Energy Efficient Liquid Desiccant Cooling Systems

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Abstract: The refrigeration and air conditioning technology have been passing through a changing phase. The problems of ozone depletion and global warming have created a void in refrigeration and air conditioning industry which have led the refrigeration community to research for alternative refrigerants and alternative cooling technologies. Desiccant cooling systems combine dehumidification, heat recovery, evaporation and heating to create a cooling process which can offer energy savings compared to conventional air conditioning systems. It is one kind of innovative technologies which employs renewable energy to produce the desired air for comfortable working/living spaces. These systems have little dependency on fossil-fuel energy and are environment friendly. Desiccant cooling uses liquid or solid desiccant in order to dehumidify the processed air. By coupling with mechanical cooling, desiccant systems can avoid the need for reheat which is essential in conventional systems. Desiccant cooling has long been adopted for both industrial and agricultural purposes, and is now taking a more and more prominent role in the air-conditioning field. It is economical and has effective humidity control at low and moderate temperatures since it makes full use of surface vapor pressure difference to realize moisture transfer between the process air and liquid desiccant. In the present paper, the heat and mass transfer in the various components of the desiccant system is analyzed and COP of the system is obtained by numerical simulation through theoretical model. The influence of air temperature, relative humidity, air flow rate, desiccant flow rate, desiccant concentration on the cooling capacity and COP of the system is studied. It is observed that when the cooling and heating is replaced by renewable energy, COP is greatly enhanced.

Keywords: Desiccant, Dehumidifier, Regenerator, Heat exchanger

Introduction:
The rising cost of energy and the global warming in recent years have highlighted the need to develop advanced energy systems to increase efficiency and to reduce emissions. Energy is universally acknowledged to be the mainstay of an industrial society. As the world supply of inexpensive, but non-renewable, fossil energy sources decreases, the need for energy conservation as well as for developing renewable technologies becomes ever more critical. Liquid desiccant cooling systems have been proposed as alternatives to the conventional vapor compression cooling systems to control humidity, essentially in hot and humid areas. Research has shown that a liquid desiccant cooling system can reduce the overall energy consumption, as well as shift the energy use away from electricity and toward renewable and cheaper fuels (Oberg and Goswami1).

Many manufacturing processes of industrial gases are major consumers of energy as electricity or fossil fuel. A big part of this energy ends up as heat in the process gas at temperatures around 150°C. Today, this thermal energy is generally released to the atmosphere through cooling towers because the manufacturing processes don’t need energy at this temperature level. However, this available energy in waste heat can be recovered for generation of steam, process heating and power generation. In the present work, an important need of air-conditioning and dehumidification is studied.

Literature review:
There is an enormous amount of interest in researchers in extracting the benefits of desiccant cooling systems in recent years. Kyude Hwang and Chan Ho Song1 have developed a theoretical model to investigate the efficacy of hybrid refrigeration system using desiccant rotor. They have found that the COP of hybrid cycle is 2 times the COP of conventional cycle. R.B.Lokapure and Joshi2 developed an experimental setup to recover waste heat from air conditioner and found that significant increase in COP is possible by waste heat recovery. Collier, Arnold et al.3, in their work presented a review of the thermodynamics of three desiccant cooling cycles: the ventilation cycle, the recirculation cycle, and the Dunkle cycle and compared their COP. They predicted that with desiccant system, COP can be enhanced significantly. Gerrit Höfker2 et al. did the parametric study of desiccant dehumidifier and showed that it is possible to reduce the regeneration air flow without a significant reduction in the dehumidification efficiency, enabling desiccant cooling systems to run with high COPs.

System Description:
The liquid desiccant system is composed mainly of Dehumidifier, Regenerator, and heat exchangers. Figure 1 presents a schematic drawing of a liquid desiccant system. Dehumidifier is used to remove the moisture of the inlet air by bringing into contact with sprinkled liquid desiccant. It consists of a circulation
pump, a strong desiccant tank, a weak desiccant tank, and a main blower. The strong desiccant is sprayed in a counter-flow direction and is brought in contact with blower air stream through packing material. Strong desiccant absorbs humidity from air and converts to weak desiccant. Packing materials is the place where mass transfer occurs between falling film of the liquid desiccant and inlet air. Hence, the selection of packing materials will undoubtedly exert influence upon the performance of the dehumidification unit. Regenerator is used to regenerate the weak (diluted) solution flowing from dehumidification unit to an acceptable concentration. The regenerator is made up of a counter-flow packed bed regeneration tower similar to dehumidifier, a circulation pump, a strong desiccant tank, a weak desiccant tank, and a main blower. The weak desiccant is sprayed in a counter-flow direction and is brought in contact with hot air stream through packing material. Heat exchangers are used to make a heat transfer between the weak and strong desiccant and between the external heat source and the weak desiccant to be regenerated, also between strong desiccant and cooling water.

Figure 1. Desiccant cooling system

The surface vapor pressure difference between liquid-desiccant film and air is acting as the driving force for mass transfer of water vapor in the air to liquid water in the liquid desiccant (condensation process). The liquid desiccant has a vapor pressure lower than that of water at the same temperature and the air passing over the solution approaches this reduced vapor pressure and is dehumidified. Vapor pressure of a liquid desiccant is directly proportional to its temperature and inversely proportional to its concentration. As the desiccant content in the mixture increases its vapor pressure decreases.

To regenerate the liquid desiccant from the diluted liquid we must heat the liquid. Heating this solution will increase the liquid surface water pressure; hence the water is then evaporated to the external air where the partial pressure of the water vapor is less. The heat source in the studied case is assumed to be hot exhaust waste heat to recover. Among many liquid desiccants available aqueous solution of Lithium chloride, Calcium chloride, Ethylene glycol are the major ones. Lithium chloride is found to be most effective since it has the lowest vapor pressure among these. Packed bed towers are more effective than the other methods of heat and mass transfer in the dehumidifier, since they provide large rate of heat and mass transfer per unit volume and hence a compact design is possible.

A theoretical model is constituted to find the COP (Coefficient of Performance) of the novel heat recovery/desiccant cooling system according to the varying influencing factors such as air temperature, humidity, and flow speed, and desiccant concentration, temperature, flow rate etc.

Figure 2. Cooling and Dehumication on Psychrometric chart

Working: Desiccant from the strong solution storage transfers sensible heat to the upcoming weak desiccant as shown in Figure 1. This results in lowered temperature of the desiccant flow, which is further cooled by the circulating cooling water from the cooling tower, which in turn creates a cooling water flow, with the temperature approaching the wet bulb point of the atmosphere. In the dehumidifier unit, firstly, the fresh air from the environment has heat/mass exchanges with the returning air from the air conditioning room through the fiber exchanger unit, and then flows into the dehumidifier channels, where it loses the superabundant moisture to the strong solution. Then the well-treated cold and dry air is supplied to the serving room.

In the regenerator unit, the forced in fresh air exchanges heat with the exhaust air, and flows to the bottom of the fiber pack, where it starts to absorb moisture from weak desiccant until it moves upwards to the top of the pack and exits. The psychrometric chart for the air undergoing dehumidification is shown in figure 2. Exhaust air temperature and humidity is changed from point 7 to 8 through the air-to-air heat/mass exchanger and then exits.

Heat and Mass transfer and COP of the system:

In the process from point 5 to 7 (Fig 1), only heat exchange occurs, but no moisture transfer, hence, the desiccant temperature in this process can be written as:

\[ T_6 = T_5 - \eta C_s (T_5 - T_1) / C_s \]

\[ C_s = \min (C_s - C_d) = \min (C_s m_5 * C_d m_d) \]
From point 3 to point 4, the strong desiccant solution is cooled by the cooling water in the cooling coil, where its temperature is reduced but its concentration remains unchanged.

From point 7 to point 1, the strong solution has heat and mass exchange with the flowing air stream, and its temperature and concentration is changed from $T_f$ and strong $\theta$ to $T_i$ and weak $\theta$ respectively. The absorbed moisture from the fresh air is given by,

$$m_{\text{absorb}} = \frac{p_f - p_d}{RT \left( \frac{1}{k_f} + \frac{H}{k_d} \right)} A_{\text{des}}$$

where $p_f$ and $p_d$ are the vapour pressure of fresh air and desiccant resp. and $H$ is the Henry's law constant for LiCl desiccant which is calculated using

$$H = -0.00256t + 0.86125t + 67$$

The dilute solution concentration is calculated as follows:

$$\theta_{\text{weak}} = \left( \rho_{\text{strong}} V_{\text{strong}} \theta_{\text{strong}} \right) l \left( \rho_{\text{strong}} V_{\text{strong}} + m_{\text{absorb}} \right)$$

Similarly in the regenerator, hot weak desiccant is regenerated. The desorbed moisture and condensed solution concentration are expressed by the following equation.

$$m_{\text{desorb}} = \frac{p_{\text{weak}} - p_f}{RT \left( \frac{1}{k_f} + \frac{H}{k_d} \right)} A_{\text{des}}$$

$$\theta_{\text{strong}} = \left( \rho_{\text{strong}} V_{\text{strong}} \theta_{\text{strong}} \right) l \left( \rho_{\text{strong}} V_{\text{strong}} + m_{\text{desorb}} \right)$$

For the whole desiccant cycle (from the dehumidifier to regenerator) heat and mass balance, the moisture absorbed by strong solution equals the moisture desorbed out from the weak solution, and the condensed desiccant concentration equals the supplying strong desiccant.

$$m_{\text{desorb}} = m_{\text{absorb}}$$

$$\theta_{\text{strong}} = \theta_{\text{condensed}}$$

As the definition of COP, it is the input energy divided by the energy produced. The input energy in this system includes three parts: cold energy cooling hot/strong desiccant offered from the cooling tower, hot energy heating the cold/weak desiccant provided by the solar collector, and electrical energy driving the pumps and running the fans.

Consumption of the cooling energy is calculated by the equation as follows:

$$Q_{\text{cold}} = c_w m_w (t_{\text{in}} - t_{\text{out}}) = c_3 m_3 (T_5 - T_6)$$

Consumption of the heating energy is calculated by the following equation:

$$Q_{\text{hot}} = c_w m_w (t_{\text{in}} - t_{\text{out}}) = c_3 m_3 (T_4 - T_3)$$

Electrical energy consumed in this system is mainly for driving the pumps and fans, which require a small amount of energy with the maximal value of about 500W.

$$Q_{\text{electrical}} = 500W$$

The output energy (cooling capacity) is energy reduction from the fresh air to supply air as given by:

$$Q_{\text{output}} = m_i h_i - m_h$$

In this proposed system, natural energy such as solar energy, and cooling tower energy, is utilised for the heating/cooling of the weak/strong desiccant. Hence, the COP is considered in two conditions: when natural energy is unavailable, and natural energy is sufficient.

When no renewable energy is utilized, the COP of the whole system is:

$$COP = \frac{Q_{\text{output}}}{Q_{\text{hot}} + Q_{\text{cold}} + Q_{\text{electrical}}}$$

When renewable energy is utilized for heating and cooling, the COP of the whole system is:

$$COP = \frac{Q_{\text{output}}}{Q_{\text{electric}}}$$

Result and Discussion:

The main influencing factors for the air-to-air exchanger are the air humidity and flow speed; for the dehumidifier are the fresh air temperature/humidity, air flow rate, desiccant concentration and flow rate; for the regenerator are the desiccant and air temperature. For saving cooling and heating energy, the working solution temperature in the strong/weak store sink is assumed to be same as in the environment. The COP of the whole system is influenced by air temperature, humidity, flow rate and desiccant concentration and flow rate. In all of the simulations, the air flow speeds into the regenerator is kept unchanged.

Air Temperature Influence on the COP

By varying the air temperature from 25 to 35°C at the relative humidity of 56%, the corresponding cooling water temperature equaling the dew point temperature, and the desiccant temperature in the storage sink equaling the environment temperature respectively. The air flow, desiccant solution and heating/cooling water flow rate, and heating water temperature, desiccant working concentration were kept unchanged. The influences of air temperature on the COP of the whole system are presented in figure 3.
From Figure 3, it can be seen that the air temperature greatly influences the COP. When the air temperature is 25°C, the COP without renewable energy is as low as 0.1, but it rises quickly to 1.3 when the air temperature reaches 35°C. When the renewable heating and cooling energy are both available, the COP of the system is 13.0. Hence, this heat/mass recovery and desiccant cooling system is applicable in the hot and humid climate with a good solar radiation.

Relative Humidity Influence on the COP
Varying the air relative humidity from 35 to 70% at the temperature of 30°C, the corresponding cooling water temperature and the dew point temperature is changed. The desiccant temperature in the storage sink is equal to the environment temperature of 30°C. The air flow rate, desiccant solution and heating/cooling water flow rate, and heating water temperature, desiccant working concentration were kept unchanged. The influences of air relative humidity on the whole system COP are presented in Figure 4.

Figure 4. Variation of COP and cooling capacity with Relative humidity of air

COP of this heat recovery/desiccant cooling system and cooling capacity, both increase with the fresh air relative humidity increasing. It’s obvious that when no renewable energy is utilized, the COP of this system is very low in the range of 0.3 ~ 0.8. However, when the cooling and heating energy both are substituted by renewable energy, the COP is as high as 6.9 ~ 11.4. Dehumidification capacity increases and regeneration capacity decreases with the fresh air moisture content. Because the cooling capacity rise could cover the regeneration capacity decline, the COP of the system rises. If the fresh air relative humidity is as high as 70%, the system can supply a cooling capacity of 5.7kW. Hence, this system gives higher COP in a humid region than in a dry place.

Air Flow Rate (into the Heat/mass Exchanger and Dehumidifier) Influence on the COP
By varying the air flow rate into the heat/mass exchanger from 300 to 900m³/h, the corresponding cooling water temperature is the dew point temperature of 18°C, and the desiccant temperature is the environment temperature 30°C. The air temperature, relative humidity, desiccant and heating/cooling water flow rate, and heating water temperature, the desiccant working concentration unchanged, The influences of air flow rate on the whole system COP are shown in Figure 5.

Figure 5. Variation of COP and cooling capacity with Fresh air flow rate
As shown in Figure 5, higher air flow rate results in a higher cooling capacity, but when the cooling capacity increases, the consumed regeneration energy is enhanced. Hence the COP changing trend is minimal, when there is no renewable energy available. This is because the greater air flow rate results in a higher dehumidification capacity, which induces more heating energy required to condense the dilute solution in the regenerator unit. The most part of the increased dehumidification capacity is counteracted by the rising heating energy, so the increase of COP is almost ignorable. When renewable heating and cooling energy are both employed in this system, the COP is enhanced from 5.8 to 12.3, with the air flow rate increasing. Therefore, for the regions with available renewable heating and cooling energy, a large amount of air ventilation gives good air quality as well as high COP.

Desiccant Working Concentration Influence on the COP:
By changing the working solution concentration from 25% to 40%, and keeping the other preset conditions, such as air temperature, relative humidity, flow rate, and desiccant solution, the heating/cooling water flow rate, and heating water temperature remained unchanged, the corresponding cooling water temperature as the dew point
temperature 18°C, and the desiccant temperature as the environment temperature 30°C. The influence of the desiccant working concentration on the whole system COP are shown in Figure 6.

**Figure 6. Variation of COP and cooling capacity with Desiccant concentration**

From Figure 6, it can be seen that the cooling capacity increases from 3.1 to 4.5, with the solution mass concentration increasing from 25 to 40%. Also the COP of the system decreases with the working solution mass concentration increasing when no renewable energy is available. When the working solution concentration increased from 25% to 40%, the regeneration capacity is reduced. With the working solution mass concentration increasing, the heat recovery effectiveness is decreased, inducing more consumption of cooling energy, and simultaneously, more regeneration energy and a high regeneration temperature is needed to condense out the absorbed moisture. Hence, the COP of the system decreases with the working LiCl solution concentration increasing when no natural energy is available. However, when the cooling and heating energy are both substituted by renewable energy, such as solar energy/waste heat, natural cooling water from cooling tower/ground water, the COP of the system increases with the increase of the working solution concentration.

**Desiccant Flow Rate Influence on the COP**

By changing the working solution flow rate from 0.1 to 0.5L/s, and keeping the other pre-set conditions unchanged, the effects of the desiccant working concentration on the whole system COP are shown in Figure 7.

In figure 7, the cooling capacity of the system increases by about 35% when the desiccant flow rate is increased from 0.1 to 0.5L/s. The COP of the system decreases with the working solution flow rate increasing when no renewable energy is available. This is because, with the desiccant flow rate increasing, the dehumidification capacity and regeneration capacity both decrease. But when the renewable cooling and heating energy is available, the COP gradually increases to the value of 8.86 and then keeps to a very low rising rate at about 0.2% when the flow rate is over 0.35L/s.

**Figure 7. Variation of COP and cooling capacity with Desiccant flow rate**

When only electrical energy is consumed, a higher desiccant flow rate results in more moisture being absorbed and supply air being more dehumidified. For this case, the cooling energy is enhanced, but the energy consumption is not accounted, so the COP is high. Hence, when natural cooling/heating energy exists, the higher desiccant solution flow rate of 0.35L/s is preferred to service good air supply conditions, with a high COP and cooling capacity. When renewable energy is absent, it is clear that the lowest desiccant flow rate could offer a high dehumidification capacity, and regeneration capacity, as well as COP, but it has the lowest cooling capacity.

**Conclusion:**

- The COP of the system increases with the increase in the fresh air temperature, especially in the case of utilizing renewable energy for cooling/ heating the strong/dilute solution, as COP is largely affected by air temperature. Therefore, this system is very suitable for use in hot/humid places. The highest COP 13.0 were achieved when the fresh air temperature rose to 36°C, with the relative humidity 50% and renewable energy available.
- Air moisture content influences the cooling capacity and COP. Eventhough its impact is less than the air temperature, but it is still an important factor impacting the system. Hence, it can be concluded that high moisture content results in high dehumidification capacity but a lower regeneration capacity, the COP of the system increases with the moisture increase.
- When no renewable energy exists, the COP changes are marginal with the air flow rate increasing. This is because a higher air flow rate results in more moisture absorbed into the solution, which accordingly needs more heating energy to evaporate it. But when renewable energy is available, such as solar energy, the COP increases to about 12 and the cooling capacity rises to about 6 kW with the air flow rate reaching 900m³/h.
- Increasing the solution concentrations results in little change of COP, when no renewable energy is utilized. When renewable energy is employed, the
cooling capacity and COP increase with the concentration rises, due to the unconsidered heating energy. When renewable energy is utilized, the highest solution concentration results in the highest cooling capacity and COP. But if there is no natural energy is available, the lowest solution concentration 25% is preferred in order to gain the highest COP about 0.6 and cooling capacity of about 3 kW.

- The cooling capacity and COP change slowly with the solution flow rate increasing. When there is no renewable energy, the lowest desiccant flow rate 0.1L/s performed the best with COP of about 0.7 and the cooling capacity of about 3.2 kW. But when the renewable energy is available, the flow rate of 0.35L/s is optimal to produce the higher COP 8.0 and the cooling capacity 3.9 kW.

Nomenclature:
- A Heat and mass transfer area, m^2
- C Specific heat capacity, J/kg °K
- D Moisture content of air stream, kg
- h Enthalpy, J/kg °K
- k Thermal conductivity, W/m °K
- q Sensible heat transfer, J
- Q Input or output energy, J
- T Absolute temp °K
- U Air flow speed, m/s
- V Volume flow speed, m/s
- α Thermal diffusivity of air, m^2/s
- µ Dynamic viscosity, Ns/m^2
- θ Mass concentration of desiccant solution
- \( \eta_{1,2,3} \) Heat recovery effectiveness of the weak desiccant-to-hot water, weak-to-strong desiccant and strong desiccant-to-cold water plate heat exchanger respectively.

Subscript:
- f Fresh air
- s Supply air weak Diluted solution from Dehumidifier. Strong Regenerated solution.

References: