CHAPTER 107

Air conditioning system by solid desiccant using solar or residual energy as a source of regeneration heat

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ABSTRACT

Energy efficiency in buildings and residences is today a primary objective for energy policy at national and international level. This article presents a review of desiccant wheel air conditioning models using solar energy or waste energy as a source of regeneration heat. The physical-mathematical modeling of the rotary desiccant dehumidifier is also presented. The advantages of using the rotary desiccant air conditioning system are discussed as it combines desiccant dehumidification and evaporative cooling technologies. What's more, it's CFC-free, uses little heat energy that can be diversified (solar energy and/or waste heat), and controls humidity and temperature separately. Recent research works suggest that new desiccant materials and their configurations have significant potential to improve the performance and reliability of the process, reducing the cost and size of the dehumidification and air conditioning system with rotary dehumidifiers, thus increasing its competitiveness in the market.

Keywords: Desiccant wheel, Refrigeration, Regeneration heat, Solar energy.

1 INTRODUCTION

A conventional air conditioner consumes a large amount of electrical energy, especially in hot and humid weather conditions, due to the high latent load that is defined by external conditions (TIWARI, 2015). In addition, it uses environmentally harmful refrigerants and consumes primary energy inefficiently (JANI; DEEP; SOHAM, 2018).

The low exergetic efficiency of conventional air conditioning systems, negative environmental impacts and depletion of fossil fuel reserves reinforce the need for alternative techniques that effectively employ renewable sources of low-quality thermal energy (RAFIQUE et al ., 2016).

The need for refrigeration systems that are more energy efficient and less likely to pollute the environment has led to the development of systems using a desiccant wheel (NETI; WOLFE, 2000). Desiccant air conditioning is an attractive technology because it is free of ozone-depleting CFCs.

The desiccant wheel has an adsorbent regeneration section, in which heat from various sources is used, such as: heat pump (TU, WANG and Ge, 2018; HUA; GE; WANG, 2019), solar energy (GAGLIANO et al. ., 2014; HASSAN, 2014) and waste heat from industrial activities (JANI; MISHRA; SAHOO, 2016). The use of renewable heat sources such as solar thermal energy reduces electricity consumption as well as achieving substantial fossil energy savings (JANI; MISHRA; SAHOO, 2016).

This work aims to review the air conditioning system by desiccant wheel using solar energy or waste energy as a source of regeneration heat and present the physical-mathematical modeling of the rotary desiccant dehumidifier.

2 AIR CONDITIONING SYSTEMS BY DESICCANT WHEEL

Desiccant wheel consists of numerous air passages that provide large surface areas for mass transfer between the air and the desiccant.

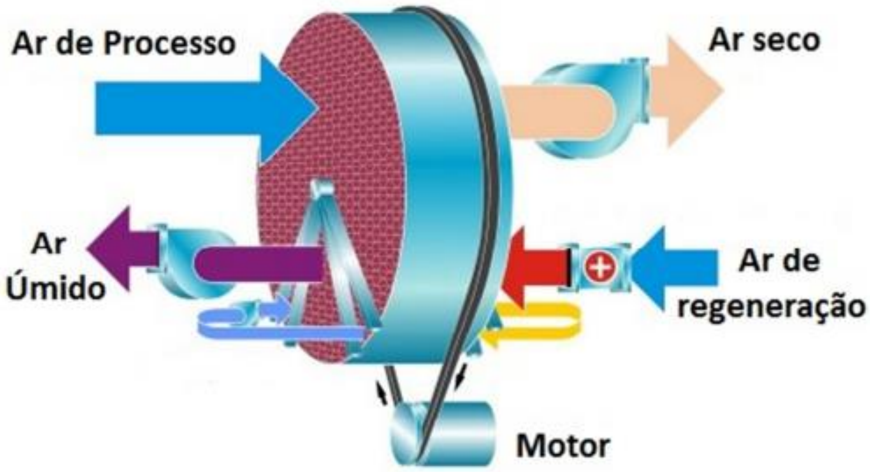
2.1 EVAPORATIVE COOLING SYSTEM

The desiccant wheel is divided into two equal sections (NIA; VAN PAASSEN; SAIDI, 2006):

a) adsorbent or process section is where the adhesion of molecules of a fluid (the adsorbed) to a solid surface (the adsorbent) occurs;
b) regeneration section is where the desorption of water vapor occurs - phenomenon of withdrawal of substance(s) adsorbed or absorbed by the desiccant.

A sketch of the desiccant wheel configuration is shown in Figure 1.

Figure 1 - Desiccant Wheel



Source: BELLEMO et al ., 2014.

The air stream to be dehumidified flows through the process section, while the regeneration air stream flows through the regeneration section in the opposite direction. A small electric motor makes the wheel turn, that is, all channels move continuously between the two sections (BELLEMO et al., 2014).

The benefits of using a desiccant dehumidifier are increased comfort due to independent humidity and temperature controls, improved indoor air quality, and the dehumidifiers are CFC free. The main factors for choosing solid desiccants are regenerative temperature, durability and adsorption capacity

(DEMIDOVA, 2013). Silica gel is one of the most common adsorbents because it has numerous advantages, such as larger pores, larger surface area and excellent dehumidification capacity (ZOUAOUI; ZILI-GHEDIRA; BEN NASRALLAH, 2015).

2.2 PHYSICO-MATHEMATICAL MODELING OF THE ROTARY DESICCANT DEHUMIDIFIER

In solid desiccant cooling system, the performance of the rotary desiccant dehumidifier is critical to the capacity, size and operating cost of the entire system.

Nia, Van Paassen and Saidi (2006) presented a work that aimed to develop and obtain solutions for a model involving heat and mass transfer in a rotating desiccator to study the performance of an air conditioning desiccant system. The equations presented were studied in order to correlate the temperature and humidity functions with the input conditions of components in air conditioning cycles.

The dehumidifier is a rotating cylindrical wheel of length L and radius R with small channels, whose walls are adhered by the silica gel adsorbent. It is divided into two equal sections: the adsorbent section and the regeneration section. The scheme of a rotary desiccator is illustrated in Figure 1 and the analysis is based on the following assumptions (NIA; VAN PAASSEN; SAIDI, 2006):

a) axial heat conduction and water vapor diffusion in air are negligible;
b) axial molecular diffusion within the desiccant is negligible;
c) there is no radial gradient of temperature or humidity in the matrix;
d) the hysteresis in the sorption isotherm for the desiccant coating is neglected and the heat of sorption is assumed constant;
e) the channels that make up the wheel are identical to constant heat and mass transfer surface areas;
f) thermal and moisture properties of the matrix (support material / desiccant and adsorbed water) are constant;
g) channels are considered adiabatic and impermeable;
h) the mass and heat transfer coefficients are constant;
i) the heat of adsorption per kilogram of water adsorbed is constant;
j) transport between two air streams is neglected.

2.2.1 Mass transfer equation for air flow

The mass transfer in the air stream is given by:

$$\frac{d\left(\rho_g \frac{\rho_v}{\rho_g} A_g L\right)}{dt} = U_g A_g \rho_g (\omega_i - \omega_o) + h_m A_c (\omega_s - \omega) \qquad (1)$$

on what:

ρ_g = air density, kg/m³
ρ_v = density of water vapor, kg/m³
A_g = cross-sectional area for airflow, m²
L = rotor depth, m²
U_g = air speed, m/s
ω_i = initial moisture content, kg/kg
ω_o = final moisture content kg/kg
h_m = mass transfer coefficient, kg/m ^{2} /s
A_c = interface area on a channel, m²
ω_s = saturation moisture rate, kg/kg
ω = moisture content, kg/kg

Considering D h the hydraulic diameter and d t the thickness of the desiccant coating (m),

$$\omega = \frac{\rho_v}{\rho_g} \qquad (2)$$

$$\frac{A_c}{A_g} = \frac{2L}{\frac{D_h}{2}} \qquad (3)$$

and knowing that the equation can be written as:

$$\frac{d\omega}{dt} = \frac{U_g}{L}(\omega_i - \omega_o) + \frac{h_m A_c}{\rho_g A_g L}(\omega_s - \omega) \qquad (4)$$

Taking C 1 and C 2 as

$$C_1 = \frac{U_g}{L} \quad \text{and } C_2 = \frac{h_m A_c}{\rho_g L A_g} \qquad (5)$$

equation (4) is:

$$\frac{d\omega}{dt} = C_1(\omega_i - \omega_o) + C_2(\omega_s - \omega) \tag{6}$$

Heat transfer equation for air flow

$$\frac{d(\rho_g A_g L C_g T_g)}{d_t} = \rho_g U_g A_g C_g (T_{gi} - T_{go}) + hA_c(T_s - T_g) \tag{7}$$

on what:

C_g = isobaric specific heat of the gas, J / kg K
T_g = gas temperature, °C
T_{gi} = initial gas temperature, °C
T_{go} = final gas temperature, °C
T_s = gas saturation temperature, °C
h = heat transfer coefficient, W/m²/K

Equation (7) can be written as:

$$\frac{dT_g}{dt} = C_1(T_{gi} - T_{go}) + C_3(T_s - T_g) \tag{8}$$

on what:

$$C_3 = \frac{hA_c}{\rho_g L A_g C_g} \tag{9}$$

Mass transfer equation for solid desiccant

$$\frac{d(\rho_d w A_d L)}{dt} = h_m A_c(\omega - \omega_s) \tag{10}$$

on what:

ρ_d = desiccant density, kg/m³
w = water content of the desiccant material, kg/kg
A_d = cross-sectional area for the desiccant layer in a channel, m²

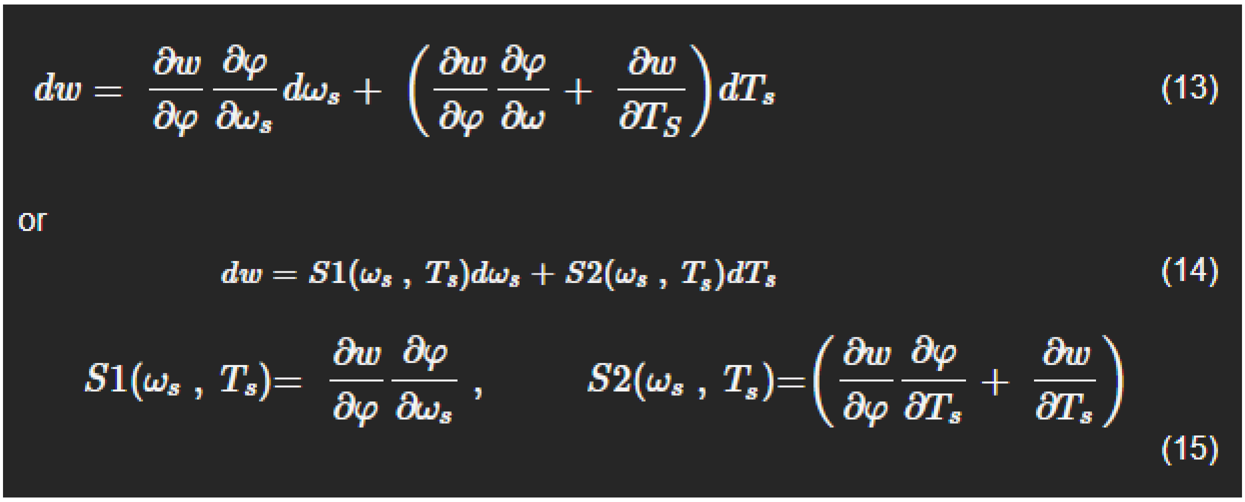
The water content of the desiccant material, w, is given by

$$\frac{\rho_{vd}}{\rho_d} = w \qquad (11)$$

$$\frac{dw}{dt} = \frac{h_m A_c}{\rho_d A_d L}(\omega - \omega_s) \qquad (12)$$

where ρvd is the density of the water vapor of the desiccant, in kg m -3

To have the equations according to the variables ω_s, T_s, ω, T, we start from:



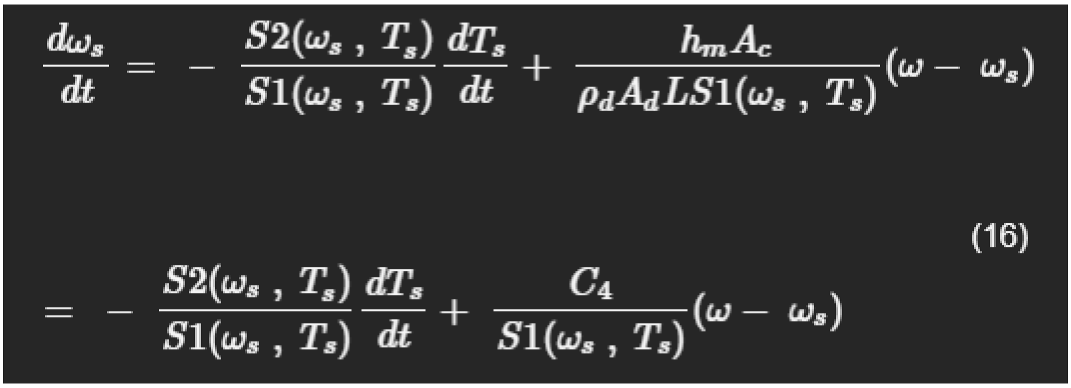
$$dw = \frac{\partial w}{\partial \varphi}\frac{\partial \varphi}{\partial \omega_s} d\omega_s + \left(\frac{\partial w}{\partial \varphi}\frac{\partial \varphi}{\partial \omega} + \frac{\partial w}{\partial T_S}\right) dT_s \qquad (13)$$

or

$$dw = S1(\omega_s\ ,\ T_s) d\omega_s + S2(\omega_s\ ,\ T_s) dT_s \qquad (14)$$

$$S1(\omega_s\ ,\ T_s) = \frac{\partial w}{\partial \varphi}\frac{\partial \varphi}{\partial \omega_s}\ , \qquad S2(\omega_s\ ,\ T_s) = \left(\frac{\partial w}{\partial \varphi}\frac{\partial \varphi}{\partial T_s} + \frac{\partial w}{\partial T_s}\right) \qquad (15)$$

Then the mass transfer equation for the desiccant layer becomes:



$$\frac{d\omega_s}{dt} = -\frac{S2(\omega_s\ ,\ T_s)}{S1(\omega_s\ ,\ T_s)}\frac{dT_s}{dt} + \frac{h_m A_c}{\rho_d A_d L S1(\omega_s\ ,\ T_s)}(\omega - \omega_s)$$

$$= -\frac{S2(\omega_s\ ,\ T_s)}{S1(\omega_s\ ,\ T_s)}\frac{dT_s}{dt} + \frac{C_4}{S1(\omega_s\ ,\ T_s)}(\omega - \omega_s) \qquad (16)$$

being,

$$C_4 = \frac{h_m A_c}{\rho_d L A_d} \qquad (17)$$

$$\frac{A_c}{A_d} = \frac{4 D_h L}{(D_h + d_t)^2 - D_h^2} \qquad (18)$$

$$h_m = \frac{h}{C_g Le} \qquad (19)$$

Le is the dimensionless Lewis number, which is generally assumed to be 1.

Heat transfer equation for the desiccant solid layer

The heat transfer to the desiccant is given by:

$$\frac{d(\rho_d A_d L C_d T_s)}{dt} = q_{st} \rho_d A_d L \frac{dw}{dt} + h A_c (T_g - T_s) \qquad (20)$$

C_d = isobaric specific heat of the desiccant, J/kg K
q_{st} = heat of adsorption, J/kg

The eq. (20) can be written as:

$$\frac{dT_s}{dt} = \frac{h_m A_c q_{st}}{\rho_d A_d L C_d}(\omega - \omega_s) + \frac{h A_c}{C_d \rho_d A_d L}(T_g - T_s) \qquad (21)$$

considering

$$C_5 = \frac{q_{st}}{C_d} \quad \text{and } C_6 = \frac{h A_c}{C_d \rho_d L A_d} \qquad (22)$$

Equation (21) is:

$$\frac{dT_s}{dt} = C_4C_5(\omega - \omega_s) + C_6(T_g - T_s) \qquad (23)$$

Relative humidity and saturation pressure can be calculated by:

$$\varphi = \frac{\omega_s P_0}{(0.622 + \omega_s)P_s} \qquad (24)$$

$$P_s = 10^6 P_0 exp\left(\frac{5294}{T_s}\right)\frac{(1 + 1.61\omega_s)}{(0.622 + \omega_s)} \qquad (25)$$

φ = relative humidity
P0 = pressure, Pa
P s = saturation pressure, Pa

2.3 SOLID DESICCANT COOLING CYCLES

The possible configurations and composition of each of the four components may vary according to the nature of the desiccant employed as described below.

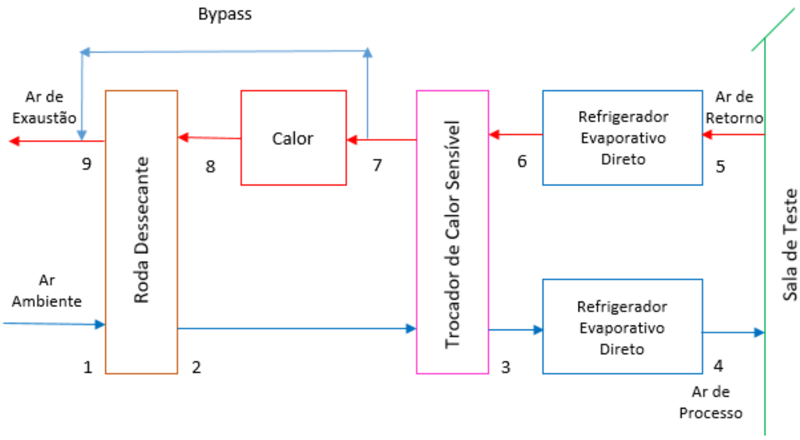
2.3.1 Pennington cycle

Figure 2 represents the Pennington cycle scheme. The ambient air at point 1, which is the process air, passes through a desiccant wheel, where its moisture is removed and the temperature increases due to the effect of heat of adsorption. Then the hot, dry air is cooled from point 2 to point 3 in a sensible heat exchanger. It is then cooled by evaporation in a direct evaporative cooler.

On the regeneration air side, the return air at point 5 is cooled and humidified in another direct evaporative cooler and then passed through the heat exchanger where it receives sensible heat from the process air leaving at point 7. In this process, the heat source heat can be solar energy, fossil fuel, electrical energy or waste energy (DAOU; WANG; XIA, 2006).

The hot air stream is then heated between points 7 and 8. After regenerating the desiccant material in the desiccant wheel, the air is exhausted at point 9 (DAOU; WANG; XIA, 2006).

Figure 2 - Pennington Cycle

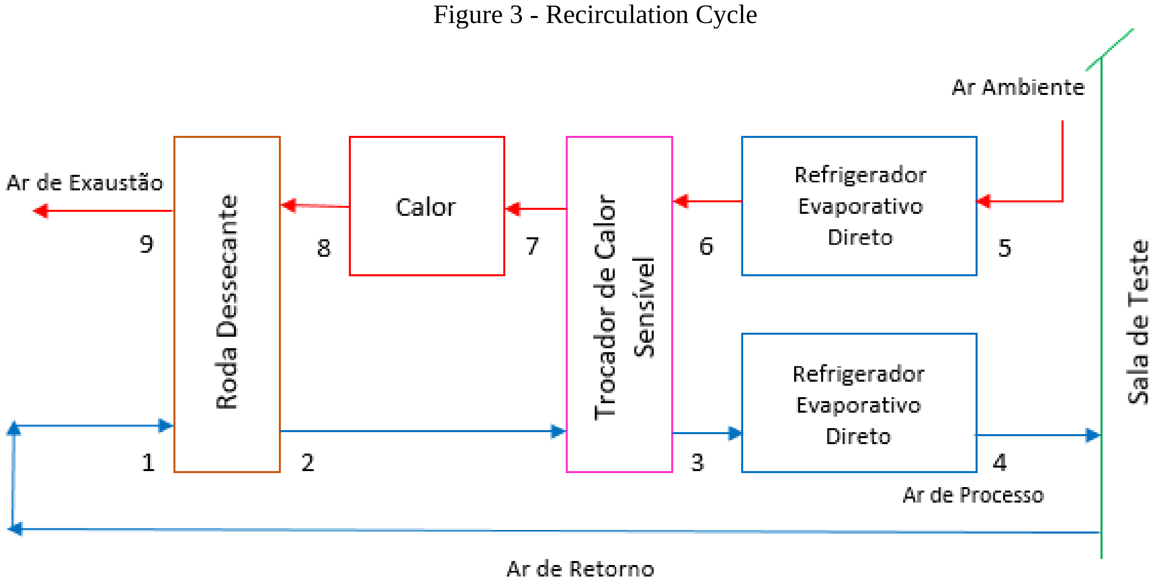


Source: DAOU; WANG; XIA, 2006.

2.3.2 Recirculation cycle

The Recirculation Cycle is used to increase refrigeration capacity, and is a modified form of the Pennington cycle. It is designed to reuse the return air from the room as process air inlet in the desiccant wheel. Figure 3 illustrates this cycle. In the recirculation cycle, the return air is recirculated through the dehumidifier while the outside air is used for regeneration of the desiccant wheel (JAIN; DHAR; KAUSHIK, 1995).

Figure 3 - Recirculation Cycle



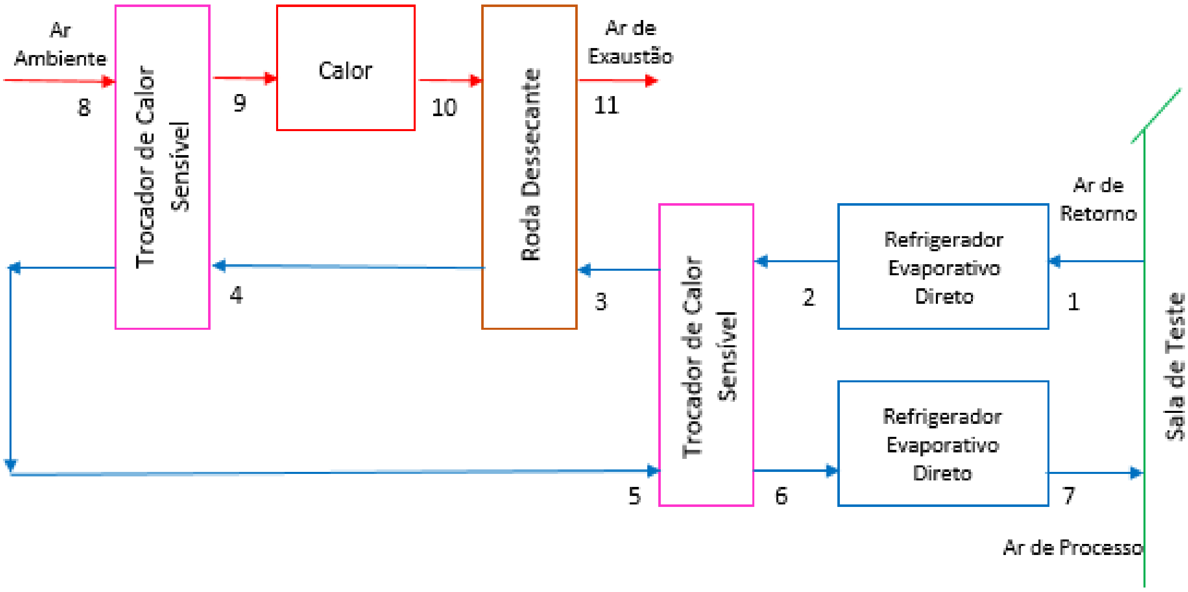
Source: DAOU; WANG; XIA, 2006.

2.3.3 Dunkle Cycle

The Dunkle Cycle combines the merits of the ventilation (Pennington) cycle and the recirculation cycle.

Figure 4 presents the scheme of this cycle (JAIN; DHAR; KAUSHIK, 1995). It has an additional sensible heat exchanger to improve cycle performance. This heat exchanger (points 5 and 6 and 2 and 3) can supply cooler process air. A large amount of ventilated fresh air that was supplied in the Pennington cycle for air conditioning in addition to comfort and health also represents an additional cooling load. In some cases, it is not necessary for ambient air to be the process air source for the system.

Figure 4 - Dunkle Cycle



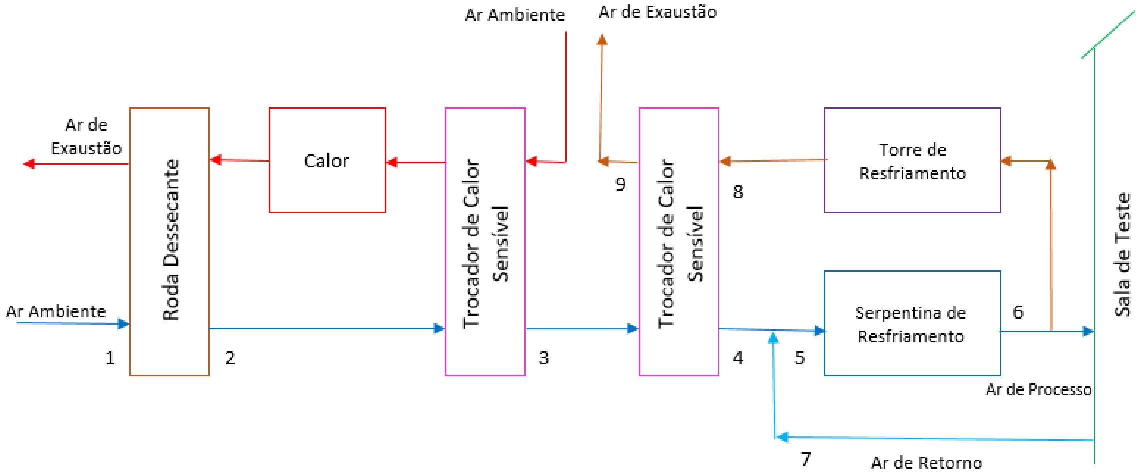
Source: JAIN; DHAR; KAUSHIK, 1995.

The Dunkle cycle also employs 100% recirculation. In practice, this is not desirable. Ventilation (process) air can, however, be easily added to the return air. The Dunkle cycle performs better compared to the Pennington and Recirculation cycles in all climatic conditions (JAIN; DHAR; KAUSHIK, 1995).

2.3.4 Sens Cycle

LA et al . (2010) studied a cycle called the SENS cycle that uses solid desiccant. As shown in Figure 5, ambient air is first dehumidified in the desiccant wheel and then cooled by two sensitive heat exchangers that are connected. It is further cooled in a cooling coil, exchanging heat with cold water from a cooling tower and then mixed with a certain amount of return air from the room. Afterwards, the process air is divided into two parts, one part being redirected to the cooling tower and exhausted to the environment after heat exchange with process air in a sensible heat exchanger, and the other part supplied to the conditioned space. .

Figure 5 - SENS Cycle

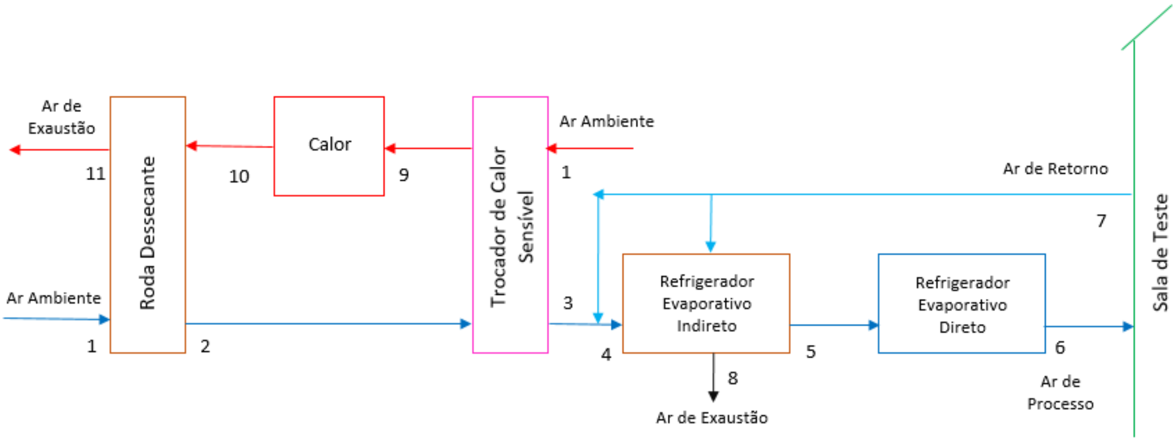


Source: LA et al ., 2010.

2.3.5 Dynamic Cycle

Figure 6 shows the direct-indirect evaporative cooling (DINC) cycle in which little modification is made over the SENS cycle. The modification that occurs is the replacement of the sensible heat exchanger, the cooling tower and the cooling coil with an indirect evaporative cooler and a direct evaporative cooler to avoid complexity and simplify the system configuration (LA et al ., 2010).

Figure 6 - DINC Cycle



Source: LA et al ., 2010.

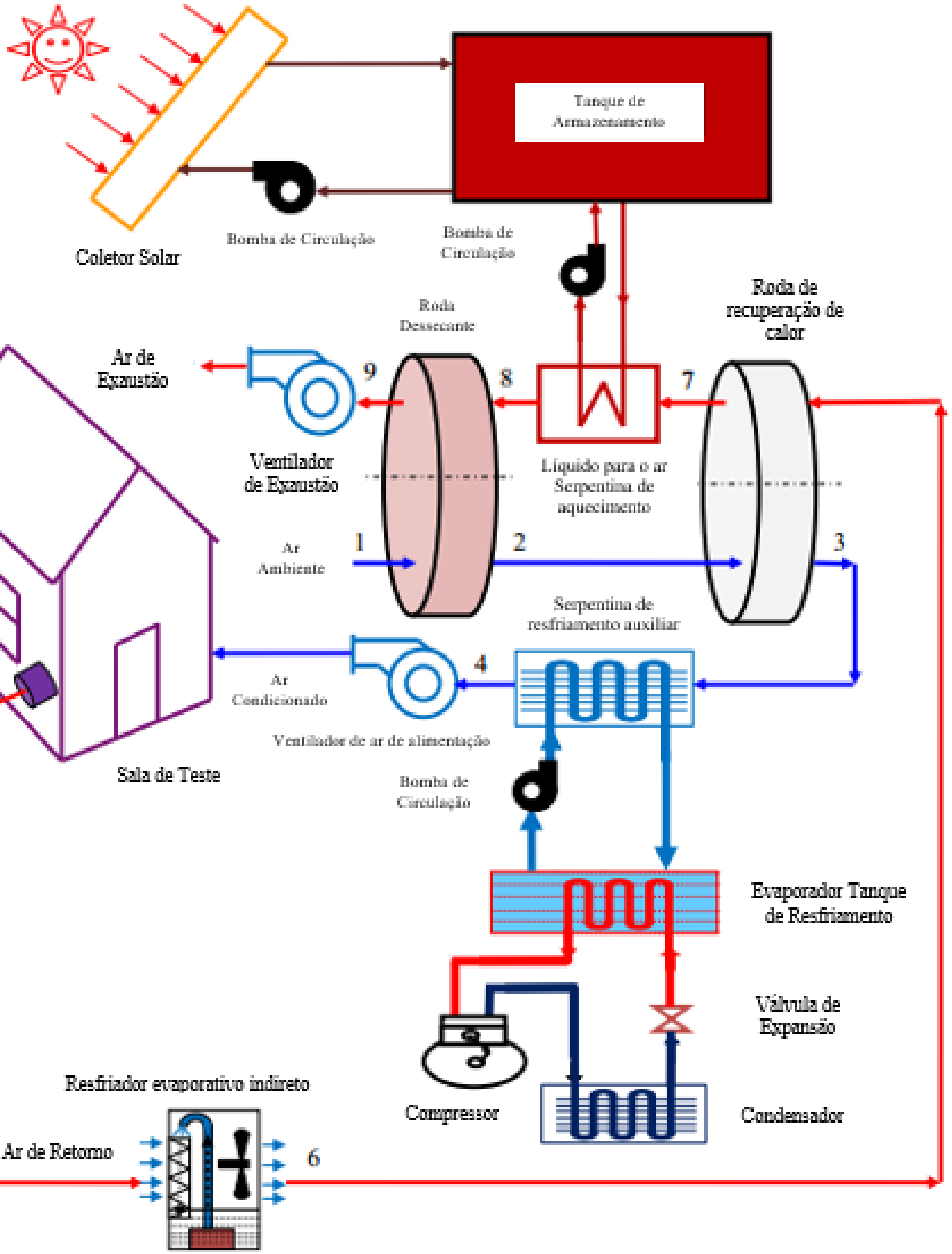
3 SYSTEMS THAT USE SOLAR ENERGY OR WASTE ENERGY AS A SOURCE OF REGENERATION HEAT

There are several types of desiccant air conditioning systems and their different installations that are available in the literature. This work presents the system that uses solar energy or waste energy as a source of regeneration heat.

The use of renewable heat sources such as solar thermal energy for the regeneration of solid desiccant dehumidifiers reduces electricity consumption as well as achieving substantial fossil energy savings. Solar heating is interesting when there is demand for cooling and, at the same time, great availability of solar energy ((JANI; MISHRA; SAHOO, 2016).

The functioning of the solar heating system includes solar collector, backup heater, storage tank, circulation pump and liquid-air heating coil. Solar collectors convert solar radiation into thermal energy in solar desiccant cooling systems. A backup heater is required for when solar energy is not sufficient, such as on cloudy and/or rainy days. Another important information is that the desiccant is regenerated by solar thermal energy produced by vacuum tube collectors (GAGLIANO et al., 2014).

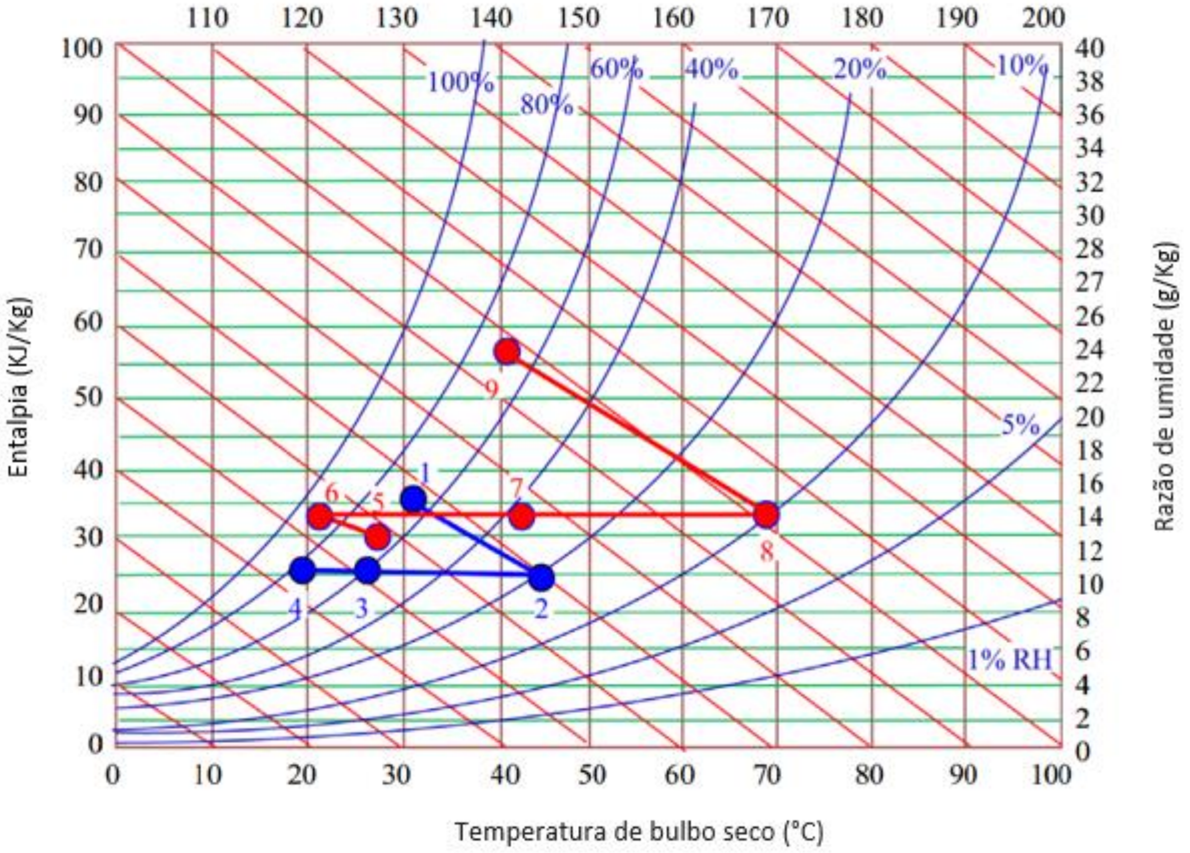
Figure 7 - Solar-assisted hybrid solid desiccant vapor compression air conditioning system



Source: JANI; MISHRA; SAHOO, 2016.

Figure 8 shows the psychrometric representation of the solar-assisted solid desiccant vapor-compression hybrid air conditioning cycle graph. It is observed that the regeneration temperature required for the desiccant dehumidifier is comparatively low and can be efficiently maintained by the solar thermal collectors. There is no additional dehumidification needed to achieve the required humidity rate, as the ambient humidity rate of the outside air is comparatively low. There is no need to post-heat the supply air as the cooling coil operates at higher evaporator temperatures. The final temperature of the process air is adjusted according to the conditioned space requirement through the auxiliary cooling coil of the vapor compression cooler.

Figure 8 - Psychrometric graph of hybrid air conditioning cycle by solar-assisted solid desiccant vapor compression



Source: JANI; MISHRA; SAHOO, 2016.

4 CONCLUSIONS

This work presented the system that uses solar energy or waste energy as a source of regeneration heat and it was concluded that solid desiccant cooling is a very environment-friendly energy saving approach within this air conditioning system. Many researchers conducted their study using simulations and experimental methodologies aimed at improving energy efficiency and cost effectiveness.

This is a technology that, despite having been proposed many years ago, has only recently gained more space in research and applicability. Thermal energy is the main source of energy in a desiccant cooling system and can come from sources that are not harmful to the environment and with lower costs.

The use of solar energy that is freely available or waste heat from industrial processes that is used in the desiccant material regeneration process can make the system more cost-effective. Another benefit is that the use of solar energy helps alleviate the high peak demand for electricity caused by the conventional vapor compression air conditioning system.

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