Self-regenerating liquid desiccant – vapour compression hybrid air conditioning system

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ABSTRACT
The liquid desiccant – vapour compression hybrid air conditioning system is analysed. The liquid desiccant circuit is primarily used to further dehumidify the supply air. It does not contribute to cooling nor requires external heat input. The results show that the hotter and drier the regeneration air, the better is the system performance. Similarly colder process air yields drier supply air.

INDEX TERMS
Hybrid air conditioner, Liquid desiccant, Dehumidification, Vapour compression system.

INTRODUCTION
The liquid desiccant cooling systems have been extensively analysed in the recent past (Jain et al., 2000, Kessling et al., 1998, Nelson and Goswami, 2002). The liquid desiccant dehumidifies the air but also heats it. The resulting warm – dry air is cooled by rejecting heat to ambient and is then humidified at constant enthalpy to get cold air for cooling applications. Thus, while these systems can provide very low humidity, their efficiency, due to heat operation, is relatively low. The vapour compression systems are widely used for air conditioning (AC) due to their compactness, high energy efficiency, etc., but have limitations in bringing down the humidity. Hybridisation of the two systems is possible to achieve low humidity at high energy efficiency and this paper deals with such a novel hybrid AC system.

Conditioned air is to be served cool and dry. The perceived indoor air quality (IAQ) increases with decrease in relative humidity (Fanger, 1999), as long as it is kept between 30 to 70 %. But air conditioning is an energy intensive process. Further, control of humidity at lower levels by reheat systems consumes lot more energy. The present system is thus useful in efficiently improving the perceived IAQ in buildings.

SYSTEM DESCRIPTION
The schematic diagram of the proposed liquid desiccant - vapour compression hybrid air conditioning system and its cycle on the psychrometric chart are shown in Figures 1 (a) and (b) respectively. The return air from the space (r) and ventilation air (A4) get mixed and the resulting mixed air at A1 flows over the evaporator of the vapour compression system and gets cooled and dehumidified to A2. This process air fed to the dehumidifier, which interacts with the cool and strong desiccant solution at D6 over the packing material. Heat and mass transfer takes place and the air gets further dehumidified to A3, which is supplied to the space for low humidity air conditioning. The desiccant solution gets diluted to D1 and is pumped to regenerator through solution heat exchanger.

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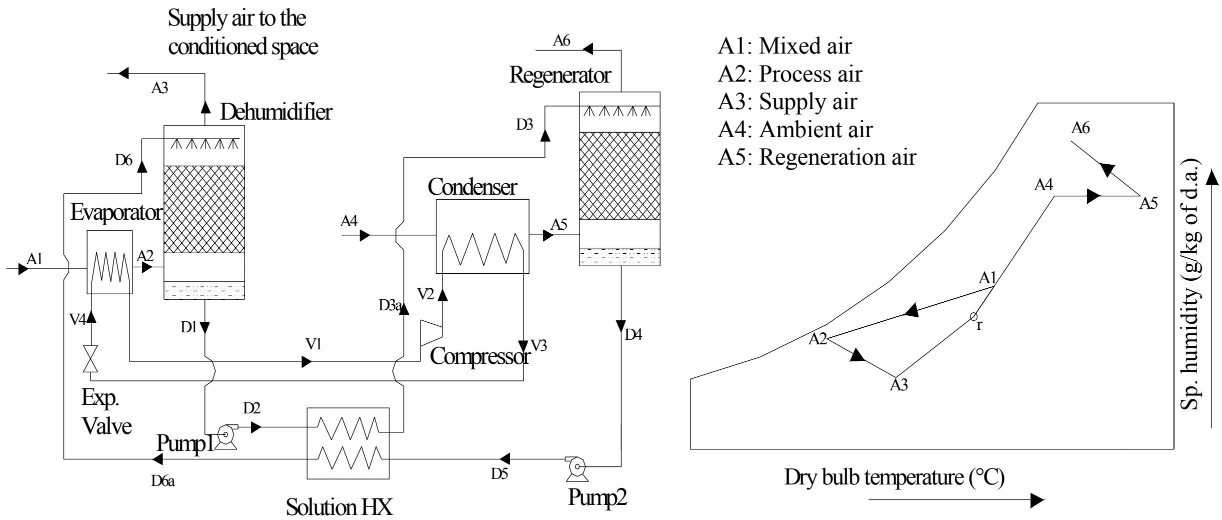
The ambient air at A4 flows over the condenser of the vapour compression system, where it gets heated. The resulting regeneration air at A5 interacts with the weak desiccant solution at D3 in the regenerator. The solution gets concentrated to D4 and then cooled in solution heat exchanger to D6 and the cycle continues.

MATHEMATICAL MODEL

The analysis is made for the specified flow rates of process air and regeneration air and their states, the flow rate of strong desiccant solution and efficiency of dehumidifier and regenerator. Property data equations for desiccant solution and air are used as follows.



(a) Schematic diagram (b) Air cycle on psychrometric chart

Figure 1. Liquid desiccant – vapour compression hybrid air conditioning system.

The concentrations of weak and strong lithium bromide solutions leaving the dehumidifier and the regenerator respectively are given by (ASHRAE, 2001),

$$X_w = f(t_{A3}, t_{d,A3}) \quad (1)$$
$$X_s = f(t_{A5}, t_{d,A5}) \quad (2)$$

Where X_w and X_s are concentrations of weak and strong solution respectively, t_{A3} and t_{A5} are temperatures of supply and regeneration air respectively and $t_{d,A3}$ and $t_{d,A5}$ are dew point temperatures of supply and regeneration air respectively. Circulation ratio (λ) is defined as,

$$\lambda = X_s/(X_s - X_w) \quad (3)$$

The moisture absorbed from the process air (m_{wv}) is found as,

$$m_{wv} = m_w - m_s = m_s/\lambda \quad (4)$$

Where m_w and m_s are mass of weak and strong solution respectively. The supply air condition is given by,

$$w_{A3} = w_{A2} - m_{wv}/m_{A2} \quad (5)$$
$$h_{A3} = (m_{A2}\, h_{A2} + m_s\, h_{D6} - m_w\, h_{D1})/m_{A2} \quad (6)$$

Where w_{A3} and w_{A2} are specific humidity of supply air and process air respectively, m_{A2} is the mass of process air, h_{A2} and h_{A3} are enthalpies of process and supply air respectively, h_{D1} and h_{D6} are enthalpies of weak and strong desiccant solutions at the respective exits. The efficiencies of dehumidifier (h_{de}) and regenerator (h_{re}) are obtained as follows.

$$h_{de} = (X_s - X_w)/(X_{s,eq} - X_w) \quad (7)$$
$$h_{re} = (X_s - X_w)/(X_s - X_{w,eq}) \quad (8)$$

Where $X_{s,eq}$ and $X_{w,eq}$ are equilibrium concentrations of strong solution corresponding to t_{A5} and $t_{d,A5}$ and weak solution corresponding to t_{A2} and $t_{d,A2}$ respectively.

RESULTS AND DISCUSSION

Mass flow rates of process air m_{A2}, and regeneration air m_{A5}, are kept constant at 14 and 18 kg/min respectively, which are typical of a 5 kW room air conditioner. The operating parameters and their ranges are listed in Table 1. Each one of the parameter is varied keeping the other variables at their respective mean value indicated in the table. The results are described in Figures 2 to 5.

Table 1. List of operating parameters and their range.

Sl. No.	Parameter	Range	Mean value
1	Mass flow rate of strong solution, m_s (g/min)	1 to 20	20
2	Process air temperature, t_{A2} (^{0}C)	10 to 17	10
3	Regeneration air temperature, t_{A5} (^{0}C)	34 to 50	45
4	Process air specific humidity, w_{A2} (g/kg-da)	4 to 7	6.86
5	Regeneration air humidity, w_{A5} (g/kg-da)	15 to 30	23.33
6	Efficiency of dehumidifier/regenerator, h (-)	0.7 to 1.0	1.0

Process air

Figure 2 illustrates the influence of process air temperature (t_{A2}) on the system parameters. While the concentration of strong solution (X_s), as it depends only on regenerator performance, remains constant, that of weak solution increases with temperature of process air (Figure 2a). This is due to the fact that as t_{A2} increases, the capacity of the solution to absorb water vapour from air decreases. Thus the moisture removed from the process air by the solution in the dehumidifier decreases as shown in Figure 2b.Therefore as Figure 2c portrays the specific humidity of supply air increases with increase in t_{A2}.

The effect of specific humidity of process air w_{A2} is somewhat opposite to that of its temperature. The concentration of the weak solution decreases with increase in specific humidity (Figure 3a) since vapour pressure of water in air increases increasing the lower limit of solution concentration during the absorption process. This will increase the moisture removal rate from the process air (Figure 3b). Even in spite of increase in moisture removed from the process air, the supply air humidity still increases as shown in Figure 3c. This is in line with other heat and mass transfer equipments. The removal rate does not increase as fast as that of increase in specific humidity of process air.

Solution flow rate

In this hybrid system the responsibility assigned to the desiccant is "further dehumidification". It does not contribute to any cooling. Therefore the solution flow rate is

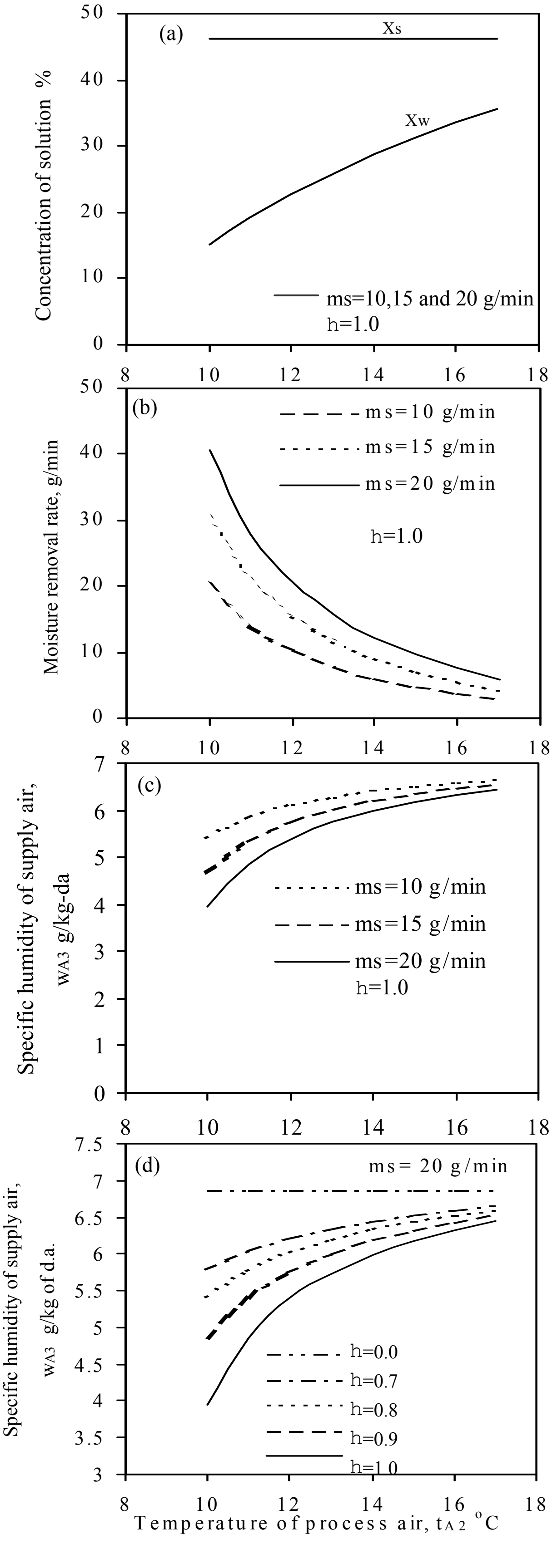


Figure 2. Influence of process air temperature

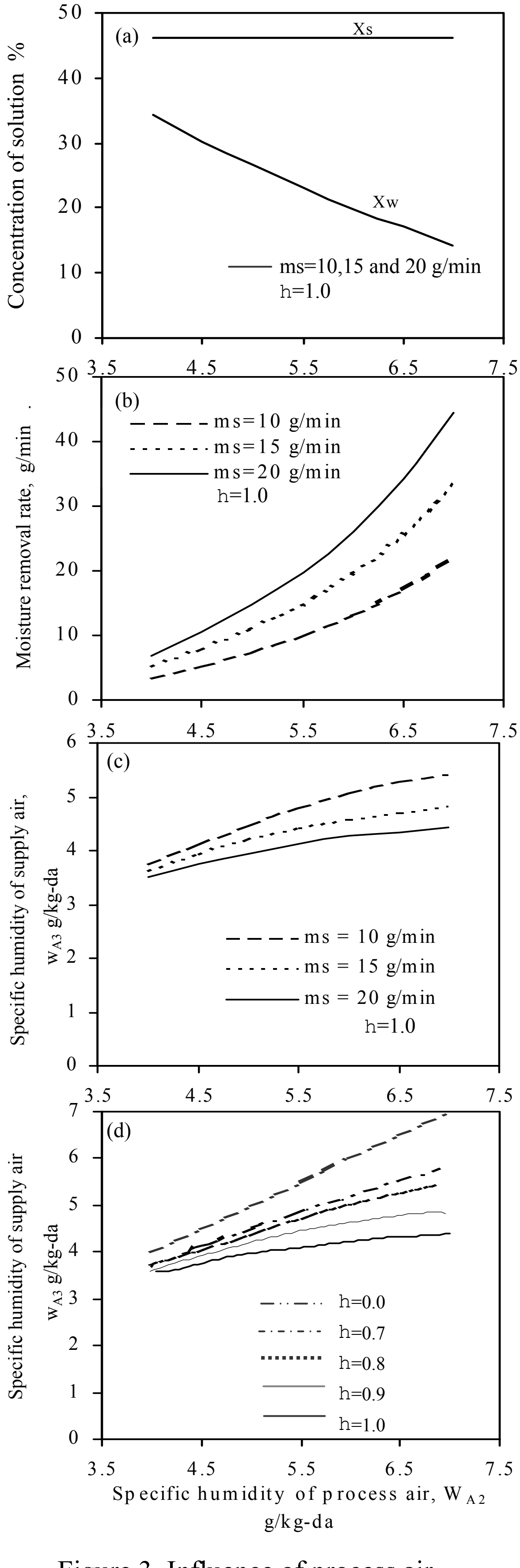


Figure 3. Influence of process air specific humidity

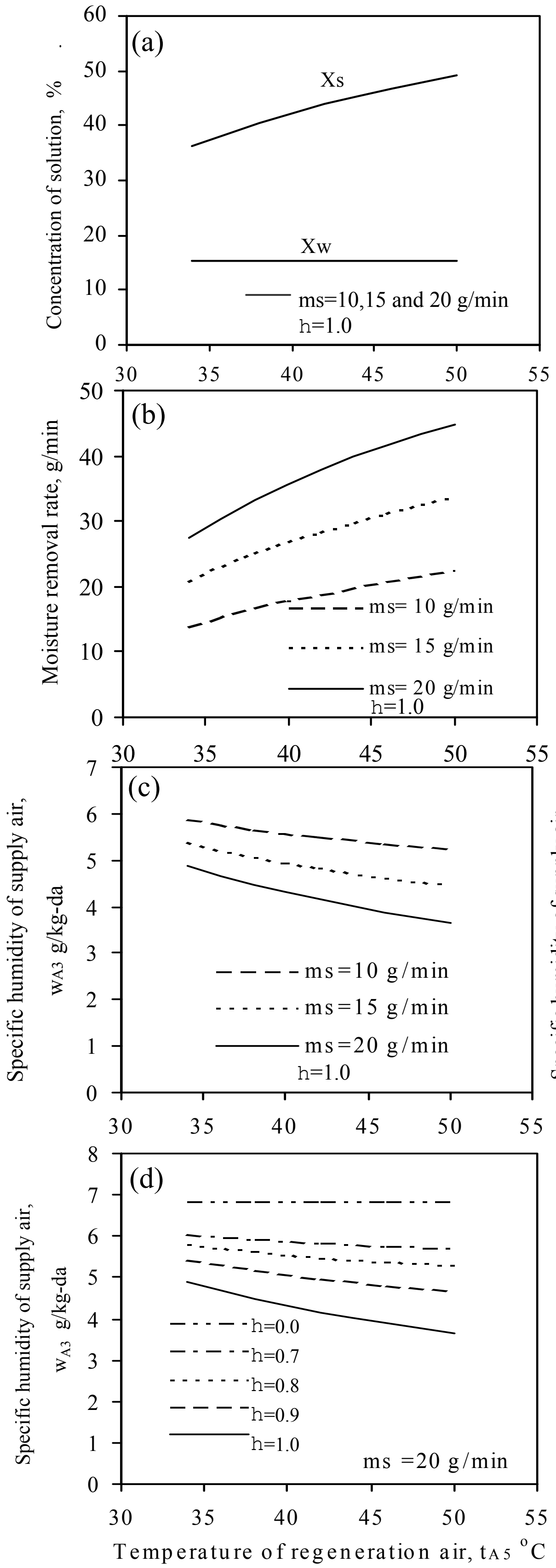


Figure 4. Influence of regeneration air temperature

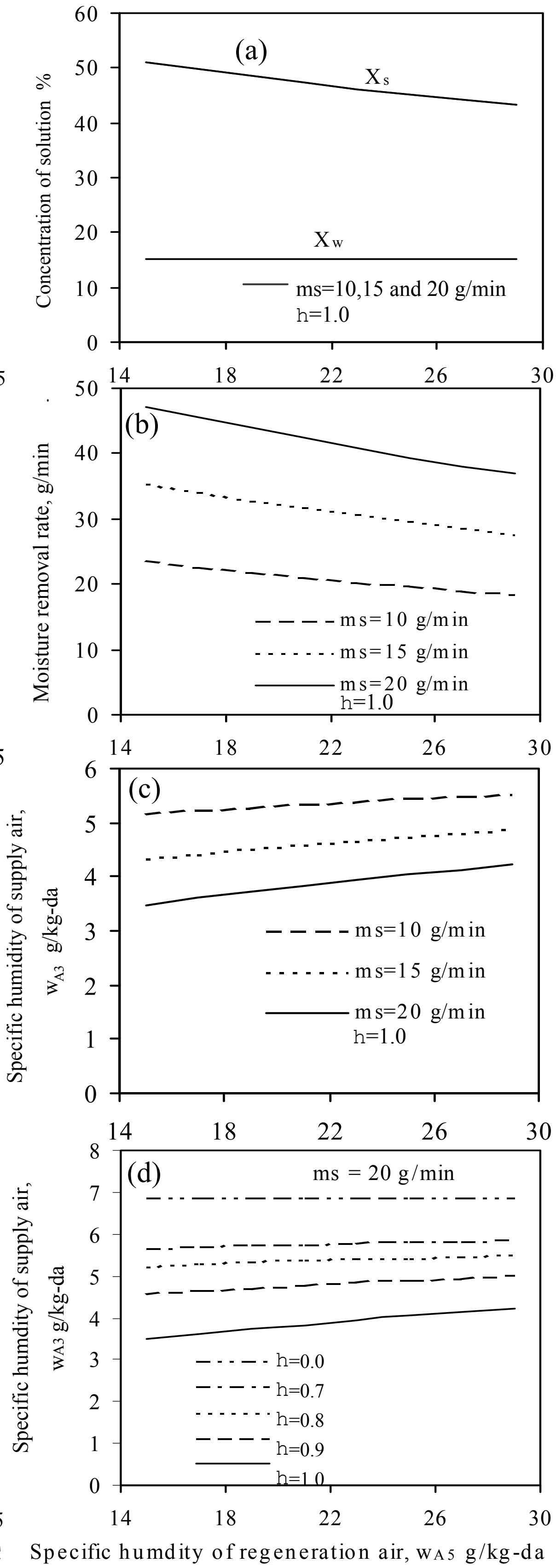


Figure 5. Influence of regeneration air specific humidity

very small at about 0.1% of that of process or regeneration air. Hence the transfer process is controlled by liquid desiccant. Therefore the solution concentrations (X_s, X_w) are independent of its mass flow rate as shown in Figure 2a. Increase in mass flow rate of solution from 10-20 g/minute which are within the limit of solution controlling range, increases the moisture removal rate and therefore decreases the specific humidity of supply air as shown in Figures 2b and 2c respectively for any given process air temperature.

Regeneration air
Regeneration air, both the temperature and humidity influences only the strong solution concentration and hence as Figures 4a and 5a portray Xs varies with its temperature and humidity respectively. It increases with temperature and decreases with humidity for the reasons explained with respect to Figures 2a and 3a above.

Moisture removal rate increases with temperature of the regeneration air Figure 4b while it decreases with increases with increase in specific humidity Figure 5b. Higher the strong solution concentration the higher is the moisture removal rate and therefore the variations are justified. Once more moisture is removed from the process air; the specific humidity of supply air will decrease as shown in Figure 4c with increase in temperature of regeneration air. For the same reason, it decreases with the decrease in specific humidity of the regeneration air as depicted in Figure 5c.

Efficiency of dehumidifier and regenerator
Figures 2a, 3a, 4a, and 5a describe the role of efficiencies of dehumidifier and regenerator on the specific humidity of supply air. Efficiency equal to zero represents the conventional air conditioner. As the efficiency increases the supply air will be more dry which can lower the space humidity. The figures display the quantitative advantage of the proposed hybrid air conditioning system in low humidity air conditioning

CONCLUSIONS
A novel liquid desiccant – vapour compression hybrid air conditioning system is presented. The flow rate of liquid desiccant is very low at about 0.1% of the regeneration air. It is meant only to assist in dehumidifying the air without contributing to cooling. The regeneration of the liquid desiccant (lithium bromide solution) is achieved by hot condenser air. The study reveals that such a hybrid system is feasible and is suitable for low humidity air conditioning. Mass flow rate of solution is found to enhance the perfor- mance of the system. It is further observed that the colder the process air and the hotter the regeneration air the better is the system performance in delivering drier supply air.

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