Parametric studies on coupled columns of liquid desiccant–vapor compression hybrid air conditioning system

B. Shaji Mohan, Shaligram Tiwari and M.P. Maiya*

Refrigeration and Air Conditioning Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India

Abstract

A coupled system of two liquid desiccant columns—one dehumidifying the air and the other regenerating the solution—has been investigated for very low solution to air flow ratios (*S*/*A*) in the range of 0.2–1.6%. The present study explores the feasibility of integrating the columns with the conventional room air conditioner (AC) to enhance the dehumidification capacity of the hybrid AC system. The air inlet conditions to dehumidifying column are assumed typical of supply air from a room AC at 8–16°C dry bulb temperature (DBT) and 75–95% relative humidity. Similarly, inlet air to regenerating column is assumed at 40–60°C DBT and 15–20 g/kg specific humidity, which are typical of the condenser exit air. It is observed that the moisture transfer from supply to condenser air takes place at the rate of 0.28–0.6 g/s for a 0.8 TR AC unit. This indeed enhances the dehumidification of the supply air considerably. Moreover, the supply air gets sensibly heated following the isenthalpic dehumidification process, which enables the hybrid system to maintain low humidity in the conditioned space.

Keywords: liquid desiccant; hybrid air conditioner; absorber; regenerator; coupled columns

*Corresponding author: mpmaiya@iitm.ac.in

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1 INTRODUCTION

High level of humidity in a given space causes the growth and propagation of bacteria and viruses. Low temperature and low humidity increase not only the human comfort but also the perceived air quality [1]. These can significantly enhance the life of books, manuscripts and tapes in the library. It is found that the life of paper gets doubled for each 5.5 K reduction in dry bulb temperature (DBT). The reduction in absolute humidity also significantly increases the paper life. The recommended design criteria for libraries are 20–24°C DBT and 30–45% relative humidity (RH) [2].

Ambient air contains a small amount of moisture, yet plays an important role in various applications such as comfort air conditioning (AC), drying, etc. The removal of moisture from air, whether complete or partial, is termed as dehumidification. This can be achieved either by condensation or sorption of water vapor. The former requires cooling equipment whereas the latter makes use of solid desiccants such as silica gel and molecular sieve or liquid desiccants such as aqueous lithium bromide and aqueous lithium chloride.

Reviews of the early work on the development of liquid desiccant systems can be found in [3]. Studies on liquid desiccant systems were carried out by Lof [3] and Jain *et al.* [4], whereas Belding *et al.* [5] have studied desiccant aging and its effects on desiccant cooling system performance. Control of humidity and temperature with the help of desiccants can result in energy-saving. The performance of a packed column operating as an absorber/regenerator gets influenced by many operating and design parameters [6]. Liquid desiccants have a lower drying capacity compared with their solid counter parts, but are employed owing to their advantages such as ease in operation, causing less pressure drop for air in the packing, and removal of dirt and suspended contaminants from air [7]. More details about desiccant types, properties and the regeneration process are given by Kinsara *et al.* [8].

Packed columns are employed for air dehumidification and their performance has been evaluated under different design and operating conditions [7, 9–11]. Heat and mass transfer between the air and laminar desiccant films in cross flow are studied by Park *et al.* [12, 13], who reported that lower air flow rates give better control over humidity and cooling. Similar

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studies for inclined parallel and counter flow configurations by Ali and Vafai [14] revealed that the inclination angles of the packing play an important role in enhancing the dehumidification, cooling and regeneration processes. The effect of packing density on the moisture removal rate and the dehumidifier effectiveness are assessed by Abdul-Wahab *et al.* [15]. Subramanyam *et al.* [16, 17] have established the feasibility of solid desiccant–vapor compression hybrid system in their study. They found that the supply air could be dehumidified and the solid desiccant could be regenerated operating between supply and return air with temperatures of about 13 and 25°C, respectively. Detailed analysis on parallel flow and counter flow packed columns has been carried out by Shaji Mohan *et al.* [18, 19]. It was concluded that the inlet air properties decide the absorption/regeneration process at low *S*/*A* values. In the present study, the authors extend the model to coupled counter flow columns, one dehumidifying the air (absorber) and the other regenerating the liquid desiccant (regenerator). The coupled columns are analyzed exploring the feasibility to integrate them with conventional AC to achieve better dehumidification of supply air.

2 THEORETICAL MODEL

Figure 1 shows the block diagram of the coupled columns in the counter flow arrangement. Aqueous lithium bromide solution is used as desiccant solution. In the absorber, the desiccant solution absorbs water vapor from the cold and already dehumidified air from evaporator. The resulting weak solution is fed to the regenerator where the hot condenser air regenerates it back as a strong solution. Here the liquid desiccant flow rate at the absorber inlet is small and of the order of 0.2–1.6% of air flow rate. The cold and dehumidified air but at high RH interacts with the solution that has very low flow rate. Hence the solution gets cooled, which results in bringing down its saturation vapor pressure (SVP) below the partial pressure of water in air, thus resulting in absorption of vapor from air into the solution. Similarly, the diluted solution at lower temperature enters the regenerator and interacts with warm air from condenser. Again due to very low flow rate of the solution, the solution gets heated resulting in increase of its SVP above the partial pressure of water in air and thus resulting in regeneration of solution. Thus, air can cool/heat the solution at the absorber/regenerator because of low heat capacity of the liquid desiccant. Therefore, no solution–solution heat exchanger is required. Unlike other lithium bromide water systems that operate under vacuum, this coupled column is an open cycle that works at atmospheric pressure and thereby makes it possible to regenerate the liquid desiccant at a condenser temperature above 40°C. As discussed by Shaji Mohan *et al.* [19], the cold air from the evaporator cools the strong liquid desiccant (lithium bromide solution) in the absorber, thereby reducing the vapor pressure of liquid desiccant below that of air facilitating the absorption of moisture. Similarly, the hot condenser air heats up the weak liquid desiccant in the regenerator, thereby increasing its vapor pressure above that of hot condenser air facilitating the regeneration of the liquid desiccant. The liquid desiccant solution is evenly distributed over the hydrophilic cellulose fills in the form of large droplets using a distributor system. The desiccant distributor consists of a dosing pump that can supply the desiccant from 5–120 ml/min, a motor that is running at 4 rpm and a dispenser to dispense the liquid desiccant in the form of large drops. Thus even distribution and wetting of the whole packing is possible even with small volume flow of solution. Moreover, the solution droplets coming out of the dispenser are large enough so that they cannot be carried away by air, thus maintaining a very low/zero carry over system. This desiccant loop is superimposed on a vapor compression AC system, forming a hybrid system. The computational model of the coupled counter flow columns is shown in Figure 2.

The thermal conductivity (k) and density (ρ) of air can be found as

$$k = f(t_a); \quad \rho = f(p_t, W_a, t_a) \tag{1}$$

Thermal diffusivity is expressed as

$$\alpha = \frac{k}{\rho c_p} \tag{2}$$

where c_p is the specific heat.

The velocity of air through either column can be written in terms of mass flow rate of air:

$$v = \frac{m_a}{A_c \rho} \tag{3}$$

where A_c is the cross-sectional area of packed column.

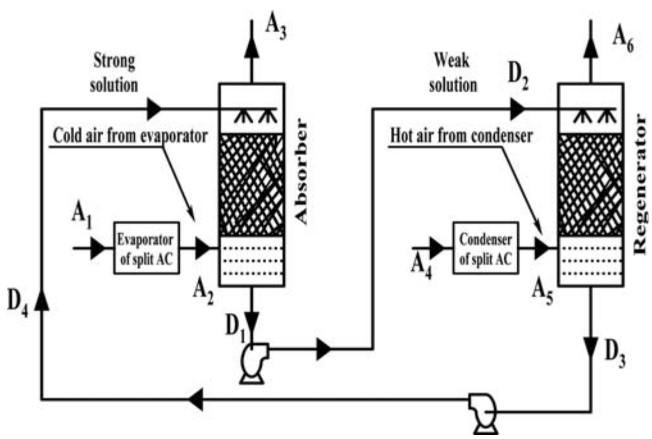

Figure 1. *Block diagram of the proposed coupled counter flow columns.*

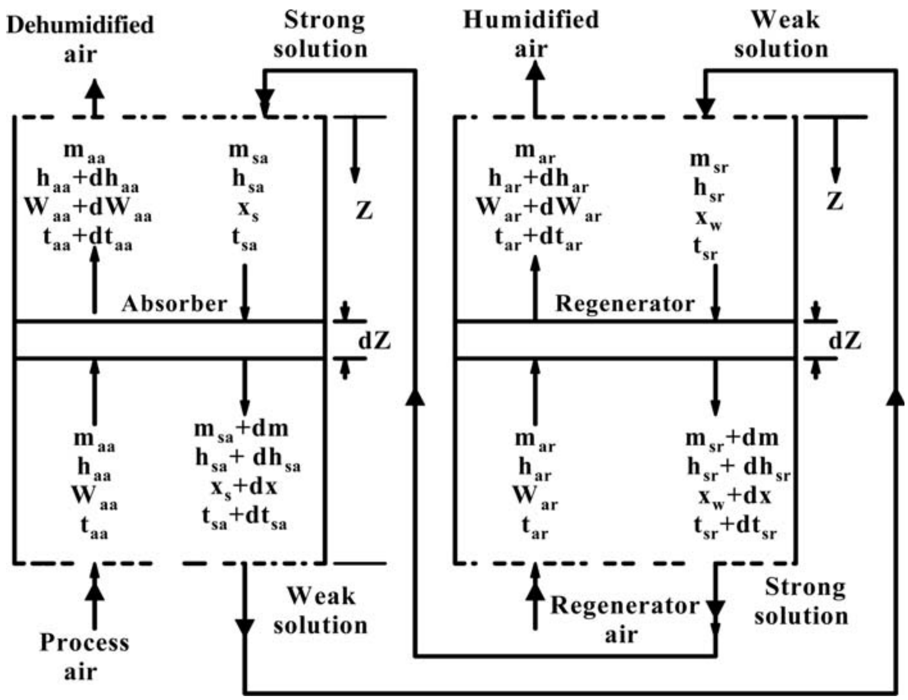

Figure 2. *Computational model of the coupled counter flow columns.*

As the state of air is known, enthalpy of air becomes

$$h_a = f\,(t_a, W_a) = c_{pa}t_a + (W_a(h_{lv} + c_{pv}t_a)) \tag{4}$$

where h_{lv} is the latent heat of vapor at 0°C.

Using correlations suggested by Dowdy and Karabash [20], the heat transfer coefficient is defined as

$$h_c = \frac{\text{Nu}\ k}{l_e}, \quad \text{where Nu} = 0.10\ [l_e/l]^{0.12}\text{Re}^{0.8}\text{Pr}^{1/3} \tag{5}$$

where Nu is the Nusselt number, l_e is the characteristic length of packed column, l is the height of packed column, Re is the Reynolds number and Pr is the Prandtl number.

Lewis number is defined as [21]

$$\text{Le} = \left(\frac{\alpha}{D}\right)^{2/3} \tag{6}$$

The mass transfer coefficient can be expressed in terms of heat transfer coefficient and Lewis number as

$$h_m = \frac{h_c}{c_p\,\text{Le}} \tag{7}$$

Thin layer of air in contact with the lithium bromide (desiccant) solution is saturated and in equilibrium with the solution. Hence, the vapor pressure of the air at the interface (p_i) is given by

$$p_i = p_s = f\,(x_s, t_s) \tag{8}$$

Consequently, the specific humidity of the air at the interface can be found as

$$W_i = \frac{M_v}{M_a}\frac{p_i}{(p_t - p_i)} \tag{9}$$

where M is the molecular weight.

Then, enthalpy of air at the interface is obtained by Equation (4).

The moisture transfer in the differential height segment can be obtained by using the mass transfer potential as

$$dm = h_m\,dA(W_a - W_i) \tag{10}$$

where $dA = a_p\,A_c\,dZ$.

The total heat transfer (dq) in the differential height segment is obtained by using the concept of enthalpy potential

$$dq = \frac{h_c\,dA\,(h_a - h_i)}{c_p} \tag{11}$$

Thus, for the differential height segment shown in Figure 2, the changes in specific humidity and enthalpy of air are given as

$$dW_a = \frac{dm}{m_a};\ dh_a = \frac{dq}{m_a} \tag{12}$$

Consequently, the updated air properties across the differential height segment become

$$W_a^* = W_a + dW_a;\quad h_a^* = h_a + dh_a;\quad t_a^* = f\,(h_a^*, W_a^*) \tag{13}$$

Table 1. *Fixed parameters.*

Parameter	Absorber	Regenerator
Air flow rate, kg/s	0.2	0.3
Height of packed column, cm	30.5	20.3
Cross-sectional area of packing, m^2	0.09	0.09
Density of packed column, m^2/m^3	409	409

Table 2. *Variable operating parameters.*

Parameter	Range	Mean value
Absorber inlet air temperature, t_{aai}, °C	8–16	12
Absorber inlet air relative humidity, ϕ_{aai}, %	75–95	85
Regenerator inlet air temperature, t_{ari}, °C	40–60	50
Regenerator inlet air specific humidity, W_{ari}, g/kg	15–20	17
Solution to air flow ratio in absorber, *S/A*, %	0.2–1.6	Varied for each parameter

Updated solution flow rate is given by

$$m_s^* = m_s + m_a dW_a \tag{14}$$

The updated concentration of lithium bromide (desiccant) solution x_s^* after water vapor transfer can be obtained from mass and material balance.

$$x_s^* = \frac{x_s m_s}{m_s^*} \tag{15}$$

Finally, the updated enthalpy and temperature of the lithium bromide solution at the exit of each differential height segment of either column in Figure 2 can be expressed in the form

$$h_s^* = \frac{(h_s m_s + dq)}{m_s^*};\ t_s^* = f\,(h_s^*, x_s^*) \tag{16}$$

where

$$h_s = f\,(x_s, t_s) \tag{17}$$

3 RESULTS AND DISCUSSION

Using the equations given in the previous section, the exit conditions of process and regenerator air and those of strong and weak desiccant solutions are obtained by successive substitution method. The parameter chosen are categorized as fixed (Table 1) and variable (Table 2) types. When one of the variable parameter is varied over the range chosen for the study, other variable parameters are maintained at their mean values.

The purpose of the coupled desiccant columns is to enhance the dehumidification capacity of the supply air by transferring some of its moisture to the warm condenser (regenerator) air through the desiccant solution. The present study explores the feasibility of such a concept. Considering a 0.8 TR window AC unit, flow rates of process and regenerator air are fixed at 0.2 and 0.3 kg/s, respectively. The inlet properties of both the process and regenerator air are varied covering the expected range of exit air properties (Table 2) at evaporator and condenser of any window AC. The flow rate of solution at the entry of the absorber is specified. The concentration of the solution entering the absorber and that of the solution entering the regenerator, including its flow rate, are the internal parameters, which depend on the operating parameters. For example, Figure 3 shows that with an increase in the process air relative humidity, the solution concentration (x_{ao}) at the exit of the absorber decreases for a given *S/A* ratio. This is attributed to an increase in the vapor pressure of the process air that is caused by an increase in its specific humidity. Similarly, for a given relative humidity of the process air, as the value of *S/A* increases, the concentration at the exit of the absorber increases although there is increased moisture removal. The increase in moisture removal is much smaller than that of solution flow rate in the absorber and hence it does not affect

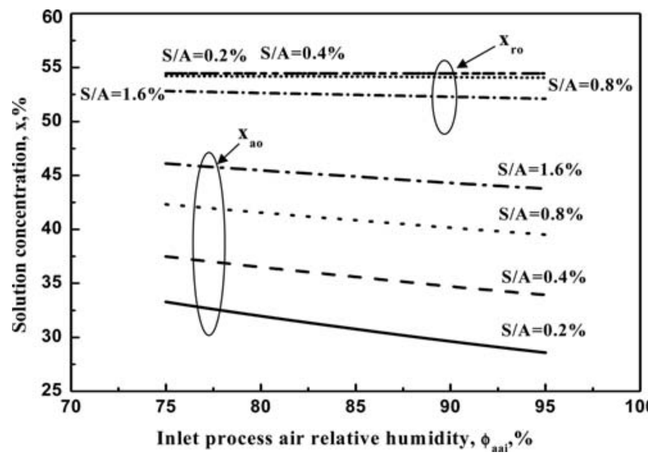

Figure 3. *Effect of inlet process air relative humidity on solution concentration.*

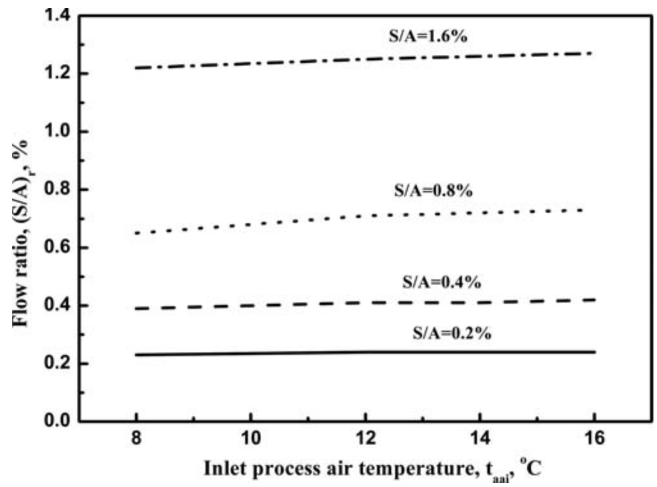

Figure 4. *Effect of inlet process air temperature on flow ratio in regenerator.*

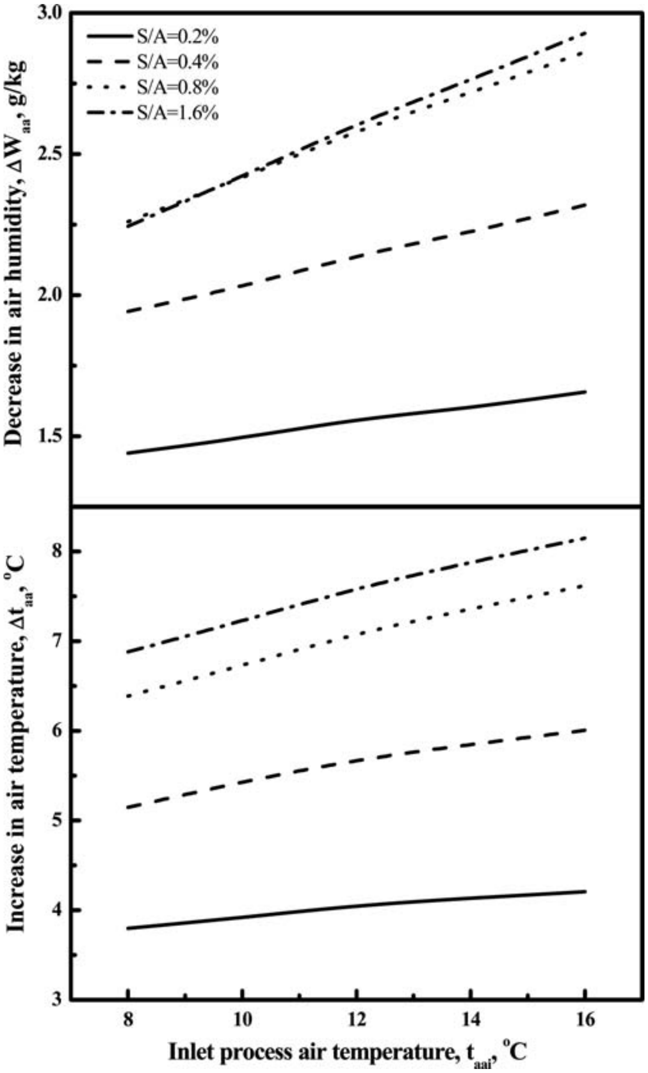

Figure 5. *Influence of inlet process temperature on dehumidification and heating of process air in absorber at constant relative humidity.*

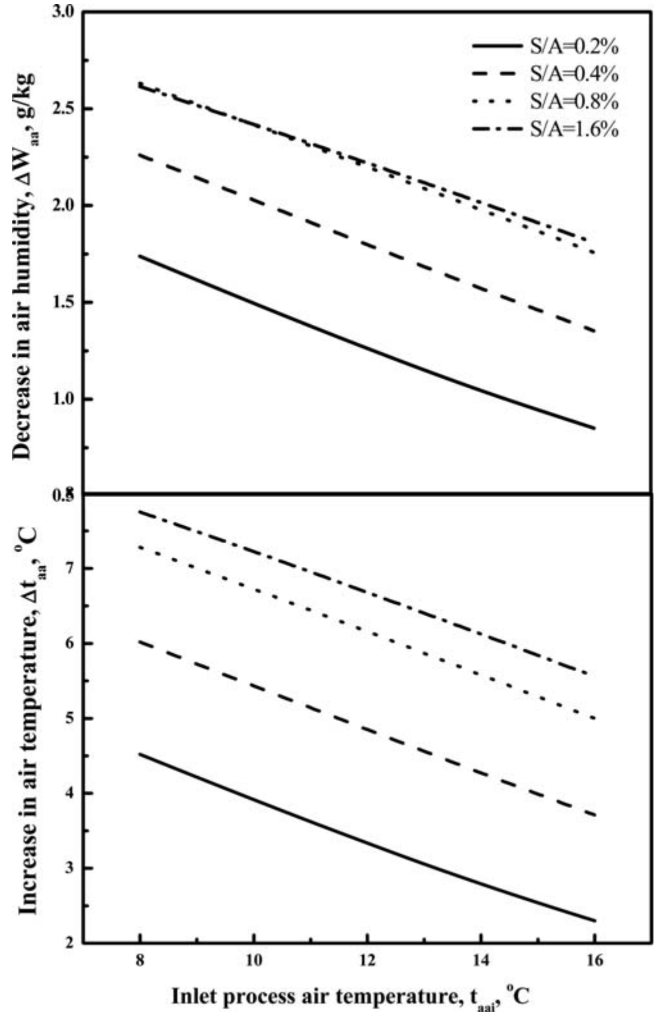

Figure 6. *Influence of inlet process temperature on dehumidification and heating of process air in absorber at constant specific humidity.*

the strength of the solution significantly. Hence, there is an increase in solution concentration at the exit of the absorber. However, in the regenerator, as the relative humidity of the process air increases, the solution concentration at the exit of the regenerator (x_{ro}) remains nearly constant for lower values of flow ratio, but decreases marginally for higher flow ratios. This is because at lower flow ratios, the capacity of air exceeds that required for regenerating the desiccant solution. With an increase in the *S*/*A* ratio, the flow of weak solution at the inlet of the regenerator also increases and more moisture gets picked up by the air. But the effect of moisture loss on the increasing solution concentration gets more than compensated by an increased solution flow rate in the regenerator. Hence, strong solution concentration decreases at the exit of the regenerator.

Figure 4 shows the variation of solution to air flow ratio in the regenerator with inlet temperature of process air for different *S*/*A* ratios at the absorber inlet. When the temperature of the process air at absorber inlet increases at constant RH, its specific humidity also increases. Hence, the solution can absorb more water vapor leading to marginally more flow rate of the solution at the exit of the absorber. Since the same solution is fed to the regenerator, solution to air flow ratio at regenerator inlet, $(S/A)_r$, also marginally increases as shown in the figure for all *S*/*A* values. However, the interesting aspect is that for *S*/*A* ratio of 0.2%, the $(S/A)_r$ is more than 0.2%, whereas the latter increase only to about 1.2% when the former is increased to 1.6%. This is due to the fact that the air flow rates at the absorber and regenerator are held constant at 0.2 and 0.3 kg/s, respectively, and at higher *S*/*A* ratios in the absorber, the moisture absorbed does not increase appreciably to significantly increase the weak solution at the inlet of the regenerator relative to that of the strong solution at the inlet of absorber.

Figure 5 shows that both the dehumidification and the heating of process air in the absorber increase with inlet temperature of process air for all values of *S*/*A* in absorber and fixed value of relative humidity whereas Figure 6 illustrates that they decrease for fixed value of specific humidity. In the present range of low *S*/*A* ratios, air cools the solution and

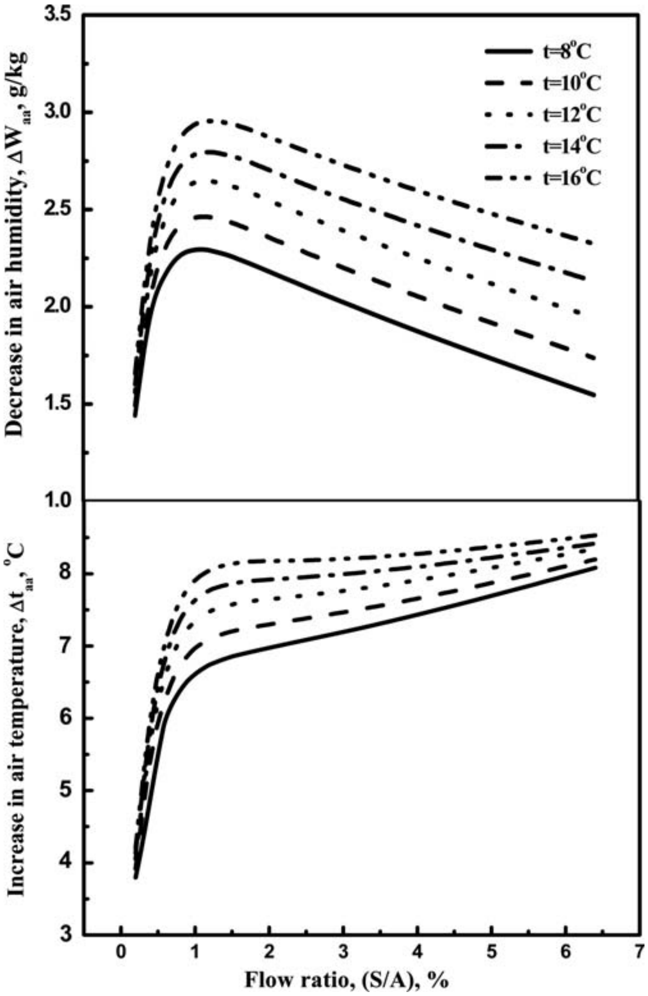

Figure 7. *Influence of* S/A *ratio on dehumidification and heating of process air in absorber at constant relative humidity.*

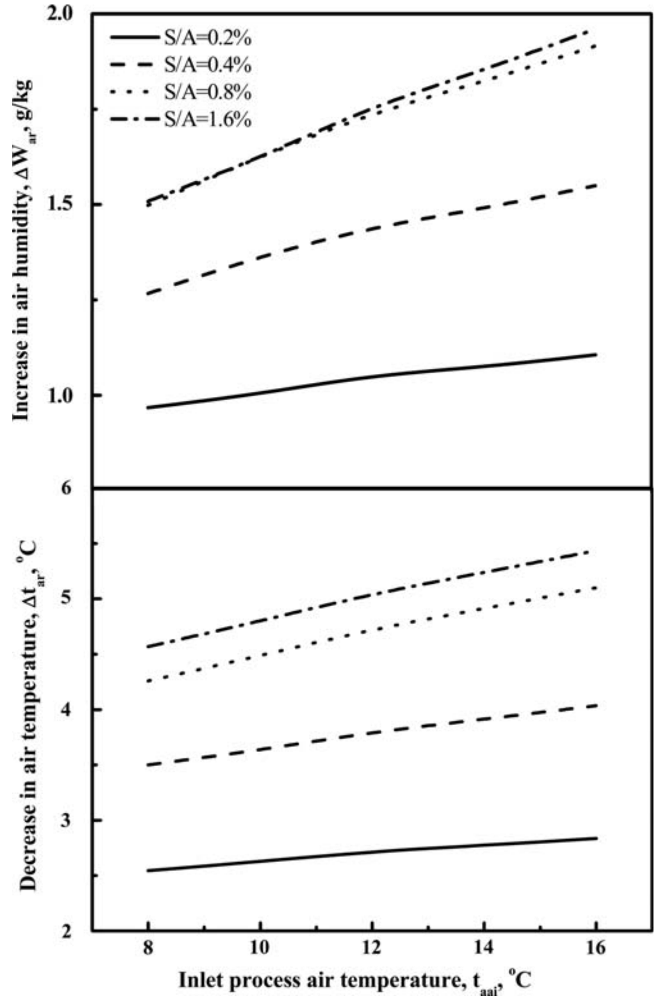

Figure 8. *Influence of inlet process air temperature on humidification and cooling of regenerator air in regenerator.*

tends to bring it closer to the inlet temperature of the process air. Hence, the lower the inlet temperature of air, more the solution would get cooled and lower would be the SVP of the solution. As the partial pressure of water vapor in air is more at high specific humidity, the potential for air dehumidification is higher either when saturation pressure of solution is low or when vapor pressure of air is high or both. Therefore, low temperature and high specific humidity are favorable for dehumidification of air in the absorber by desiccant solution. Thus, the nature of variation in Figure 6 gets justified when inlet process air temperature is increased at constant specific humidity. In Figure 5, the influence of increasing specific humidity by maintaining constant relative humidity is partially nullified by that of an increase in the inlet temperature of process air. Hence, both dehumidification and heating of air show a subdued increase with inlet temperature of process air.

Figure 7 presents an extended interpretation of Figure 5 and highlights the influence of *S/A* on dehumidification and heating of the process air. There exists an optimum *S/A* ratio (about 1.1%) at which the dehumidification of the process air is maximum. At low value of *S/A* in the absorber, the heat capacity of the solution is small compared with that of air. Hence the solution cools down to the inlet air temperature even when the inlet solution is warmer. The moisture transfer from air to solution and the consequent heat transfer from solution to air are controlled by solution capacity. At high *S/A* ratio, the solution heat capacity is higher. It does not cool down appreciably. Hence its vapor pressure remains high and consequently does not absorb moisture from the air. Further, it heats up the air appreciably. So the air temperature increases at higher *S/A* even while the dehumidification is reduced.

Figure 8 presents the effect of inlet temperature of process air on the regeneration of the liquid desiccant. An increase in the inlet process air temperature increases the regeneration of the liquid desiccant. As the inlet temperature of the process air increases for fixed value of relative humidity, there is more moisture removal in the absorber, leading to a decrease in the concentration of the weak solution, which is fed directly to the regenerator. The decrease in the concentration of the liquid desiccant causes an increase in its vapor pressure, and hence water

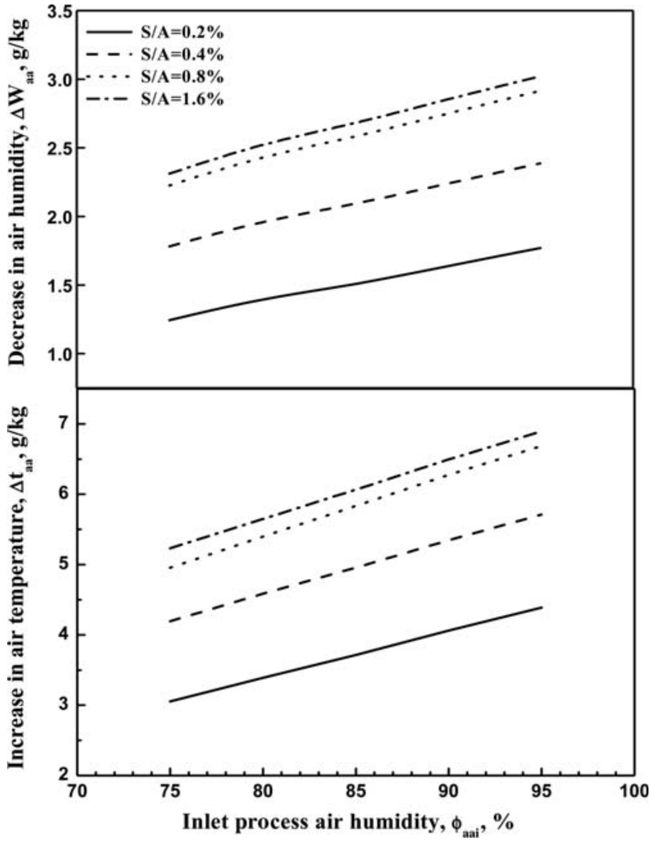

Figure 9. *Effect of inlet process air humidity on dehumidification and heating of process air in absorber.*

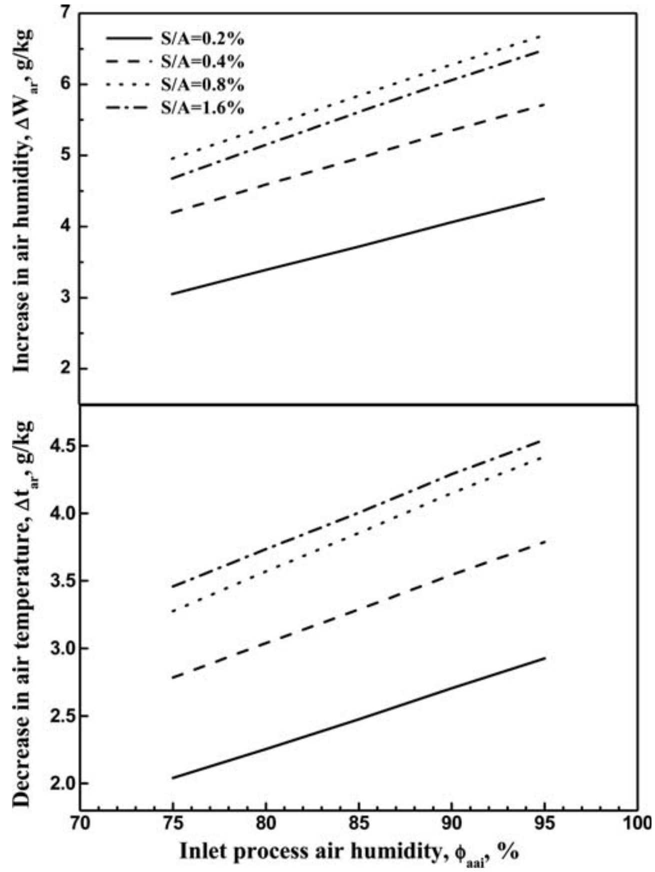

Figure 10. *Effect of inlet process air humidity on humidification and cooling of regenerator air in regenerator.*

vapor transfer to air increases leading to more air humidity. Being an isenthalpic process, it also results in more cooling of air as shown in the figure. Further, as absorber and regenerator are in a closed desiccant loop, there would be an equilibrium in terms of water vapor transfer in the two components. Therefore, as expected, Figures 5 and 8 are quite similar and all the discussions of the former and that of Figure 7 hold good for the latter.

Figures 9 and 10 illustrate the effect of process air relative humidity on the performance characteristics of the absorber and regenerator, respectively. An increase in the relative humidity from 75 to 95% results in increased dehumidification in the absorber. This is because the increase in vapor pressure of air owing to its higher specific humidity facilitates the transfer of moisture from air to the solution. Being an isenthalpic process, more dehumidification leads to more heating of air, and hence increase in air temperature enhances with inlet process air humidity. Flow rate of air being constant, an increase in the *S/A* increases solution flow rate, and correspondingly the dehumidification also increases for the reasons discussed earlier for Figure 7. For the steady state operation, whatever moisture absorbed from the process air by the desiccant solution in the absorber has to be desorbed by it to the regenerator air in the regenerator. Therefore, the variations in Figures 9 and 10 are similar.

The effect of the regenerator air temperature on the performance of the absorber is presented in Figure 11. It shows that with an increase in the regenerator air temperature, the dehumidification in the absorber gets enhanced. This is because with an increase in regenerator air temperature, the SVP of air becomes more and hence can hold more moisture. Also the increased air temperature in turn increases the desiccant temperature. This increases the vapor pressure of the solution, resulting in more regeneration, thereby increasing the concentration of the solution at the exit of the regenerator. This strong solution is fed into the absorber and there is more moisture removal in the absorber. As the *S/A* increases, the moisture removal rate in the absorber also increases, which can be attributed to the increased solution flow rate. As expected, Figure 11 also illustrates that the absorber air temperature increases with increase in the regenerator air temperature. The performance of the regenerator would be similar with change in regenerator air temperature.

Figure 12 presents the effect of regenerator air specific humidity on the absorber performance. As the regenerator air specific humidity increases, the moisture pickup by air gets reduced. The desiccant solution does not get enriched and its capacity to absorb moisture in absorber reduces. The absorption being an isenthalpic process, the increase in air temperature also reduces.

The intended purpose of the coupled desiccant columns for low *S/A* ratios, which are to be superimposed on a typical

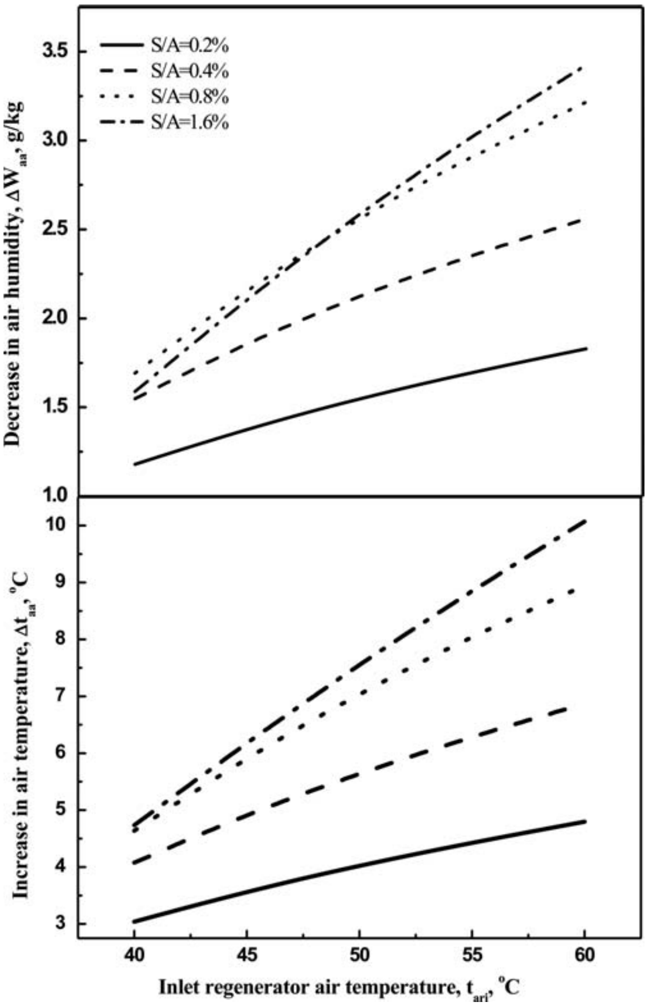

Figure 11. *Effect of regenerator air temperature on dehumidification and heating of process air in absorber.*

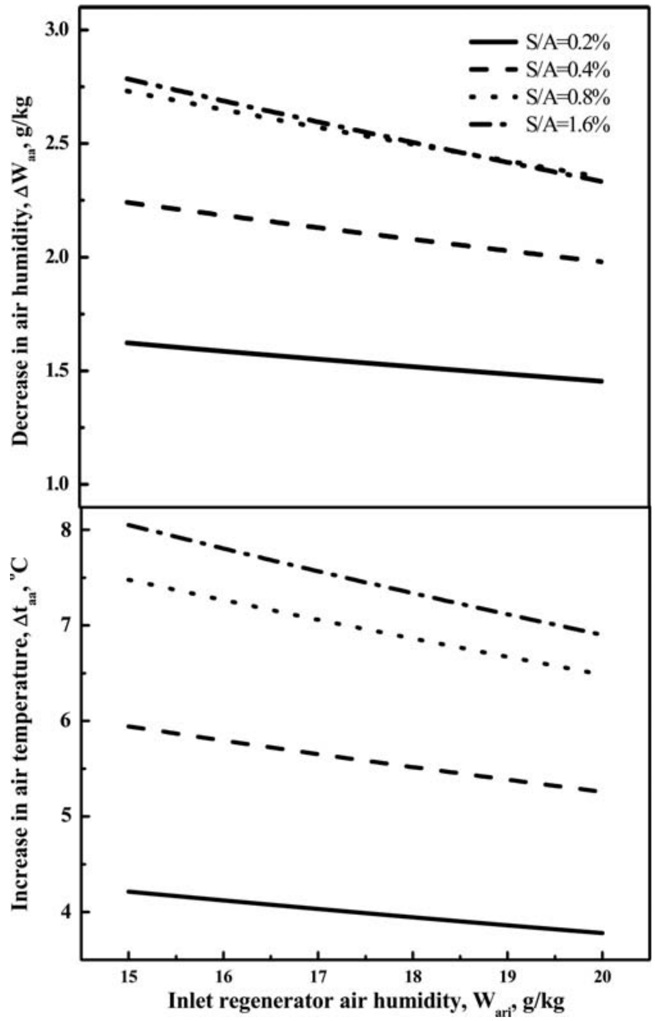

Figure 12. *Effect of regenerator air humidity on dehumidification and heating of process air in absorber.*

split/window AC, is to enhance the overall dehumidification capacity. As an illustration, Figure 13 quantifies the transfer of water vapor (moisture) from supply air to the solution in the absorber and the solution to regenerator air in the regenerator for typical operating conditions of a 0.8 TR window AC. The results in the figure are justified as they are extensions of those in Figures 5 and 8, which are multiplied by the respective mass flow rates of air in evaporator/absorber (0.2 kg/s) and condenser/regenerator (0.3 kg/s). As expected from material balance for water, the two moisture transfers closely match but for small differences in the used property data equations and computational error in the convergence criterion. For the typical mean operating conditions, the figure illustrates that 0.5 g/s of water is transferred from the process air to regenerator air via the desiccant solution circulating in the coupled columns. This transfer is quite significant especially when compared with the nominal vapor condensation of about 0.35 g/s by the cooling and dehumidifying coil of the normal window AC. Thus, additional dehumidification of the supply air is achieved.

The earlier-mentioned dehumidification aspect is further demonstrated by representing the data of Figure 5 on a psychrometric chart as shown in Figure 14. Conditions of supply air from the typical window AC are represented by A_2 for different operating conditions whereas A_3 represents one of the corresponding conditions after the absorber of the desiccant loop. The typical room condition to be maintained is represented by '*r*'. The conventional room process is represented by $A_2 - r$ with a room sensible heat factor (RSHF) as shown, while $A_3 - r$ represents that by the hybrid system with RSHF′. Thus moisture absorption capacity of the supply air from the hybrid system is more than doubled from $\Delta W' = 2.5$ to $\Delta W = 5.2$ g/kg. During the simultaneous adiabatic heat and mass transfer process in the absorber, sensible heat is released to air while absorbing moisture from it, the supply air gets reheated while losing moisture. Thus RSHF of the normal AC is 0.7, whereas it is dropped to 0.3 (RSHF′) with the proposed column. This indicates the capability of the hybrid system to handle high latent heat loads while the cooling capacity remains the same. In other words, for the

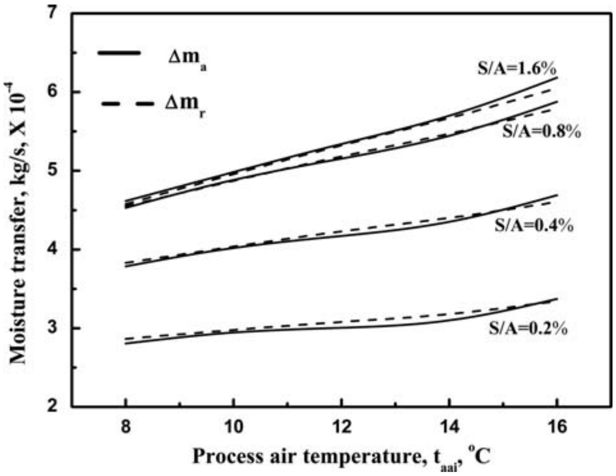

Figure 13. *Effect of inlet process air temperature on moisture transfer.*

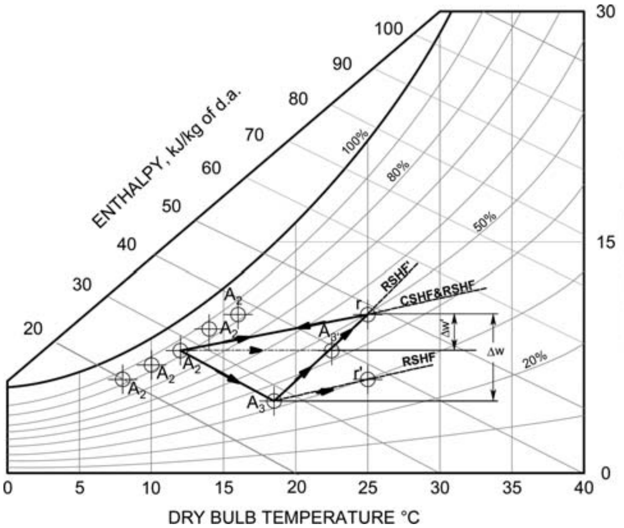

Figure 14. *Dehumidification process representation on a psychrometric chart.*

same RSHF, the system with the proposed coupled columns can maintain a room relative humidity of 30% (state r') as against that of 50% (state r) by the normal AC unit at the same room temperature of 25°C. Further, it is interesting to compare the system performance with that of a reheat AC system. The dehumidified air is reheated from A_3 to $A_{3'}$ to cater the same RSHF′. It is clearly illustrated that the proposed system stands superior by eliminating the reheat and further retaining the cooling capacity from A_3 to r against $A_{3'}$ to r.

4 CONCLUSIONS

A performance study on coupled columns of a hybrid AC based on liquid desiccant vapor compression system has been presented. It is observed that an increase in solution-to-air-flow ratio in the absorber increases the dehumidification of the process air. Both the dehumidification and the regeneration get suppressed when the solution to air flow ratio exceeds a certain value. For small solution flow rates, the desiccant solution can be regenerated using the waste heat from the condenser heat. It is also observed that the use of a coupled desiccant column can enhance the moisture removal by nearly 50%. In fact, the coupled desiccant column can attain an RH of 30% as against that of 50% by the normal AC unit at the same room temperature of 25°C. Consequently, it is beneficial to integrate a counter flow desiccant column with the conventional AC system.

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REFERENCES

[1] Fanger PO. Human requirements in future air conditioned environments. *Int J Refrig* 2001;**24**:148–53.
[2] ASHRAE. *Handbook—HVAC Applications*. American society of Heating, Refrigeration and Air conditioning Engineers, Inc., 1995.
[3] Lof GOG. *Cooling with Solar Energy*. Congress on solar energy, 1955, 171–89.
[4] Jain S, Dhar PL, Kaushik SC. Evaluation of solid desiccant based evaporative cooling cycles for typical hot and humid climates. *Int J Refrig* 1995;**18**:287–96.
[5] Belding WA, Marc Delmas PF, Holeman WD. Desiccant aging and its effects on desiccant cooling system performance. *Appl Therm Eng* 1996;**16**:447–59.
[6] Ö berg V, Goswami DY. Experimental study of the heat and mass transfer in a packed bed liquid desiccant air dehumidifier. *J Sol Energy Eng* 1981;**20**:89–97.
[7] Factor HM, Grossman G. A packed bed dehumidifier/regenerator for solar air conditioning with liquid desiccant. *Sol Energy* 1980;**24**:541–50.
[8] Kinsara AA, Elsayed M, Al-Rabghi OM. Proposed energy-efficient air-conditioning system using liquid desiccant. *Appl Therm Eng* 1996;**16**:791–806.
[9] Elsayed MM. Analysis of air dehumidification using liquid desiccant system. *Renew Energy* 1994;**4**:519–28.
[10] Abdul-Wahab SA, Zurigat YH, Abu-Arabi MK. Predictions of moisture removal rate and dehumidification effectiveness for structured liquid desiccant air dehumidifier. *Energy* 2004;**29**:19–34.
[11] Liu XH, Qu KY, Jiang Y. Empirical correlations to predict the performance of the dehumidifier using liquid desiccant in heat and mass transfer. *Renew Energy* 2006;**10**:1627–39.
[12] Park MS, Howell JR, Vliet GC, *et al*. Numerical and experimental results for coupled heat and mass transfer between a desiccant film and air in cross flow. *Int J Heat Mass Transf* 1994;**37**:395–402.
[13] Park MS, Howell JR, Vliet GC, *et al*. Correlation for regeneration of a falling desiccant film by air in cross flow. *Sol Eng* 1995;**2**:1239–47.

[14] Ali A, Vafai K. An investigation of heat and mass transfer between air and desiccant film in an inclined parallel and counter flow channels. *Int J Heat Mass Transf* 2004;**47**:1745–60.

[15] Abdul-Wahab SA, Abu-Arabi MK, Zurigat YH. Effect of structured packing density on performance of air dehumidifier. *Energy Convers Manage* 2004;**45**:2539–52.

[16] Subramanyam N, Maiya MP, Srinivasa Murthy S. Parametric studies on a liquid desiccant assisted air conditioner. *Appl Therm Eng* 2004;**24**: 2679–88.

[17] Subramanyam N, Maiya MP, Srinivasa Murthy S. Application of desiccant wheel to control humidity in air conditioning systems. *Appl Therm Eng* 2004;**24**:2777–88.

[18] Shaji Mohan B, Prakash Maiya M, Tiwari S. Analysis of adiabatic liquid desiccant absorber for hybrid air conditioner. In: *The 22nd IIR International Congress of Refrigeration*, August 21–26, 2007. Paper No. E1-825.

[19] Shaji Mohan B, Prakash Maiya M, Tiwari S. Performance characterization of liquid desiccant columns for a hybrid air-conditioner. *Appl Therm Eng* 2008;**28**:1342–55.

[20] Dowdy JA, Karabash NS. Experimental determination of heat and mass transfer coefficients in rigid impregnated cellulose evaporative media. *ASHRAE Trans Part 2* 1987;**93**:382–95.

[21] Threlkeld JL. *Thermal Environmental Engineering*. Prentice-Hall INC, 1962.