An Evaporative and Desiccant Cooling System for Air Conditioning in Humid Climates

Evaporative cooling operates using water and air as working fluids. It consists in water evaporation, through the passage of an air flow, thus decreasing the air temperature. This system has a great potential to provide thermal comfort in places where air humidity is low, being, however, less efficient where air humidity is high. A way to solve this problem is to use dehumidifiers to pre-conditioning the process air. This paper presents a system that can be used in humid climates coupling desiccant dehumidification equipment to evaporative coolers. The paper shows, initially, the main characteristics of the evaporative cooling and of the adsorption dehumidification systems. Later on the coupled systems, in which occurs a dehumidification by adsorption in a counter flow rotary heat exchanger following the evaporate cooling of the air in evaporative coolers, are analyzed. The thermodynamic equations of state are also presented. Following, this paper analyzes some operation parameters such as: reactivation temperature, R/P relationship (reactivation air flow/process air flow) and the thermodynamic conditions of the entering air flow. The paper shows the conditions for the best operation point, with regard to thermal comfort conditions and to the energy used in the process. In addition this paper presents an application of the system in different climate characteristics of several tropical and equatorial cities.

Keywords: Evaporative cooling, desiccant system, thermal comfort

Introduction

In the last 10 years, evaporative and desiccant cooling technology for air conditioning systems has increased as an alternative to the conventional vapor compression systems. A typical system combines a dehumidification system that uses a rotary desiccant wheel, with direct or indirect evaporative systems, allowing a filtered and cooled air supplying temperature, humidity and speed conditions that propitiate environmental thermal comfort, even in equatorial and tropical climates. These systems cause a lot of electrical power saving, mainly in places where thermal energy sources are easily found, where the price of electrical energy is high, where the latent heat percentage is high or where the needed air dew point is low. So, evaporative cooling systems that use adsorption pre-dehumidification present a great perspective in thermal comfort. It can be used in co-generation systems, where the needed heat to regeneration can be gotten from gas turbines exhaust gases or from internal combustion engines or, still, from steam in plants that use steam turbines.

This paper aims to analyze the influence of some operation parameters, such as the reactivation temperature of the adsorbent, and the relationship between the reactivation air flow and the process air flow (R/P) on the performance of the system. In addition, this paper presents an application of a proposed system in different climate characteristics of several tropical and equatorial cities.


Nomenclature

- $c_p$ = specific heat of moist air at constant pressure, 1.013kJ/kg°C
- $DBT$ = dry bulb temperature, °C
- $H$ = altitude above sea level, m
- $L$ = latent heat of vaporization, kJ/kg
- $\gamma$ = auxiliary coefficient defined by Eq. (6), kPa/°C
- $\epsilon_d$ = DEC effectiveness, dimensionless
- $\epsilon_{ecw}$ = ECW effectiveness, dimensionless
- $\eta_p$ = process mass flow, kg/s
- $P$ = atmospheric pressure, kPa
- $P_v$ = vapor pressure, kPa
- $P_{sv}$ = saturation vapor pressure at DBT, kPa
- $P_{swb}$ = saturation vapor pressure at WBT, kPa
- $Q$ = heater power, kW
- $R$ = process air flow, kg/s
- $RH$ = relative humidity, %
- $R/P$ = reactivation air flow/process air flow, dimensionless
- $T$ = temperature, °C
- $x$ = percent of outdoor air to process, dimensionless
- $w$ = specific humidity, gw / kg dry air
- $WBT$ = wet bulb temperature, °C

Greek Symbols

- $\rho$ = density, kg/m³
- $\nu$ = viscosity, m²/s

Subscripts

- $a$ = ambient values
- $d$ = desiccant
- $e$ = evaporative
- $f$ = flow
- $m$ = mass flow
- $sw$ = saturation water
- $w$ = corresponds to WBT
- $x$ = process mass flow
- $y$ = product mass flow
- $y^*$ = wet bulb
- $z$ = process air flow


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Evaporative Cooling Systems

Evaporative cooling consists in the use of the water evaporation or other fluid in the presence of a draught, with a consequent cooling of the air. Although it is not common in Brazil, evaporative cooling systems have a great potential to provide thermal comfort in places where the wet bulb temperature is low. Evaporative cooling equipment can be of the direct evaporative cooling (DEC) type or indirect evaporative cooling (IEC) type. Direct evaporative cooling equipment cool the air by direct contact with a liquid surface or with a wet solid surface, or even with sprays (Camargo, 2000). So, in a DEC, water is vaporized in the airstreams and the heat and mass exchanged between air and water decrease the air dry bulb temperature (DBT) and increase its humidity, keeping constant the enthalpy, the minimum temperature that can be reached is the wet bulb temperature (WBT) of the inlet air.
The effectiveness of an evaporative cooler is the rate between the real decreasing of the dry bulb temperature and the maximum theoretical decrease that the dry bulb temperature could be if the cooler was 100% efficient and the outlet air was saturated. In this case, the outlet dry bulb temperature would be equal to the wet bulb temperature of the inlet air. To an ideal evaporative cooler the dry bulb temperature and the dew point might be equal to the wet bulb temperature.

Adsortion Dehumidification System and Energy Conservation Wheel

The adsorption dehumidification is a physical process that fixes molecules of an adsorbate (water, in this case) on the adsorbent surface, usually porous and granulated. Desiccants attract moisture from the air by creating an area of low vapor pressure at the surface of the desiccant. The partial pressure of the water in the air is high, so the water molecules move from the air to the desiccant and the air is dehumidified (Harriman III, 1990). Thus, the essential characteristic of desiccant is their low surface vapor pressure. If the desiccant is cool and dry, its surface vapor pressure is low and it can attract moisture from the air, which has a high vapor pressure when it is moist. Actually, the desorbents more used are SiO2 (Silica Gel), CaCl2 (Lithium Chloride), Al2O3 (Activated Alumina), LiBr (Lithium Bromide) and Zeolithe. These substances are usually deposited in a support structure of fiberglass or aluminum. The aspect seams to a fine honeycomb. This process is regenerative because the adsorbent material, after saturated by the humidity, sets the water free, when submitted to a heat source (desorption). The thermal energy to the regeneration can be obtained by electric power, water vapor or hot air.

A typical configuration uses a rotary desiccant wheel that moves slowly and continuously between two crosswise air fluxes, the process and reactivation airstreams. The process air flow through the flutes formed by the corrugations, and the desiccant in the structure adsorbs the moisture from the air. As the desiccant picks up moisture it becomes saturated and its surface vapor pressure rises. Then as the wheel rotates into the reactivation air stream, the desiccant is heated by the hot reactivation air, and the surface vapor pressure rises, allowing the desiccant to release its moisture into the reactivation air. Following reactivation, the hot desiccant rotates back into the process air, where a small portion of the process air cools the desiccant so it can adsorb more moisture from the balance of the process air stream.

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Figure 1. Rotary dehumidifier wheel.

In typical applications, 75% of the air passage is used by the process air and 25% by the reactivation air. Desiccant rotary wheels do not reduce the air energetic load; they only change latent heat (humidity) by sensitive heat (temperature). Figure 1 shows a dehumidifier wheel type honeycomb.

The addiction of a desiccant dehumidifier to an evaporative cooling air conditioning system provides a humidity control separate of the temperature control. It is especially good in applications where the latent thermal load is high comparing to the sensitive load, or when they get the maximum in different time. Usual applications are supermarkets, shopping centers, theaters, hospitals, hotels, motels and officers buildings.

The energy conservation wheel (ECW) is a rotary counter flow air-to-air exchanger used to transfer both sensible and latent heat between supply and exhaust air streams.

Physical Diagram of the System

Figure 2 shows the schematic diagram of the system utilized in this research. In this configuration the outdoor air is first mixed to the return air and flows through the deshumidifier changing latent heat into sensible heat. After, it is cooled in an ECW and in a DEC, providing to the room air conditioned in thermal conditions to human thermal comfort (process 0-1-2-3-4).

The reactivation air stream is also composed by a mixed of outdoor and return air stream that flows first through a DEC and, after, through an ECW. Immediately it is heated by a heat source that can be electrical, vapor or direct burn of a fuel and flow through the dehumidifier, removing the moisture of the adsorbent (reactivation process 5-6-7-8-9).

Figure 3 shows the psychrometric processes for the supply air according to the points that appears in Fig. 2. Point 0 corresponds to the external design conditions for each city, point R corresponds to return air, point 1 corresponds to mixed outdoor and return air condition, point 2 is the dehumidifier exit, point 3 is the ECW exit and point 4 is the DEC exit and it is the final condition of the process air.
Methodology

The analyzed operational parameters that have influence in the system performance are: temperature and moisture of inlet air (that is an outdoor and return mixed air), the reactivation temperature of the adsorbent and the relationship between the reactivation air flow and the process air flow (R/P).

To outdoor conditions it was used values according to ASHRAE 1% summer design conditions (ASHRAE, 1993) and to return air it was used conditions according to ARI (American Institute of Refrigeration).

To determine the temperatures and moisture in the points presented in Fig. 2, the methodology described bellow was used:

a) The DEC and ECW effectiveness was estimated as 90% and 80%, respectively (Munters, 1999).

b) The used process air flow is constant and equal to 1.67 m³/s. The return air and exhaust air from room flow rates are 50% to each side.

d) The adsorbent utilized is silica gel that has a low reactivation temperature (between 70ºC and 120 ºC).

e) The air condition at point 1 is determined by mixing return air with outdoor air, according to equations (1) and (2). Considering \( c_p \) independent of air specific humidity,

\[
T_1 = x T_0 + (1-x) T_{R1}
\]  

where \( T_1 \) is the dry bulb temperature and \( x \) is the percent of outdoor air to process, according to:

\[
x = \frac{\text{outdoor air flow}}{\text{total process air flow}}
\]  

\( T_{R1} \) is the dry bulb temperature at point R1 and the wet bulb temperature at point 1 (\( T_{1w} \)) is found by the same way. The conditions at point 5 are also found using equations (1) and (2) by replacing the process air flow by the reactivation air flow.

f) If the dry and wet bulb temperatures are known all thermodynamic properties can be found using the following equations.

The atmospheric pressure at \( H \) (m) above the sea level and the saturation vapor pressure at DBT is given by Moreira (1999) as:

\[
2559.55 - 80.55 \times 10^{-3} H = e_{s}(T) = \gamma_p \times \frac{T}{P}
\]

where \( F_1 = -741.9242; F_2 = -29.7210; F_3 = -11.55286; F_4 = -0.8685635; F_5 = 0.1094098; F_6 = 0.439993; F_7 = 0.2520658 \) and \( F_8 = 0.05218684 \).

The vapor pressure is given by Jensen et al (1990) as:

\[
P = 101.325(1 - 2.25577 \times 10^{-5} H)^{2.596}
\]

The reactivation temperature (\( T_8 \)) is known but if the heater power (\( Q_R \)) is known, the reactivation temperature can be determined as:

\[
T_8 = T_7 + \frac{Q_R}{\eta c_p} (R/P)
\]

\( \eta \) is the heater efficiency. Normally, the reactivation temperature (\( T_8 \)) is known but if the heater power (\( Q_R \)) is known, the reactivation temperature can be determined as:

\[
T_8 = T_7 + \frac{Q_R}{m_P c_p} (R/P)
\]

\( m_P \) is the mass flow rate of the process air and \( c_p \) is the specific heat at constant pressure.

Based on Eqs. (1) to (20) the authors developed a software, named SISREAD (in Portuguese: SISTEMA DE RESFRIAMENTO EVAPORATIVO-ADSORTIVO) that allows to determine the supply air conditions. Figure 4 shows the SISREAD flow chart.

Results

This paper analyzes some operational parameters such as: reactivation temperature, R/P relationship and the thermodynamic conditions of the entering air flow.
Figure 5 shows the influence of the reactivation temperature in the process supply air. To obtain it the inlet data was the following: to point 1, Fig 2, TDB = 28.85 °C; WBT = 21.83 °C; e w = 0.0135 kgw/kgair, that is the mixer conditions of 50% outdoor air and 50% return air to São Paulo (Brazil). To point 7, DBT = 48.2 °C; WBT = 28.35 °C; e w = 0.0162 kgw/kgair, that is the outlet conditions of the ECW, calculated from Eqs. (16) and (17). The performance of the dehumidifier is obtained from two softwares available by manufacturers of desiccant wheels: Novelaire Technologies - Desiccant Wheel Selection Program – Version 1.0.5 and Munters Cargocaire DH Selection Program – Version 9.5a.

Table 1 presents the values of the outdoor air (point 1, Fig 2) and supply air (point 4, Fig. 2) for several cities, characterized by humid climates.

Fig. 5(a) shows the influence of the reactivation temperature on the temperature of the supply air leaving the dehumidifier (point 2, Fig. 2) and Fig. 5(b) shows the influence of the reactivation temperature on absolute humidity.

Figure 6(a) shows the influence of mass flows of the reactivation and process air on the temperature and Fig. 6(b) shows the influence of mass flows of the reactivation and process air on the absolute humidity of the supply air leaving the dehumidifier. In this simulation the relationship R/P changes and the reactivation temperature is keeping constant and equal to 115°C.

Figure 5. Influence of the reactivation temperature.

Figure 6. Influence of mass flows of the reactivation and process air.
evaporative coolers. In this system occurs a dehumidification by adsorption in a counter flow rotary heat exchanger following the evaporative cooling of the air using direct and indirect evaporative coolers.

This paper analyzes some operation parameters such as: reactivation temperature, R/P relationship (reactivation air flow/ process air flow) and the thermodynamic conditions of the entering air flow. The paper shows still the conditions for the best operation point with regard to the thermal comfort conditions and to the energy used in the process. In addition this paper presents an application of the system in different climate characteristics of several tropical and equatorial cities.

An analysis of the results shows that the lesser R/P relationship and lesser reactivation temperature take to the best operation point. The analyzes of the supply air condition shows that the system is able to provide human thermal comfort in humid climates, and it can be an alternative for the conventional air conditioning systems.

References
Camargo, J. R., 2000, “Análise de métodos para avaliar a viabilidade técnica de sistemas de resfriamento evaporativo aplicados ao condicionamento de ar para conforto”, Departamento de Engenharia Mecânica, Universidade de Taubaté, Dissertação de Mestrado, Taubaté, SP, 106p (in portuguese).

Discussion
In this paper it is analyzed the influence of the outdoor air condition on the air conditioning system performance for several cities in low latitudes as Belém, Monrovia, São Luís and Manaus, that are typical equatorial climates (hot and humid) and medium latitudes cities as Hanoi, Rio de Janeiro, São Paulo and Tainan, representing tropical climate. The city that presents the drier climate is Brasilia and the one that presents the wetter is Tainan. Table 1 shows that the minimum supply DBT is obtained for Brasilia (18.2°C) and the maximum one for Manaus (22.7°C). In despite of the influence of the adsorbent reactivation temperature on the heat power used for reactivation. To the studied conditions, a DBT2 temperature, what is desired to the supply air temperature and to the heat power used for reactivation. To the studied conditions, a variation of R/P from 0.385 to 0.670 takes to a variation in the power consumption from 51.7 kW to 90.1 kW, i.e. about 80.5 kJ/m³ of air.

Conclusions
This paper presents an air conditioning system that couples a desiccant dehumidification equipment to indirect and direct

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