumidified EA is exhausted to the ambient. Thus, significant amount of indoor humidity is trapped inside the HPD unit. On the other hand, the hot refrigerant flowing inside the condenser regenerates the adsorption material on the condenser by releasing the trapped humidity from the previous cycle. Since the OA flows through the condenser with the help of the supply fan according to the position of the air dampers, the moisture released by the regeneration process is removed from the condenser. Thus, the HPD unit adds the trapped indoor humidity to the OA flow. Consequently, the humidified and high temperature OA is supplied to the indoors as the SA. When the evaporator needs to be regenerated, the HPD unit changes the position of the 4-way valve. Thus, it operates according to the second cycle, provided in Figure 2b, where the evaporator used for the dehumidification process in the first cycle becomes the new condenser and the condenser regenerated in the first cycle becomes the new evaporator. The air dampers adjust the new air paths in order to direct the OA through the new condenser and the RA through the new evaporator. Thus, the continuous humidification can be maintained to the indoors. When the new evaporator needs to be regenerated, the position of the 4-way valve and the positions of the air dampers are changed to their original positions, and thus the HPD unit reverts to the first cycle.

The OA-SA and RA-EA air streams are separated with a physical barrier so that the dehumidified air and the regeneration air do not mix inside the HPD unit during the dehumidification mode, and the humidified air and the regeneration air do not mix inside the HPD unit during the humidification mode. The HPD unit works to maintain the indoor humidity ratio at a target level of 10 g/kg in both summer and winter seasons. Basically, if the OA and indoor humidity ratios are higher than the target level, then the HPD unit operates in the dehumidification mode. On the other hand, if the OA and indoor humidity ratios are lower than the target level, then the HPD unit operates in the humidification mode. However, if the OA and indoor humidity ratios are at around the target level, then only the supply and exhaust fans of the HPD unit operates for the ventilation without operating the vapor compression cycle.

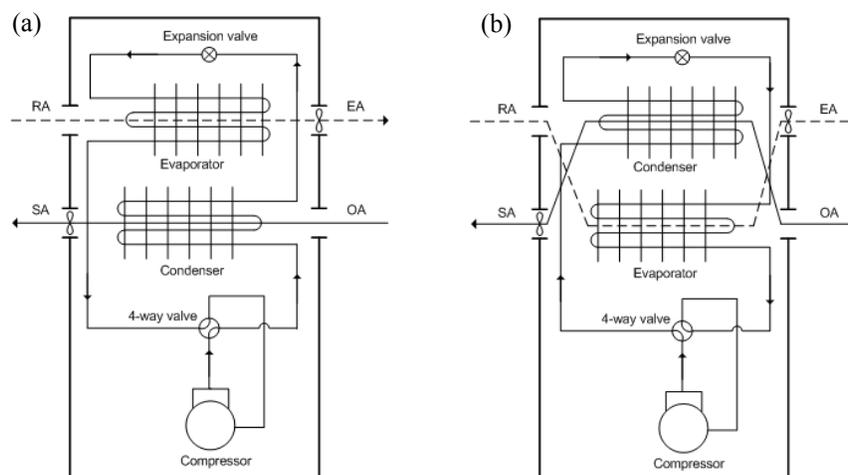


Figure 2: Operation of the HPD unit in the humidification mode, (a) first cycle, (b) second cycle

3. EXPERIMENTAL SET-UP AND INSTRUMENTATION

3.1 Experimental Set-up

The HPD unit was installed in an office suite to provide ventilation for two rooms. The schematic layout of the office suite is provided in Figure 3.

Since the HPD unit was tested for two rooms, the other air-conditioning and ventilation units located in the other rooms are not included in the investigation reported here. The detailed description for the rest of the suite can be found from Aynur *et al.* (2006). The volumes of the Rooms A and B are 55 m³ and 73 m³, respectively, and the HPD unit was installed in the ceiling of Room B. The dimensions of the proposed HPD unit are 450x1300x1000 mm, and the design air flow rate is 0.139 m³/s.

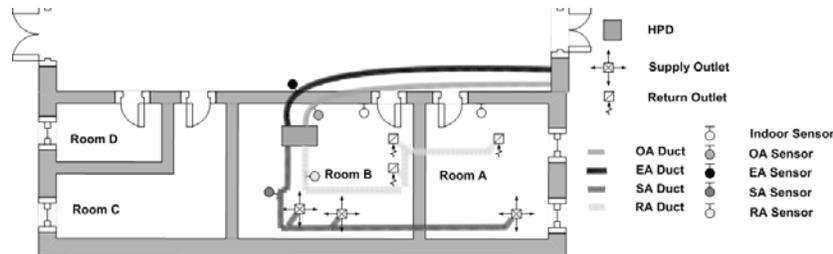


Figure 3: Layout of the office suite

3.2 Instrumentation

Two T-type thermocouples with an accuracy of $\pm 0.5^\circ\text{C}$ and two wall-mount type relative humidity sensors with an accuracy of $\pm 3\%$ were used to measure the indoor air temperature and relative humidity, respectively. The indoor measurement locations can be seen from Figure 3. A T-type thermocouple with an accuracy of $\pm 0.5^\circ\text{C}$ and a duct-mount type relative humidity sensor with an accuracy of $\pm 2\%$ were installed in the OA duct. Two hygrometers with accuracies of $\pm 0.2^\circ\text{C}$ and $\pm 2\%$ were installed in EA and SA ducts. Besides a T-type thermocouple with an accuracy of $\pm 0.5^\circ\text{C}$ and a duct-mount type relative humidity sensor with an accuracy of $\pm 2\%$ were installed in the RA duct to measure the air temperature and relative humidity. The duct measurement locations can be seen from Figure 3. A power meter with accuracy of $\pm 0.2\%$ of reading was used to measure the power consumption of the HPD unit. The power measurement is the total of the compressor and fan power. And a one-time measurement was performed to determine the SA volumetric flow rate, which was found to be 0.106 m³/s. The maximum uncertainty values for the sensible, latent and dehumidification capacities, as well as the COP of the HPD unit are ± 0.066 kW, ± 0.220 kW, ± 0.74 g/kg, and ± 0.456 , respectively.

4. EVALUATION METHODOLOGY

The HPD unit decreases not only the humidity ratio, but also the dry-bulb temperature of the OA during the dehumidification mode, and increases during the humidification mode. The sensible and latent capacities of the HPD unit in both modes are defined with Equations (1-3), and (4-5), respectively.

$$\dot{Q}_{sen,dehum} = \dot{m} \cdot c_p \cdot (T_{OA} - T_{SA}) \quad (1)$$

$$\dot{Q}_{lat,dehum} = \dot{m} \cdot (w_{OA} \cdot h_{gOA} - w_{SA} \cdot h_{gSA}) \quad (2)$$

$$h_g \cong 2500.9 + 1.82 \cdot T \quad (3)$$

$$\dot{Q}_{sen,hum} = \dot{m} \cdot c_p \cdot (T_{SA} - T_{OA}) \quad (4)$$

$$\dot{Q}_{lat,hum} = \dot{m} \cdot (w_{SA} \cdot h_{gSA} - w_{OA} \cdot h_{gOA}) \quad (5)$$

The COP of the HPD unit in both dehumidification and humidification modes is defined with Equation (6).

$$COP = \frac{\dot{Q}_{sen} + \dot{Q}_{lat}}{\dot{W}} \quad (6)$$

The dehumidification capacity (D) of the HPD unit in the dehumidification mode is defined with Equation (7). On the other hand, a significant amount of moisture is trapped on the evaporator of the HPD unit during the

dehumidification process of the RA in the humidification mode. This moisture is transferred to the OA during the regeneration process. Since this amount of moisture extracted from the RA is transferred to the indoors with the OA, the process is referred as the circulation of the moisture or the humidification capacity of the HPD unit, and evaluated with Equation (8).

$$D = w_{OA} - w_{SA} \quad (7)$$

$$H = w_{SA} - w_{OA} \quad (8)$$

5. RESULTS AND DISCUSSIONS

5.1 Dehumidification Mode

A typical operation of the HPD unit in the dehumidification mode is provided in Figures 4 with a test performed on one particular day in August, 2006. Figure 4a shows the variation of the power consumption of the HPD unit and the outdoor humidity ratio throughout the test period with 5-second interval. Figure 4b depicts the variations of the sensible and latent capacities, power consumption, indoor and outdoor humidity ratios throughout the test period with 18-minute averaged data. As can be seen from Figure 4a, since the HPD unit shifts from one cycle to the other in every 3 minutes during the operation as described in Figure 1, the power consumption of the HPD unit fluctuates within a range of around 0.2 kW most of the operation. As seen, when the OA humidity ratio decreases to around 12 g/kg, the vapor compression cycle of the HPD unit stops and fan-only operation takes place which consumes around 0.18 kW. As seen from Figure 4b, even though the OA humidity ratio varies within 14-16 g/kg most of the operation time, the HPD unit maintains the indoor target level during the ventilation. It is observed that, since the humidity ratio is the driving force for the latent capacity, the latent capacity of the HPD unit and the OA humidity ratio have similar trends. The drastic drops in both latent and sensible capacities of the HPD unit occurred at around 14:30 and 15:30 correspond to the fan-only operation of the HPD unit.

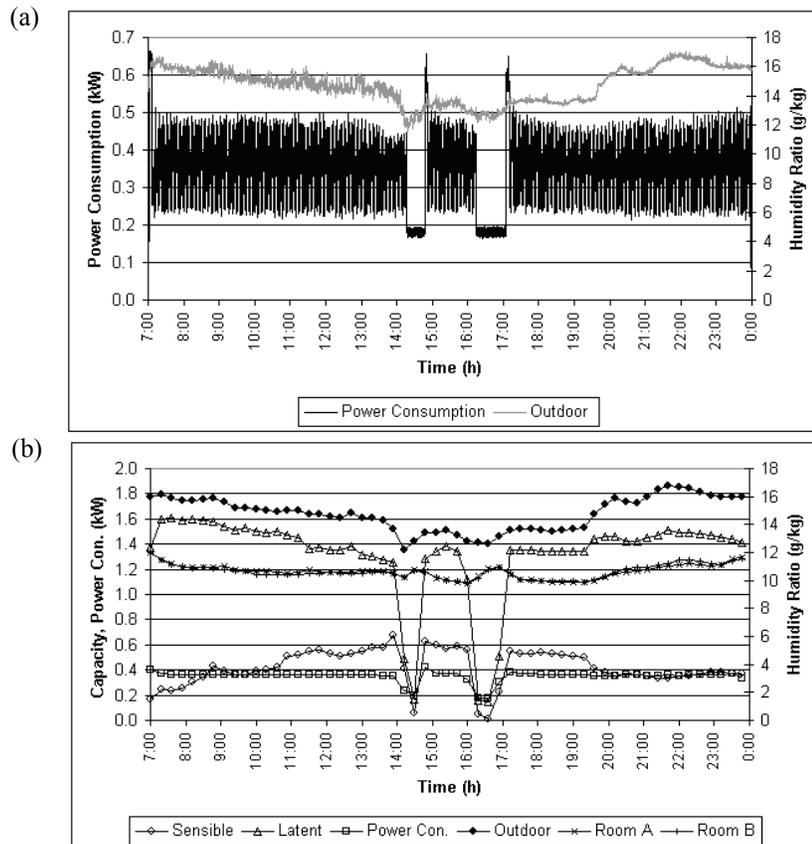


Figure 4: Operation of the HPD unit in dehumidification mode, (a) variation of the power consumption, (b) variations of the capacities, power consumption, indoor and outdoor humidity ratios

Figures 5a and 5b show the seasonal variations of the COP, the power consumption of the HPD unit and the provided indoor humidity ratio with the dehumidification capacity. The data is provided with 18-minute averages. The dehumidification capacity lower than 2 g/kg, corresponds to the fan-only operation. As seen from Figure 5a, the HPD unit has a maximum dehumidification capacity of around 9.5 g/kg for a COP of around 4, and a power consumption of 1 kW. On the other hand, as seen from Figure 5b, the indoor humidity ratios can be maintained at the target level throughout the season.

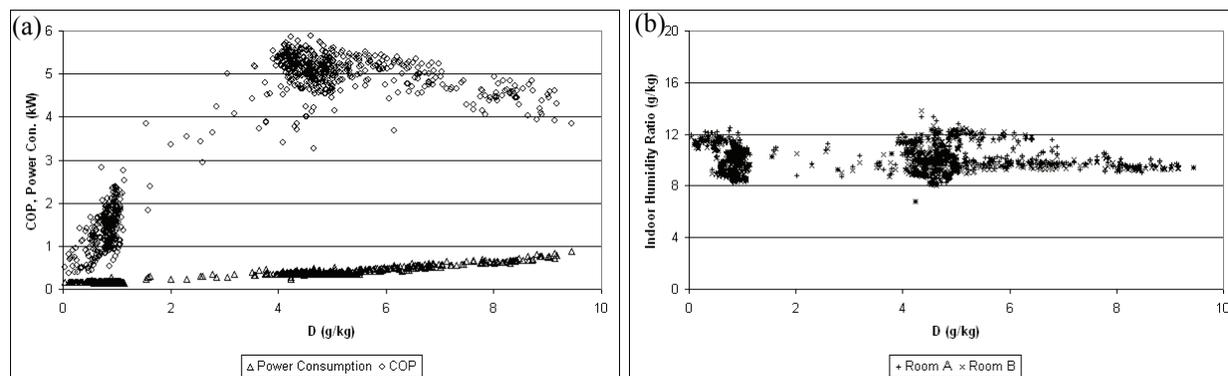


Figure 5: Variations of the COP, power consumption and indoor humidity ratios with dehumidification capacity

5.2 Humidification Mode

A typical operation of the HPD unit in the humidification mode is provided in Figure 6 with a test performed on one particular day in December, 2006. Figure 6a shows the variation of the power consumption of the HPD unit and the outdoor humidity ratio throughout the test period with 5-second interval. Figure 6b depicts the variations of the sensible and latent capacities, power consumption and outdoor humidity ratio throughout the test period with 18-minute averaged data. As seen from Figure 6a, similar to the dehumidification mode, since the HPD unit shifts from one cycle to the other, the power consumption of the HPD unit fluctuates within a range of around 0.4-0.6 kW most of the operation. It is observed that the power consumption increases when the OA humidity ratio decreases, and decreases when the OA humidity ratio increases. On the other hand, since the OA flows over the condenser during the humidification mode and the OA humidity ratio is relatively low, the sensible capacity of the HPD unit is found to be higher than the latent capacity of the HPD unit, as shown in Figure 6b.

Figure 7 shows the variations of the OA, SA, EA, humidification capacity (H) and indoor humidity ratios throughout the test period. As seen, the EA humidity ratio can be kept lower than the indoor humidity ratios, and the SA can be maintained higher than the OA, which shows that the HPD unit can trap significant amount of RA humidity (around 2.5-4 g/kg) and add it to the OA. The humidification capacity varies within 2.5-4 g/kg and the corresponding SA humidity ratio varies 7.5-8.5 g/kg. Since the SA humidity ratio reaches around the target level at 22:00, the vapor compression cycle of the HPD unit stops and fan-only operation takes place which consumes around 0.18 kW, as seen from Figures 6a and 6b. The reason of the lower indoor humidity ratio than the SA humidity ratio is attributed to the non-homogeneous humidity variation within the zones. Long term data collection is required for a seasonal evaluation of the HPD unit in humidification mode, and the required tests are planned for the coming winter seasons.

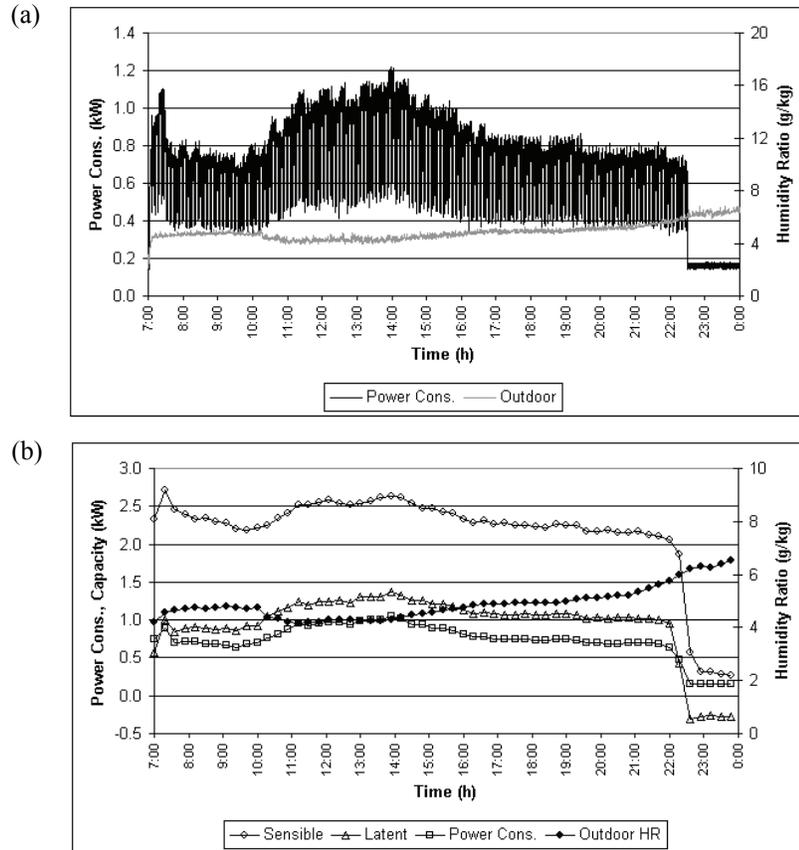


Figure 6: Operation of the HPD unit in humidification mode, (a) variation of the power consumption, (b) variations of the capacities, power consumption, and outdoor humidity ratio

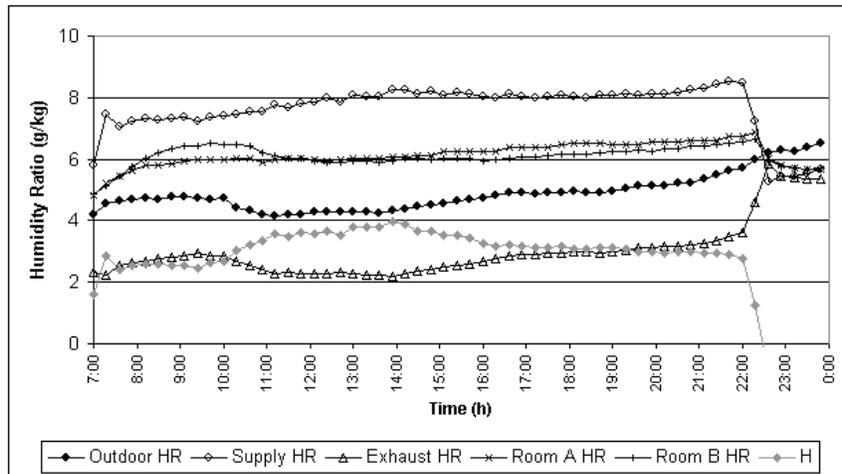


Figure 7: Variations of the OA, SA, EA, H and the indoor humidity ratios

6. CONCLUSIONS

A novel self-regenerating electric vapor compression heat pump desiccant (HPD) unit, which dehumidifies the outdoor air in the cooling season, and uses only the moisture in the outdoor and return air to humidity the indoors in

the winter season was introduced. The characteristics of the HPD unit were experimentally investigated during field tests. From the experiments, the following conclusions are deduced.

- The HPD unit provides and maintains the target indoor humidity ratio of 10 g/kg during the cooling season.
- The power consumption of the HPD unit increases with the increasing dehumidification capacity. The HPD unit provides the maximum dehumidification capacity of around 9.5 g/kg for a COP of around 4, and a power consumption of 1 kW.
- The HPD unit in dehumidification mode not only takes care of the latent load, but also meets some portion of the sensible load during the ventilation process. The HPD unit has the potential to reduce the energy consumption of the air conditioning system which operates in conjunction with it.
- The HPD unit has a significant sensible capacity compared to the latent capacity in the humidification mode. Thus, the HPD unit humidifies the indoors, and reduces the heating load.
- The EA humidity ratio can be maintained lower than the indoor humidity ratios during the humidification mode, which shows that the HPD unit can trap significant amount of RA humidity and transfer it to the OA.

Overall, the proposed HPD unit has the potential to provide and maintain the proper humidity level for a comfortable indoor environment.

NOMENCLATURE

			Subscripts		
\dot{Q}	capacity	(kW)			
h	enthalpy	(kJ/kg)	<i>sen</i>	sensible	SA supply air
\dot{m}	mass flow rate	(kg/s)	<i>lat</i>	latent	EA exhaust air
c_p	specific heat	(kJ/kg.K)	<i>dehum</i>	dehumidification	RA return air
T	temperature	(°C)	<i>hum</i>	humidification	D dehumidification
COP	coefficient of performance	(-)	<i>g</i>	saturated vapor	H humidification
w	humidity ratio	(kg/kg)	OA	outdoor air	

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ACKNOWLEDGEMENT

The support of this research through Daikin Industry, Ltd and the Alternative Cooling Technologies and Applications Consortium of the Center for Environmental Energy Engineering at the University of Maryland is gratefully acknowledged.