A Solar Powered Liquid-Desiccant Cooling System for Greenhouses

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Abstract

Liquid desiccant systems are of potential interest as a means of cooling greenhouses to temperatures below those achieved by conventional means. However, only very little work has been done on this technology with previous workers focussing on the cooling of human dwellings using expensive desiccants such as lithium salts. In this study we are designing a system for greenhouse cooling based on magnesium chloride desiccant which is an abundant and non-toxic substance. Magnesium chloride is found in seawater, for example, and is a by-product from solar salt works. We have carried out a detailed experimental study of the relevant properties of magnesium rich solutions. In addition we have constructed a test rig that includes the main components of the cooling system, namely a dehumidifier and solar regenerator. The dehumidifier is a cross-flow device that consists of a structured packing made of corrugated cellulose paper sheets with different flute angles and embedded cooling tubes. The regenerator is of the open type with insulated backing and fabric covering to spread the flow of desiccant solution. Alongside these experiments we are developing a mathematical model in gPROMS® that combines and simulates the heat and mass transfer processes in these components. The model can be applied to various geographical locations. Here we report predictions for Havana (Cuba) and Manila (Philippines), where we find that average wet-bulb temperatures can be lowered by 2.2 and 3°C respectively during the month of May.

INTRODUCTION

The extension of the optimum growing season for crop cultivation in greenhouses, located in hot countries, has been suggested by other researchers as a way of decreasing food imports. This can be achieved by reducing the high temperatures induced inside the greenhouses during summer with a cooling system that is less energy intensive and more effective than the conventional ones already used e.g. evaporative pad and fan ventilation systems.

Liquid desiccant cooling technology has been investigated extensively focusing on applications such as cooling of human dwellings, commercial buildings, hospitals (Jain et al., 2000; Oliveira et al., 2000; Dai et al., 2001; Gommed and Grossman, 2004; Mei and Dai, 2008). The desiccants utilised are lithium salts (LiCl, LiBr), calcium chloride (or mixtures of LiCl and $CaCl_2$) and tri-ethylene glycol. Although magnesium chloride is not as hygroscopic as the lithium salts or their mixtures, it is less expensive and non-toxic. Therefore it could be used potentially as a liquid desiccant in solar refrigeration systems providing low grade cooling in particular systems for cooling greenhouses in hot and humid climates. Davies (2005) theoretically demonstrated a solar powered liquid desiccant cooling system that lowers summer maximum summer temperatures by $5^{o}C$. The use of bitterns (brines rich in Mg^{+2}) as the liquid desiccant in such a system was

proposed by Davies and Knowles (2006). The feasibility of the system has to be investigated thoroughly at the laboratory scale by conducting experiments. Thus we constructed a rig which consists of a dehumidifier and a solar regenerator. We have also developed mathematical models to simulate the processes of dehumidification and regeneration.

In this study, we report on the progress made in developing mathematical models that combine and simulate the mass and heat transfer processes that take place in the system and the preliminary experimental results, along with predictions of the efficacy for different geographic locations.

METHODS AND EXPERIMENTAL PROCEDURES

A schematic description of the liquid cooling system constructed in lab is shown in Fig.1. It consists of the following components: a) the air dehumidifier consisting of the packed column and cooling tubes, b) the humidifier and heater of the air at the inlet, c) a fan that draws the air out of the dehumidifier, d) two air sampling tubes for measuring the dry bulb and wet bulb temperatures of the incoming humid air and the out coming dehumidified air, e) the liquid desiccant regenerator, f) a peristaltic pump for circulating the liquid desiccant.

The packed column is constructed with four separate cellulose structured pads each one sized 0.1×0.1×0.3m. Each pad consists of specially impregnated and corrugated cellulose paper sheets with different flute angles, one steep (60 deg) and one flat (30 deg) that have been bonded together (CELdek® 7090-15). Fifty copper tubes (15mm OD) are embedded into the packed column providing cooling (tap water is used as the cooling fluid). The strong magnesium chloride solution flows through two manifolds from the top to bottom inside the column, wetting the cellulose structured packing. As the humid air passes horizontally (ie. in cross-flow configuration) through the column, moisture is removed as the water vapour is absorbed by the liquid desiccant. The weak magnesium chloride solution is collected at the bottom of the column inside a tank and by gravity flows freely through a tube to the regenerator-manifold.

The regenerator is an open type flat plate regenerator (no glazing) set with an inclination of 2.5 degrees to the horizontal. The regenerator surface is covered by a 5mm black neoprene foam sheet and a woven black mulch sheet (polythene) on the top for better dispersion of the solution on the surface. The weak magnesium chloride solution is regenerated by flowing as a fluid film in contact with the ambient air. Under real conditions the solution will be heated by the sun. Therefore in lab we had to construct a solar simulator which is an array of 90 bulbs (4.5kW power supply) arranged in a triangular pattern. Each bulb was an EIKO Q50MR16 Solux bulb, 50W, 4700 K (daylight simulation bulb), 36 deg. dichroic spot. They were arranged with a pitch of 109 mm between them. The solar simulator provides the necessary heat to drive the water off the solution. The regenerated liquid desiccant is collected in a tank and from there the peristaltic pump returns it to the packed column.

The temperatures are measured using platinum resistance detectors (PT104 Pico Technology, UK) and the readings are scanned and recorded by the PicoLog data logging software. gPROMS® software is used to model the processes of heat and mass transfer taking place inside the system. gPROMS® was chosen as an equation-oriented modelling system used for building, validating and executing first-principles models within a flowsheeting framework. This software will be used to model the overall solar liquid

cooling system which incorporates secondary processes such as the pumping process of the liquid desiccant and the cooling tubes of the packed column.

RESULTS AND DISCUSSION
Theory

The heat and mass transfer processes in liquid desiccant cooling systems occurring in structured and random packed columns have been investigated by several authors (Stevens et al., 1989; Al-Farayedhi et al., 2002; Gandhidasan, 2004; Liu et al., 2007a; Liu et al., 2007b; Yin and Zhang, 2008). The mathematical model developed here is based on the analysis done by Ying and Zhang (2008) which is an extension of Stevens et al (1989) model. The structured packed column is considered as a control volume. Taking a differential control volume (Fig. 2) the following equations can be derived.

For the heat transfer between the air and the liquid:

$$G_a \cdot C_{Pa} \cdot dT_a = h_C \cdot (T_s - T_a) \cdot a_w \cdot L \cdot dx \cdot dy \tag{1}$$

For the mass transfer between the air and the liquid:

$$G_a \cdot d\omega_a = h_D \cdot (\omega_{Ts,sat} - \omega_a) \cdot a_w \cdot L \cdot dx \cdot dy \tag{2}$$

The enthalpy change of the moist air is given by:

$$dh_a = C_{Pa} \cdot dT_a + h_{fg} \cdot d\omega_a \tag{3}$$

And the energy balance between the air and the liquid by:

$$G_a \cdot dh_a = G_s \cdot C_{Ps} \cdot dT_s + C_{Ps} \cdot T_s \cdot G_a \cdot d\omega_a \tag{4}$$

Finally the mass balance between the air and the liquid gives:

$$dX_s = \frac{G_a \cdot d\omega_a}{G_s - G_a \cdot d\omega_a} \cdot X_s \tag{5}$$

The $\omega_{Ts,sat}$ is the saturated water content of the air at the surface of the solution and can be calculated by

$$\omega_{Ts,sat} = \frac{0.622 \cdot ERH \cdot P_s}{P_{at} - ERH \cdot P_s} \tag{6}$$

where ERH is the equilibrium relative humidity of the magnesium chloride solution, which is a function of temperature and desiccant's concentration. At temperatures of 20 to 40°C, it can be expressed only as a function of concentration, from very dilute up to saturation, with an error of ±0.3% by the following polynomial fit to experimental data reported by Zaytsev and Aseyev (1992):

$$ERH = -4.7629 \cdot X_s^2 - 0.1528 \cdot X_s + 0.9923 \tag{7}$$

The heat and mass transfer coefficients are calculated based on correlations of Nusselt and Sherwood numbers for cellulose structured pads (Chung et al., 1996).

$$Nu = 2.78 \cdot 10^{-6} \cdot Re^{1.6} \cdot Pr^{0.333} \cdot \left(\frac{G_s}{G_a}\right)^{0.4} \cdot (1 - X_s)^{1.8} \tag{8}$$

$$Sh = 2.25 \cdot 10^{-4} \cdot Re \cdot Sc^{0.333} \cdot \left(\frac{G_s}{G_a}\right)^{0.1} \cdot (1 - X_s)^{-0.75} \tag{9}$$

The pad can be divided into an infinite number of differential elements, each with volume dV, $dV = L \cdot dx \cdot dy$ where L is the length of the pad. In this analysis each pad was divided in 100 differential volumes. The enthalpy effectiveness and moisture effectiveness of the dehumidifier describe the combined heat and mass transfer performances and they were calculated by the following equations:

$$\eta_h = \frac{h_{a,in} - h_{a,out}}{h_{a,in} - h_{e,in}} \cdot 100\% \tag{10}$$

$$\omega_h = \frac{\omega_{a,in} - \omega_{a,out}}{\omega_{a,in} - \omega_{e,in}} \cdot 100\% \tag{11}$$

Experimental Results and Model Predictions

Table 1 summarizes the results from the preliminary experiments with the system. It is seen that the average percent error between the predicted and the experimental values of mass flow rate of water absorption per unit wetted surface area, M_w, is approximately 13%. There are more significant differences in the case of enthalpy effectiveness than in the case of moisture effectiveness. It is worth noting though that the model presented here does not describe the heat and mass transfer that take place at the surface of the cooling tubes inside the packed column and that in the experiments carried out no cooling was used.

The model was used to predict the air wet bulb temperature drop when passing through the dehumidifier using weather data from Havana, Cuba and Manila, Philippines (average hourly data for whole month obtained from the US Department of Energy). The month chosen was May of year 2005. As seen in Fig. 3, the wet bulb temperature drops were approximately 2.2^{o}C and 3°C respectively.

CONCLUSIONS

This study has shown that the proposed heat and mass transfer model for the dehumidifier can be the basis for developing a more accurate model which will incorporate secondary heat and mass transfer processes occurring inside the packed column. We have applied the model in two geographic locations and found that the wet bulb temperature was decreased by 2.2-3.0^{o}C. The results from the preliminary experiments with the constructed liquid desiccant system are promising since it managed to produce a 3.1-3.5^{o}C drop without cooling. Further work is needed to be done in optimising the heat and mass transfer model and more experimental data will be required for validation.

ACKNOWLEDGEMENTS

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Tables

Table 1. Experimental and predicted results of the preliminary experiments. The volumetric flow was set at 0.0276 m^3 s^{-1} and the initial mass concentration of the magnesium chloride solution was 34.58%.

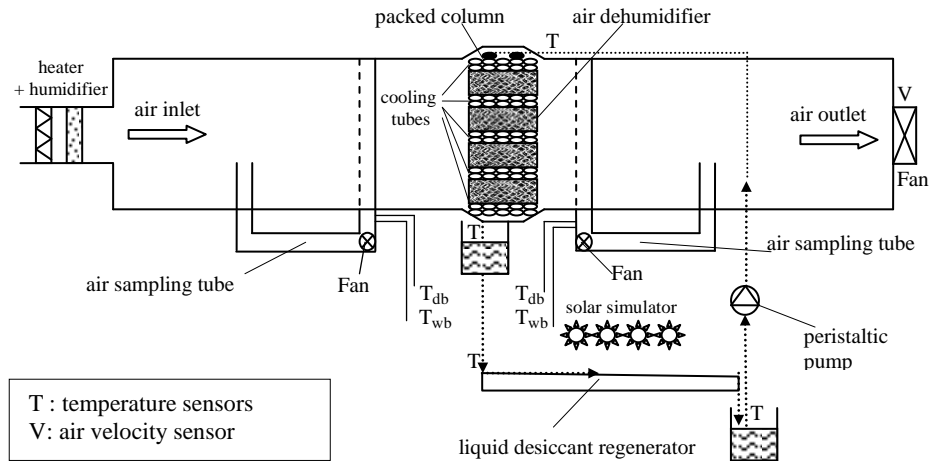|	1st run		2nd run	
	Exp.	Pred.	Exp.	Pred.
	Air inlet	Air outlet	Air inlet	Air outlet
RH (%)	66	51	72	52
Tdb (^{o}C)	31.55	31.35	31.30	31.23
Twb (^{o}C)	26.33	23.43	27.07	23.50
Mw (g h^{-1} m^{-2})	133.5	154.8	169.2	182.5
η_h (%)	52.8	35.4	56.8	34.1
η_w (%)	53.8	63.0	57.8	62.9

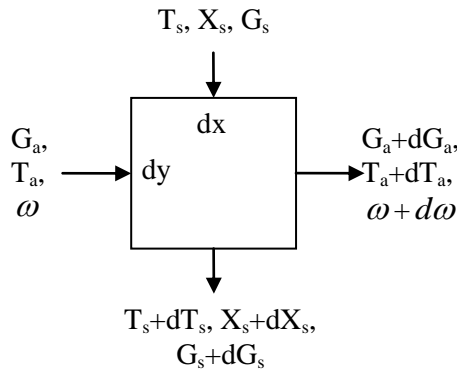Fig. 1. Schematic diagram of the experimental rig.

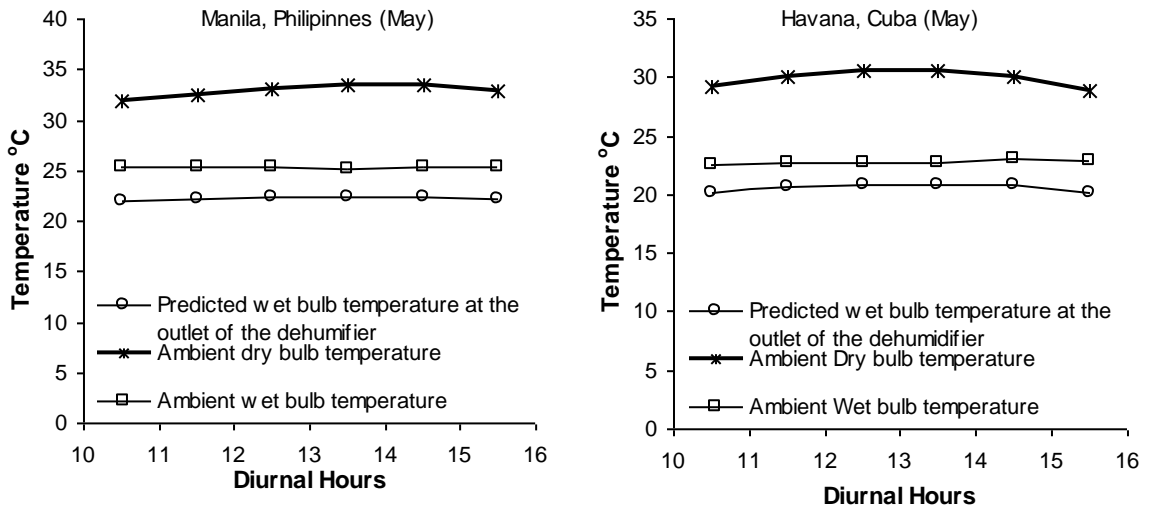Fig.2. Differential control volume.

Fig. 3. Wet bulb temperature drop of the air at the outlet of the dehumidifier during 10.00-16.00 hrs in Manila (left) and Havana (right).

List of Symbols

	Definition	**UNITS**
G_a	mass flow of air through a differential volume	kg s^{-1}
a_w	wetted surface per unit volume	m^{-1} m^{-3}
C_{Pa}	heat capacity of air	J kg^{-1} K^{-1}
C_{Ps}	heat capacity of liquid desiccant solution	J kg^{-1} K^{-1}
T_a	air temperature	^{o}C or K
T_s	solution temperature	^{o}C or K
ERH	equilibrium relative humidity	
G_s	mass flow of liquid desiccant in a differential volume	kg s^{-1}
P_{at}	ambient vapour pressure	Pa
h_C	convective heat transfer coefficient	W m^{-2} K^{-1}
h_D	mass transfer coefficient	kg m^{-2} s^{-1}
P	vapour pressure of the liquid desiccant	Pa
h_a	enthalpy of air	J kg^{-1}
X_s	mass concentration of desiccant solution	%
Greek variables		
η_h	enthalpy effectiveness	%
η_w	moisture effectiveness	%
ω_a	water content of the air	kg/kg
$\omega_{Ts,sat}$	water content of the air in equilibrium with the desiccant solution	kg/kg