Mathematical Model Development of a Solar Assisted Liquid Desiccant Air Conditioning System with Fin Coil Dehumidifier

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Abstract: A novel scheme of a solar assisted, liquid desiccant supported comfort air conditioning system has been proposed in this paper. The primary intent of the system is to supply air at 25°C and 52% relative humidity, even during the hot and humid summer months prevailing in the plains of sub-tropical countries like India. A mathematical model has been put forward to predict the output air temperature, humidity ratio and the effectiveness of dehumidifier as well as the regenerator. The predicted air humidity ratio has been validated against data available in the literature. The model has been used to predict the optimum mass flow rates required to achieve the desired output conditions for the selected location (Kolkata). The study thus strengthens the need and feasibility of solar assisted desiccant based air conditioning systems for the sub-tropical climates as a replacement of the traditional VCR (vapor compression refrigeration) systems.

1. Introduction
Economic development and rising standards of living have made heating, ventilation and air conditioning (HVAC) a necessity, rather than a luxury. Air conditioning is an integral part of HVAC sector and studies have shown that about 50% of the total energy expended in buildings, is consumed by air conditioning systems alone [1]. This figure is even higher for countries witnessing tropical or sub tropical climates. The conventional VCR systems have exhibited poor control capacity, when it comes to variations in latent and sensible heat loads [2]. Damped spaces are often formed within such systems, which enhance the likelihood of mould and bacterial infestations. Moreover, refrigerants used by vapor compression systems have been known to cause ozone layer depletion and are responsible for making detrimental changes to the environment. As energy and environmental issues are ubiquitous, developing environmentally benign and sustainable energy technologies have become the need of the hour. Against this backdrop, liquid desiccant air conditioning (LDAC) system can be a promising technology to address this problem. Unlike conventional vapor compression systems, LDAC can handle both the latent and sensible loads independently, thereby reducing energy consumption up to 50% [3]. Although initial cost of LDAC systems have been found to be high, yet studies show that they have the potential to lower the overall cost by 54%[4]. Regeneration of liquid desiccant solution at temperatures lower than 80°C has provided such systems an edge over the solid desiccant air conditioning systems [5]. At the same time such systems can be powered using the solar energy, which is available in plenty in the plains of the Gangetic Bengal in the Indian sub-continent. With 250-300 sunny days per year and an average solar radiation of 200 MW/m², India has a huge demand for air conditioning systems and the potential to power such systems using the solar energy [6].
In the past studies several novel designs have been proposed by researchers, but very few research works are available that discuss the aspect of integration of the fin-coil type of dehumidifier in a LDAC system that too for the hot and humid climate prevailing in the plains of India. The purpose of this current study is to propose a mathematical model of a LDAC system using fin-coil type of dehumidifier to provide conditioned air at a temperature of 25°C and 50-55% relative humidity which falls well within the standards of human comfort set forth by ASHRAE standard 55-2010. Calcium chloride solution with specific heat capacity of 2.5 kJ/kg°C and, equilibrium enthalpy and equilibrium specific humidity of 31.84 kJ/kg and 11.4 g/kg has been used as the desiccant for the present study.

2. System Description

The layout of the proposed solar driven LDAC system has been shown in Fig. 1. The system essentially comprises a dehumidifier, a regenerator, a cooling tower and heat exchangers. A fin-coil type internally cooled dehumidifier (shown in Fig. 3) as developed by Liu et al.[7] has been incorporated in the proposed system. A forced flow flat plate solar collector has been used as the regenerator for the system (shown in Fig. 4). The collector prototype similar to what has been proposed by Alizadeh and Saman [8] has been adopted for the present study. The water from a cooling tower which supplies chilled water at 12°C [9] has been used in the heat exchangers to cool desiccant and air.

![Proposed LDAC model](image_url)
desiccant solution from TC₁ is passed on to heat exchanger HX₂, where the desiccant solution is cooled using chilled cooling water coming from the cooling tower. Thereafter, the relatively cool and concentrated desiccant is pumped into the dehumidifier and the cycle continues.

3. Mathematical Model

Assumptions made while developing the mathematical model are as follows [9][8]:

i. Desiccant is well spread between the tubes, and there is no direct heat transfer between the cooling water and the incoming humid air.

ii. The regenerator unit is considered to be in steady state, and the temperature gradient in the thin desiccant film in the regenerator is not considered.

iii. The heat of vaporization for the water from the weak solution and the specific heat capacities of air and desiccant are constant for the operating range of temperatures.

iv. The rear loss coefficient of the collector is neglected since the bottom end is sufficiently coated.

Based on the assumptions made, three types of heat and mass transfer processes take place inside an internally cooled dehumidifier. For heat and mass transfer processes taking place in the dehumidifier, the equations for energy conservation are given as follows [9]:

\[
\dot{m}_a \frac{dh_a}{dx} + d(m_i h_i) - c_p w \dot{m}_w dT_w = 0
\]  

Where \( \dot{m}, h, c_p \) and \( T \) represent mass flow rate, enthalpy, specific heat capacity and temperature respectively. Throughout the paper, the subscripts a, s and w have been used to denote air, desiccant and water respectively. Whereas subscripts i and o has been used to denote inlet and outlet respectively.

The heat transfer between cooling water and desiccant can be expressed as follows [9]:

\[
c_{p,w} \dot{m}_w \frac{dT_w}{dx} = \frac{K_s F_s}{H} (T_w - T_i)
\]

\( K_s \) and \( F_s \) denote heat transfer coefficient and heat transfer area between cooling water and desiccant. \( H \) is the height of the dehumidifier and \( x \) represents distance along the height of dehumidifier.

Along the height of the dehumidifier, the heat transfer and moisture removal can be denoted in terms of change in humidity ratio and enthalpy of air as follows [9]:

\[
\frac{\dot{m}_a}{\dot{m}_a} \frac{\Delta h}{\Delta x} = \frac{K_m F_m}{H} (h_i - h_o)
\]

\[
\frac{\dot{m}_a}{\dot{m}_a} \frac{\Delta \omega}{\Delta x} = \frac{K_m F_m}{H} (\omega_i - \omega_o)
\]

Where \( K_m \) and \( F_m \) denote mass transfer coefficient and mass transfer area between air and desiccant. \( h_i \) and \( \omega_i \) represent enthalpy and specific humidity of air in equilibrium with the desiccant.

In the regenerator, the mass balance equation can be represented using Eq. (5), where \( \dot{m}_r \) represents the rate of desorption.

\[
\dot{m}_r = \dot{m}_o (\omega_{so} - \omega_{ai})
\]

Equation (6) shows the relations between the concentrations of desiccant (\( X_s \)) with the rate of desorption, mass flow rate of desiccant and the initial desiccant concentration [8].

\[
\frac{1}{X_{ai}} = \frac{1}{X_{si}} (1 - \frac{\dot{m}_r}{\dot{m}_o})
\]

Energy balance can be represented by Eq. (7), where \( I_L \) denotes the mean solar power collected by the collector.

\[
I_L = \dot{m}_i h_i + \dot{m}_s c_{ps} \Delta T_s + \dot{m}_w c_{pw} \Delta T_w
\]

The effectiveness of dehumidifier (\( \eta_{dh} \)) and effectiveness of regenerator (\( M_{ev} \)) has been computed as follows:
4. Results and Discussions

A Computer code in MATLAB 2019 R3 has been developed based on the model discussed in the previous section. The program takes ambient air temperature and humidity ratio as input and predicts output temperature and humidity ratio of air keeping mass flow rates of air, desiccant and water as well as concentration of desiccant as constant. The air humidity ratio at the outlet has been validated (shown in Fig. 2) against a data available in the literature [9]. The predicted results deviate only by 3.47% and hence show good agreement with data available in literature. Figures 3(a) and 3(b) represent the hourly variation of temperature and humidity inside the conditioned space with the proposed LDAC system respectively for the mean day of the months during May, June and July in Kolkata. These months correspond to the summer and the monsoon season for the place when both the surrounding relative humidity and temperature levels are high. It is observed that the variation in the temperature and relative humidity closely follow the daylong pattern of the variation in the ambient temperature and humidity, first increases, reaching a maxima around the noon and then again diminishes. However, it is found that with the proposed system, both the temperature and the humidity can be restricted within the target value (25°C with a relative humidity of 51.19% that is equivalent to around 10.3 g/kg of specific humidity) for major time of the day for the months under consideration. Fig. 3(c) and 3(d) depicts the hourly variation of dehumidifier efficiency and evaporation rate in regenerator, respectively, for a representative day in May, June and July keeping all mass flow rates and desiccant concentration as constant. The system could achieve dehumidifier efficiency of about 64%, significantly higher than 49% as presented in [7]. This increase in efficiency can be attributed to higher concentration of desiccant (45% CaCl2 solution) and higher mass flow rates of water and desiccant (0.28 kg/s and 0.1 kg/s). The evaporation rates achieved by the model for the set parameters is higher than that achieved by [8]. The cooling capacity has been found to be approximately 3 kW.

\[ \eta_{de} = \frac{\omega_{a0} - \omega_{a}}{\omega_{a0}} \quad \text{and} \quad M_{w} = m_{w} \left(1 - \frac{X_{w}}{X_{w0}}\right) \]  

(8)

Figure 2. Outlet air humidity ratio Vs inlet air temperature for predicted and published data
Figure 3. Hourly variation of (a) output air temperature, (b) output air humidity, (c) dehumidifier efficiency and (d) evaporation rate of regenerator, for the mean day of the month for May, June and July in Kolkata.

Figure 4 shows the variation of outlet air temperature and relative humidity versus air mass flow rate keeping desiccant and water mass flow rates as constant. The desiccant concentration is also kept constant. It is observed that with increase in the mass flow rate of air, the relative humidity of output air increases and output temperature of air decreases. While decrease in temperature is desirable, increase in humidity levels is not. Hence an optimum value of mass flow rate needs to be chosen in order to balance the humidity and temperature effects. It can be observed that for an air mass flow rate of 0.06 kg/s, optimum conditions with respect to the target temperature and humidity levels can be achieved.

**Figure 4.** Variation of output air humidity and output air temperature with mass flow rate of air

5. Conclusion

The study reveals the following:

1. With the proposed system, the target temperature and humidity levels (25°C, 50-55%) can be maintained for major part of the day even for the months of May, June and July when the climatic conditions are much more severe.
2. The proposed system could achieve dehumidifier efficiency of about 64%, significantly higher than 49% with that available in the literature.
3. Optimum value of air mass flow rate has been obtained to be 0.06 kg/s.
4. The study buttresses the viability and need of solar assisted LDAC system with fin-coil dehumidifier to maintain the target comfort conditions for the plains of country like India.

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