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An experimental study on the dehumidification performance of a low-flow falling-film liquid desiccant air-conditioner

S. Bouzenada[a*], C. McNevin[b], S. Harrison [c], A. N. Kaabi[d]

[a,d] *Laboratory of Energy and Environment, Department of Architecture, University 3 Constantine, 25000, Algeria*
[b,c] *Solar Calorimetry Laboratory, Department of Mechanical and Materials Engineering, Queen's University, Kingston, Ontario, Canada*

Abstract

The dehumidifier is one of the main components in open-cycle liquid desiccant air-conditioning systems. An experimental study was carried out to evaluate the performance of a solar thermally driven, low-flow, falling-film, internally-cooled parallel-plate liquid desiccant air-conditioner in Kingston, Ontario at Queen's University. A solution of LiCl and water was used as the desiccant. Unlike high-flow devices, the low-flow of desiccant solution flowing across the unit's dehumidifier and regenerator sections produces large variations in solution concentration. In this study, a series of tests were undertaken to evaluate the performance of the dehumidifier section of the unit. Results presented are based on mass flow and energy transport measurements that allowed the moisture transport rate between the air and liquid desiccant solution to be determined. Based on these results, a relationship between the desiccant concentration and the rate of dehumidification rate was found and the effect of inlet-air humidity on the dehumidification effectiveness identified. The moisture removal rate of the system was found to range from 1.1 g/s to 3.5 g/s under the conditions evaluated. These result corresponded to an average dehumidification effectiveness of 0.55.

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Keywords: liquid desiccant; air-conditioning; dehumidification effectiveness; lithium chloride; falling film; low flow; HVAC

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1. Introduction

The current energy crisis, climate change, and increased air-conditioning demand have generated a need to develop new space cooling technologies based on renewable energy sources.

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* Corresponding author. Tel.: +213 663 330 227; Fax: +213 31 904 580.
E-mail address: saliha_610@yahoo.fr

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Nomenclature		**Subscripts**	
h	specific enthalpy (kJ/kg)	*a*	air
h_f	enthalpy of water vapour (kJ/kg)	*a-d*	air to desiccant
h_{fg}	latent heat of condensation (kJ/kg)	*abs*	absorbed
$\dot{m}$	mass flow rate (kg/s)	*c*	conditioner
P	atmospheric pressure (Pa)	*cw*	cooling water
p	partial pressure (Pa)	*d*	desiccant solution
$\dot{Q}$	power (kJ/s)	*d-cw*	desiccant to cooling water
X	mass fraction (-)	*dil*	dilution
ε	effectiveness (-)	*eq*	equilibrium
ω	absolute humidity (kg_w/kg_a)	*in*	inlet
		out	outlet

Liquid desiccant air-conditioning systems (LDAC) have emerged as a potential alternative to conventional vapour compression systems for air-conditioning. Desiccants are materials that have high affinity for absorbing water vapour. This technology, which can efficiently serve large latent loads, can greatly improve indoor air quality by allowing for easier humidity control while reducing the electrical energy consumption of traditional vapour compression systems. Air dehumidification is an important process not only in industrial applications, but also in space cooling for occupant health and comfort. In the case of desiccant based dehumidification systems, much of the thermal energy required to operate the systems can be drawn from sustainable sources such as solar thermal collectors. The present work studies one such desiccant system. The dehumidifier component (also referred to as the conditioner) of this system is the principle topic under investigation as it is directly responsible for the dehumidification of the air and the other components of the system exist to support its operation. Its performance greatly influences the overall performance of the complete system.

In the dehumidifier of the system studied, the concentrated desiccant solution is brought into direct contact with the process-air to absorb the moisture from the inlet-air (i.e., process air stream)[1]. During this process, the solution becomes diluted by the water removed from the air-stream and its ability to further absorb moisture is reduced. In order to reuse the desiccant solution in the process, the solution must be pumped through the regenerator section of the unit. Regeneration occurs when the desiccant is exposed to a scavenging air-stream (separate from the dehumidified process-air stream) while being heated. The heat drives off the absorbed water from the solution, increasing its salt concentration and regenerating its capability to remove moisture. It is the heat consumed in the regeneration process that can be provided from low-grade waste heat processes or renewable energy sources such as solar thermal energy[2].

An early liquid desiccant system was developed and experimentally tested by Löf[3], who used triethylene glycol as the hygroscopic solution. In this system, air was dehumidified and simultaneously cooled in an absorber and then evaporatively cooled. Recently, the concept of air dehumidification by a liquid desiccant has again been investigated by numerous researchers. Mesquita et al.[1] developed mathematical and numerical models for falling-film liquid desiccant dehumidifiers using three approaches. The first approach was based on heat and mass transfer correlations. The second was numerically solved by the finite-difference method assuming constant film thickness. The third approach introduced a variable film thickness to the numerical model. All approaches assumed fully developed laminar flow for the liquid and air streams. Jain and Bansal[4] proposed an analysis of packed bed dehumidifiers for three commonly used desiccant materials; triethylene glycol, lithium chloride, and calcium chloride, using effectiveness values drawn from the literature. The analysis revealed significant variations and anomalies in trends between the predictions of various correlations for the same operating conditions. This highlighted the need for benchmarking the performance of desiccant dehumidifiers. Sreelal and Hariharan[5] studied the effect of air velocity on the heat and mass transfer in a falling film type liquid desiccant dehumidifier using a two-dimensional simulation of a two-phase system. The results indicated that the air velocity had a significant impact on the dehumidification process.

In the present work, an experimental study was carried out using a solar thermally driven LDAC to evaluate the dehumidification effectiveness of an internally cooled, low-flow, falling-film, parallel plate desiccant dehumidifier, designed and constructed by AIL research[6]. A liquid solution of lithium chloride and water was used as the desiccating agent. This particular system has been studied previously in several works with a focus on the complete system's performance and modelling[2,7,8]. In the present work, the process parameters affecting the performance of the dehumidifier, namely the desiccant inlet concentration, and the inlet-air relative humidity, were analysed. The unit investigated had also recently suffered freezing damage in the internal cooling channels associated with the conditioner plates. The freezing damaged of some of the flow channels resulting in the leakage of cooling water into the desiccant solution. Most of the channels were repaired prior to this study but a small volume of continuous leakage could not be stopped. It was feared that the slow leakage of cooling water into the desiccant solution would reduce the performance of the unit, as the additional water might be diluting the desiccant solution faster than the regenerator could reject the moisture. The performance of the dehumidifier was also analyzed to evaluate the effectiveness of the repair.

The resulting performance data for the dehumidifier is presented in terms of moisture removal rates and dehumidification effectiveness as determined from process-air measurements as described below.

2. System Description and Experimental study

The liquid desiccant air-conditioning system shown in Fig. 1(a) is principally composed of a dehumidifier and regenerator, as well as: blowers; pumps; a desiccant sump; boiler; evaporative cooling tower; data acquisition; and control equipment. Another major component is the evacuated tube solar thermal collector array shown in Fig. 1(b). The array has a total area of 95 m² and is automatically controlled and fully instrumented. The array stores heat in a pair of 435 litre insulated storage tanks. The capacity of these tanks is insufficient to store large quantities of energy for the LDAC as their primary function is to operate as buffers between the solar array and the LDAC as both the operating times and the water flow rates are different for each system. During times of low solar availability, the natural gas boiler provided additional thermal energy to the system to maintain the hot water set-point temperature[2].

Fig. 1. (a) Liquid desiccant air handling unit and cooling tower as installed at Queen's University; (b) Photo of the solar thermal collector array

The LDAC uses an internally cooled parallel-plate heat and mass exchangers for the conditioner, shown in Fig. 2 (a). The cooling water flows inside narrow channels within each plate, Fig. 2(b), while a thin film of desiccant solution falls down the outer faces of each plate. A source of cooling water is required for continuous operation of the unit. The water reduces the temperature of the desiccant, which improves its latent cooling rate, as well as reducing the temperature of the air stream, allowing for a degree of sensible cooling. During the dehumidification process, the latent heat of condensation heats up the desiccant as it flows down the plate, and if uncooled, will reduce its ability to absorb moisture. Consequently, the unit tested uses integral cooling channels in the dehumidifier plates to reduce the temperature of the desiccant solution as it runs down the entire length of the plate.

During normal operation, air is blown in-between the plates and across the desiccant flow, (i.e., in a crossflow configuration). The complete dehumidifier consists of multiple (curved) plates separated by a 2.5 mm air gap. Each conditioner plate was 2.5 mm thick, 305 mm wide, and 1250 mm from top to bottom. The plates had a thin (0.5 mm) coating to promote uniform wetting by "wicking" the desiccant solution across the surface of the plates. A sump pump was used to deliver concentrated desiccant solution to the top of the conditioner and the solution returned to the sump via gravity flow over the plates.

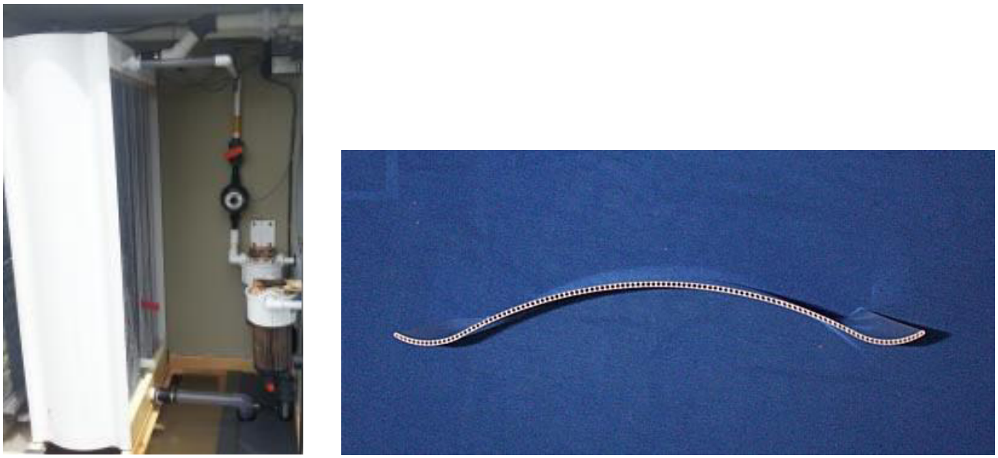

Fig. 2 (a) Internally cooled low-flow parallel plate falling-film conditioner; (b) top-view of a single plate showing the internal channels[6]

The system used a lithium chloride and water solution as the desiccant. The cooling cycle is driven by the dilution and re-concentration of the liquid desiccant solution. In addition to the heat of condensation being absorbed into the desiccant stream (due to the conversion of latent energy into sensible heat); the chemical reaction caused by the addition of water to the desiccant solution also releases the heat of dilution energy into the desiccant stream.

The conditioner and regenerator both return to and draw from a shared sump located beneath the unit. The regenerator contains an additional heat exchanger to preheat the incoming desiccant solution from the sump using the hot desiccant solution leaving the regenerator. The energy used to heat the water used in the regenerator was supplied from the solar system and supplemented by an auxiliary natural gas boiler. Figure 3 shows a simplified schematic of the system.

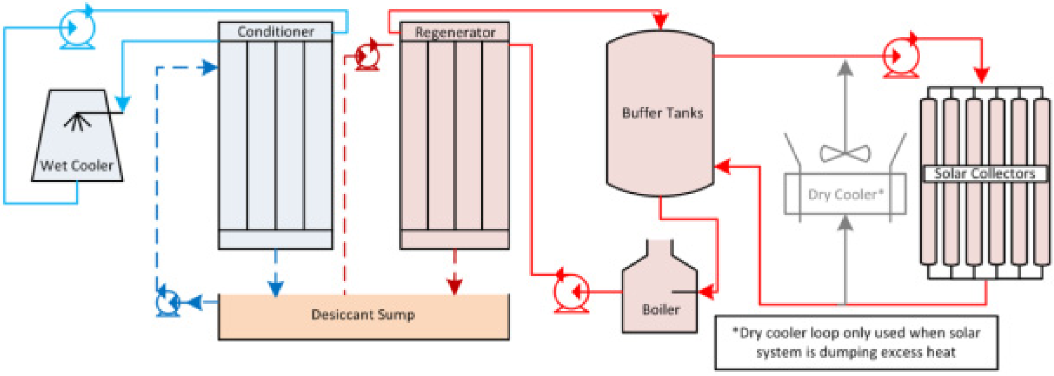

Fig. 3. Simplified system schematic[8]

The system was operated for four days during July and August 2014 at the Kingston, Ontario test site. During this period, the temperature and humidity of the ambient air was monitored to identify the properties of the inlet air streams for the conditioner and regenerator. The properties of the air exiting the regenerator and conditioner were continuously measured with commercial air-temperature and humidity sensors. The air flow rate through the conditioner was recorded with pitot-tube array positioned in a long uniform-cross-section air duct. The inlet and outlet temperatures of the cooling and heating water were monitored as well as their flow rates. Desiccant temperatures and flow rates were recorded throughout the experiment. Further details on the operation and instrumentation of this system can be found in the original work on this system by Jones[7]. The data system scanned the instruments every five seconds and recorded the averaged data every minute. Samples of desiccant solution were regularly tested by a density meter. Correlations from Conde[9] were then used to convert these density values to mass fractions. A separate data logging system monitored the performance of the solar array as described by Crofoot et al.

^{2}. The estimated accuracy of the measurement instrumentation is shown in Table 1 based on the manufacturer's specifications. The accuracy data was used to estimate the relative uncertainty in the calculated values based on a "root mean square" propagation of the component measurement errors. These values were used to set the magnitude of the error bars shown in the data plots.

Table 1. Estimated measurement accuracy values

Instruments	Accuracy
Cooling Water	
inlet and outlet thermistors	±0.3 °C
flow meter	±0.5 LPM
Desiccant Solution	
inlet and outlet thermistors	±0.3 °C
flow meter	±1.5 % of reading
density meter	±0.0001g/cm^3
Process Air	
inlet and outlet temperature	±0.2°C
inlet and outlet relative humidity	±2%
flow meter	±3% of reading

3. Performance analysis

The driving force for the mass transfer of moisture between the air stream and the liquid desiccant solution is the difference between the water vapour-pressure caused by the desiccant solution and the partial-pressure of water vapour in the process-air stream. The vapour-pressure of the desiccant solution is a function of its concentration and temperature, whereas the partial-pressure of water-vapour in the air is a function of the air's moisture content.

In the conditioner, there are three working fluids: moist air, liquid desiccant solution, and cooling water. Heat transfer occurs between all three fluids, and mass transfer occurs between the air and the liquid desiccant. The mass and energy balance for the moist air stream are given by Eq. (1) and Eq. (2).

$$\dot{m}_{a,in,c}\,\omega_{in,c} = \dot{m}_{abs} + \dot{m}_{a,in,c}\,\omega_{out,c} \tag{1}$$

$$\dot{m}_{a,in,c}\left(\omega_{in,c}\,h_{f,in,c} + h_{a,in,c}\right) = \dot{m}_{a,out,c}\left(\omega_{out,c}\,h_{f,out,c} + h_{a,out,c}\right) + \dot{m}_{abs}\left(h_{fg}\right) + \dot{Q}_{a-d} \tag{2}$$

The mass and energy balance equations for the desiccant stream are given by Eq. (3) and Eq. (4). The energy balance is only valid if it is assumed that the moisture transferred into the desiccant ($\dot{m}_{abs}$) is very small compared to the total desiccant flow rate ($\dot{m}_{d,in,\,c}$).

$$\dot{m}_{d,in,c}\,X_{in,c} = \dot{m}_{d,out,c}\,X_{out,c} = (\dot{m}_{d,in,c} + \dot{m}_{abs})\,X_{out,c} \tag{3}$$

$$\dot{m}_{d,in,c}\,h_{d,in,c} + \dot{Q}_{a-d} = \dot{m}_{d,outc}\,h_{d,out,c} + \dot{m}_{abs}\,(h_{dil}) + \dot{Q}_{d-cw} \tag{4}$$

The energy balance on the cooling water stream is given by Eq. (5). A mass balance is not needed for this stream because the flow rate was effectively fixed. The amount of water lost due to leakage (caused by the freezing damage) was considered to be is negligible as it was small compared to the total cooling water flow rate.

$$\dot{m}_{cw}\,h_{cw,in} + \dot{Q}_{d-cw} = \dot{m}_{cw}\,h_{cw,out} \tag{5}$$

The mass transfer performance of the dehumidifier was evaluated in terms of the moisture removal rate, calculated using Eq. (1), and the dehumidification effectiveness (ε_{de}) as calculated by Eq. (6). The effectiveness value was defined to describe the conditioners ability to dehumidify the air [2]. The dehumidifier effectiveness represents the ratio of experimental humidity ratio change to the theoretical maximum possible change.

$$\varepsilon_{de} = \frac{\omega_{in} - \omega_{out}}{\omega_{in} - \omega_{eq}} \tag{6}$$

The maximum possible change is dictated by the difference between the inlet air humidity ratio (ω_{in}) and the humidity ratio of air in equilibrium (ω_{eq}) with lithium chloride solution at the inlet cooling-water temperature and inlet desiccant-stream mass fraction. This is calculated from the standard psychrometric equation shown in Eq. (7) where p_{eq} is determined using correlations by Conde[9].

$$\omega_{eq} = 0.622\,\frac{p_{eq}}{P - p_{eq}} \tag{7}$$

4. Results and discussion

The objective of the study was to determine the dehumidification rate and impact of several factors affecting the dehumidification effectiveness in order to evaluate the conditioner's performance. The parameters studied were the difference between the desiccant solution's inlet and outlet concentration as well as the effects of the inlet desiccant concentration on the water condensation rate. The effect of the difference in the relative humidity of the process-air at the inlet and outlet of the dehumidifier was studied and finally, the dehumidification effectiveness was analysed.

The LDAC ran for eight to ten hours each test day. The ambient temperature ranged from 15 °C to 26 °C during the unit's operation. Figure 4 shows the variation between inlet and outlet desiccant concentration during the experiment on July 25th. As expected, this data indicated that the system was absorbing moisture into the desiccant. In addition, the inlet concentration values were maintained at reasonably high levels and this was due to the regeneration of desiccant solution. The data indicates that the small leaks in the cooling water channels in the dehumidifier did not adversely affect the operation or capacity of the system.

A transient warm-up period is evident during the first hour of operation and is also reflected in the results, with the desiccant solution rapidly becoming diluted until the regenerator reaches its operating temperature and capacity.

The data in Fig. 4 shows several outliers at 9:00, 13:00 and 14:00 hours. These outliers are attributed to sampling error associated with the collection and analysis of the desiccant samples. The desiccant solution was drawn from the working machine with syringes at thirty minute intervals and transferred to the density meter for analysis. Bias measurement errors may have occurred if the samples were not well-mixed, or contained any contaminants such as air bubbles. As these points were outside the bounds of the predicted measurement error a smooth data line was chosen to represent the test data.

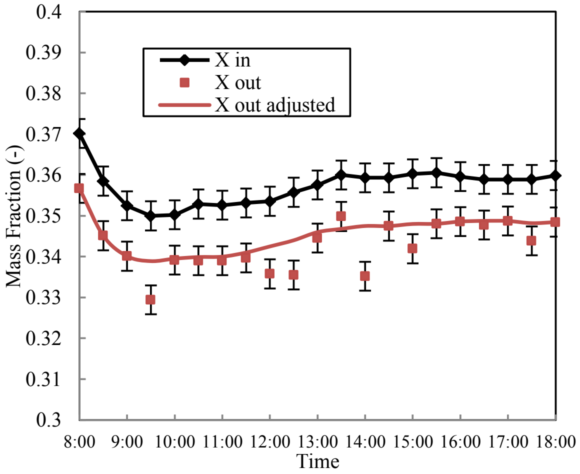

Fig.4. Inlet and outlet desiccant concentration during July 25

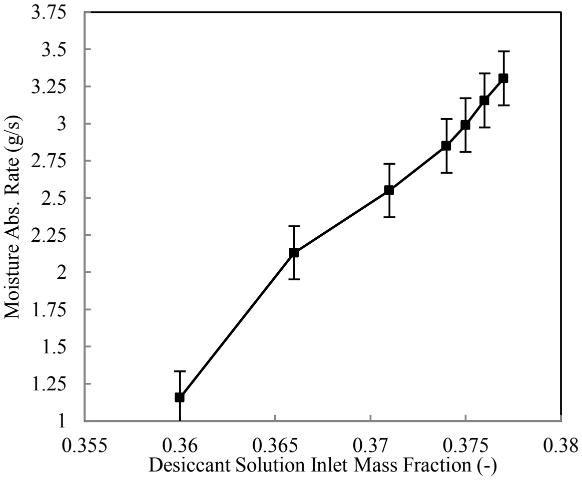

Fig. 5. Influence of inlet desiccant concentration on moisture absorption rate

The graph shown in Fig. 5 illustrates the effect of inlet desiccant concentration on the moisture removal rate. It can be seen that the dehumidification rate increased with the increasing inlet concentration. This increase was due to the increase in the magnitude of the difference in the vapour pressure between the air and the desiccant solution. This was due to the reduced vapour pressure of the desiccant solution at higher concentrations as shown in Fig. 6.

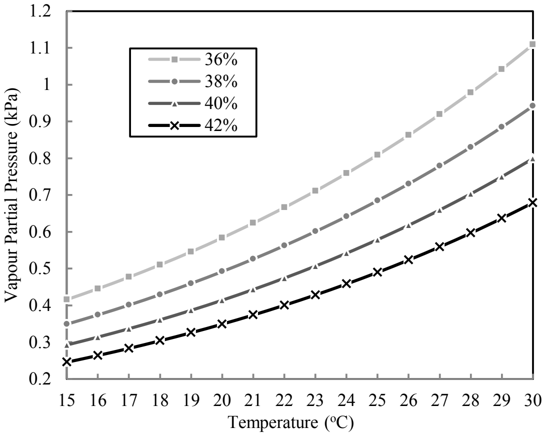

Fig. 6. Vapour pressure of lithium chloride at different concentrations and temperatures as calculated using the Conde[9] correlations

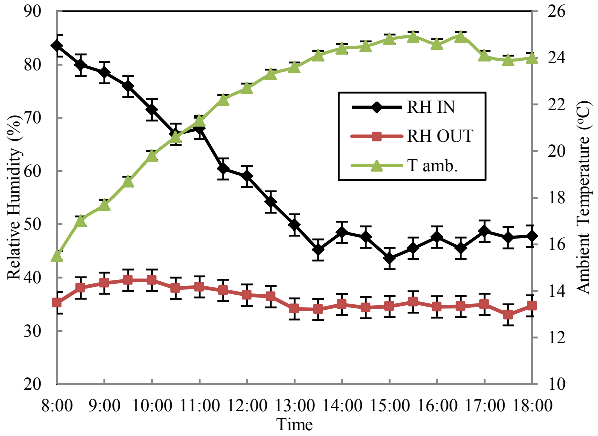

Fig.7. Dehumidifier inlet- and outlet-air relative humidity over the course of July 25

Figure 7 clearly shows the variation between the relative humidity of the process-air stream before and after the dehumidification process on July 25th. The drop in relative humidity throughout the day can be attributed to the increasing ambient temperature. From this figure, it can be seen that the inlet-air relative humidity does not have a large effect on the outlet air relative humidity. The outlet-air relative humidity was primarily dependant on the desiccant concentration, and the cooling water temperature (as would be expected according to Fig. 6). An important note regarding this particular installation is that the cooling water temperature was closely linked to the ambient-air temperature and humidity due to the use of an evaporative cooling tower to reject heat. High humidity levels should increase the dehumidification rate in the conditioner, but higher ambient relative humidity will lower the capacity of the cooling tower, leading to higher cooling water temperatures and reduced system capacity.

Figure 8 shows the results from August 1st during which the ambient air's relative humidity changed from a high to low value over the course of the test period. The spikes evident in the data records can be attributed the different firing stages of the boiler as it cycled between low/high/off while attempting to maintain the unit's set-point. Also, the opening of the unit's access doors for brief periods to obtain desiccant samples shut down the unit's fans briefly (for safety reasons) and this caused some fluctuations. The overall effect of these incursions was considered to be negligible.

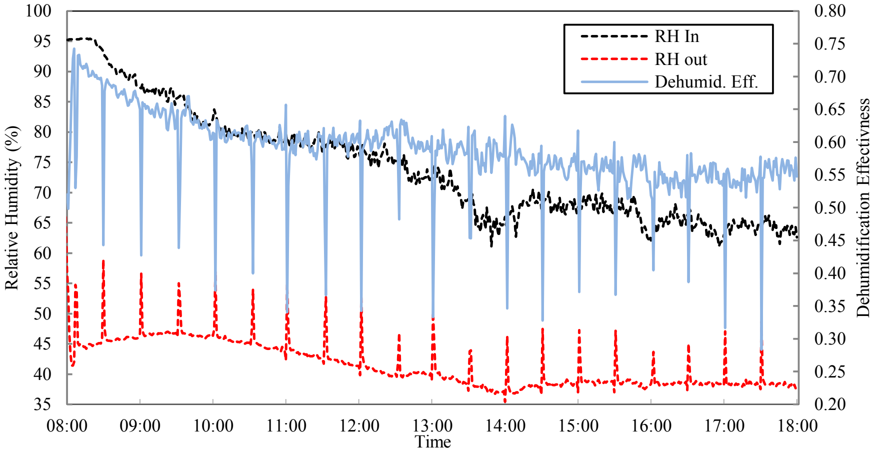

Fig.8. Dehumidification effectiveness of system over August 1st shown with the inlet and outlet dehumidifier outlet air relative humidity

The large change in inlet-air relative humidity was only marginally reflected by a slight increase in outlet-air relative humidity. This caused an increase in the dehumidification effectiveness. This is an interesting result, typical of LDAC systems. In locations with high latent cooling loads, a LDAC system such as the one studied, would be a suitable choice to maximize HVAC system efficiency. However, the lack of significant sensible cooling capacity would make a desiccant system a poor choice in areas with low humidity and high temperatures.

Across all experimental days, the average value of conditioner effectiveness reached 0.55. A previous study[2] on the unit achieved an average value of 0.59. This value does vary depending on the ambient conditions so the difference between the two is marginal.

5. Conclusion

This paper experimentally studied the performance of a liquid desiccant dehumidifier using aqueous lithium chloride. Reliable sets of data for air dehumidification were obtained. The experimental results showed the effect of the difference between the inlet and outlet relative humidity and the inlet and outlet desiccant concentration. It was found that dehumidification rate increased with increasing desiccant inlet concentration. The inlet concentration of the desiccant solution was relatively consistent throughout the day, indicating adequate regeneration capacity, even with the additional dilution of desiccant caused by the minor cooling-water leak into the unit's sump. The average value of dehumidifier effectiveness was measured at 0.55, consistent with previous measurements and was shown to be influenced by the inlet air's relative humidity.

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