Desiccant-Based Cooling And Dehumidifying System In Hot-Humid Climate

Aniket Sawant[1], Nandesh Natekar[2], Viresh Saushik[3], Bhushan Sawant[4]
[1, 2, 3, 4] Dept of Mechanical Engineering
[1, 2, 3, 4] SSPM's COE

Abstract- *Now a day's air conditioning is one of the major aspects of our society. While using conventional air conditioning system most commonly Vapor compression refrigeration system (VCR) in Air conditioners and Direct evaporative cooling system (DEC) in swamp coolers there exists lot of energy consumption because of the compressor and also uses refrigerant which causes harm to the environment. Our motive is to introduce this system so as to provide alternative to conventional air conditioning system. So a combined unit consisting of a cooling unit coupled with solid desiccant wheel for dehumidification process was effective. It is found that the optimal rotation speed is lower for lithium chloride or compound rotors than for silica gel rotors hence we select rotors with silica gel embedded on it. The feasibility of the desiccant cooling system for cooling building in hot-humid climate is proven and the advantages it can offer in terms energy and cost savings are underscored. Process air is drawn by the blower & this air is fed to desiccant wheel where the moisture present in that air is absorbed by desiccant material in wheel & this dry air is fed into indirect evaporative cooler. After passing through indirect evaporative cooler the temperature drops due to change in sensible heat & cooled air is now fed into room. Desiccant cooling dehumidifies the incoming air stream by forcing it through a desiccant material & drying the air to the desired indoor temperature. Higher regeneration air temperatures lead to higher dehumidification potentials at almost equal dehumidification efficiencies but keeping in mind with increasing regeneration specific heat input and enthalpy changes of the process air. The influence of the regeneration air humidity was also notable and accordingly low relative humidity increased the dehumidification potential. For desiccant cooling applications in humid climates this finds a positive trend. It is notable that the desiccant materials when associated with evaporative cooling or chilled ceiling radiant cooling can assist them applicable under a diversity of climatic conditions.*

Keywords- Evaporative cooling, desiccant wheel, hot-humid climate, thermal comfort

I. INTRODUCTION

Air conditioning loads can be divided into two namely the sensible and the latent loads. An air conditioner must counterbalance the two sorts of load in order to maintain the desired indoor conditions. In order to remove the latent heat the traditional refrigerant vapour compression system (VCS) or the not yet traditional vapour sorption system (VSS) is used which cools the process air down below its dew point in order to condense out water vapour contained therein. The dehumidified air is then reheated to meet the required indoor temperature conditions. If the latent load is handled by other means than by this deep cooling two kinds of the burden on the conditioner brought about by the presence of latent load will be avoided namely (1) the energy required to bring the air from the supply temperature down to the temperature of condensation of water vapour contained in the process air (below the dew point of the air) and (2) the energy needed to reheat the air from that temperature up to the supply air temperature. When the sensible heat ratio (SHR) of the conditioned space is low, the sum of these two components increases dramatically furthermore the VCS are actuated by electricity, the generation of which involves most often the utilization of fossil fuelled power plant with the consequent emissions of carbon dioxide (CO2) into the atmosphere. Finally the refrigerants used in this air conditioning technology are more or less CFCs based ones, that many countries are taking steps to phase out or are considering doing so. The desiccant cooling can be either a perfect supplement to the traditional vapour compression air conditioning technology to attenuate the effects of its drawbacks or as an alternative to it for assuring more accessible, economical and cleaner air conditioning.

The desiccants are natural or synthetic substances capable of absorbing or adsorbing water vapour due the difference of water vapour pressure between the surrounding air and the desiccant surface. In addition of having lower regeneration temperature and flexibility in utilization, liquid desiccant have lower pressure drop on air side. Solid desiccant are compact, less subject to corrosion and carryover. Commonly used desiccant materials include lithium chloride, triethylene glycol, silica gels, aluminum silicates (zeolites or molecular sieves), aluminium oxides, lithium bromide solution and lithium chloride solution with water etc. The desiccant materials can be used in diverse technological arrangements. One of typical arrangements consists of using a slowly rotating wheel (8–10 rev/h) impregnated or coated with the desiccant with part of it intercepting the incoming air stream while the rest of it is being regenerated. Another arrangement uses the packing of solid desiccants to form a sort of adsorbent beds exposed to the incoming air stream thus taking up its moisture & these beds need to be moved periodically in the direction of the regeneration air stream and then returned to the process air stream. These desiccants can be coupled with the traditional air conditioning system to eliminate the overcooling and the reheat thus downsizing the equipment's and reducing their costs. They are used in conjunction with the chilled-ceiling evaporative cooling. Indeed, the evaporative cooling is the oldest technique of cooling. It has been superseded by the current more efficient and conveniently operated conventional air conditioning subsequent to the invention of this new technology. But the energy costs and the concerns related to environmental harms engendered by the refrigerants used in this system have prompted the researchers to begin looking back at the old cooling technique and trying to solve its main drawbacks. More importantly when powered by free energy sources such as solar energy, and waste heat, it can significantly reduce the operating costs and increase considerably the accessibility to the air conditioning for the populations in remote areas, especially in developing countries.

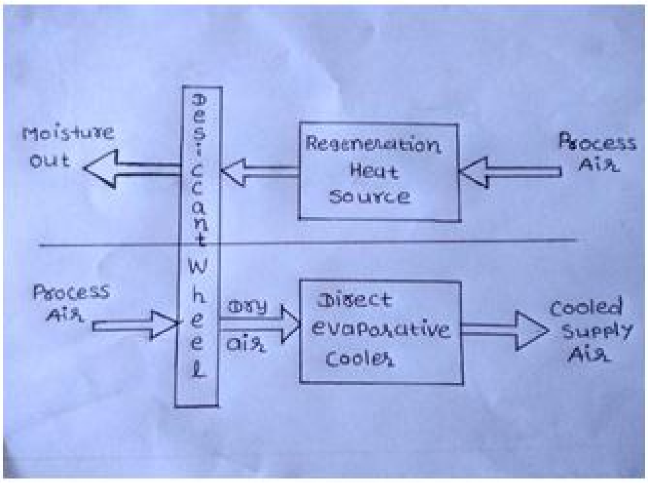

Fig 1: Schematic diagram of the system

II. SOLID DESICCANT COOLING PRINCIPLES ANDCONCEPT

A. Concept andOperation

This system mainly works on principle of desiccant dehumidification. For many industrial& domestic applications, dry air is produced by using solid desiccant. This desiccant can be used once or many times. When it is used once, there is wastage of desiccant. For using it again, it is regenerated by using conventional heater which consumes high grade energy. Various solid desiccants like silica gel, activated charcoal, activated alumina and zeolite etc. can be regenerated at low temperature byusing minimum energy, temperature required for regeneration of desiccant wheel is depended on the desiccant materials which were being used for theregeneration

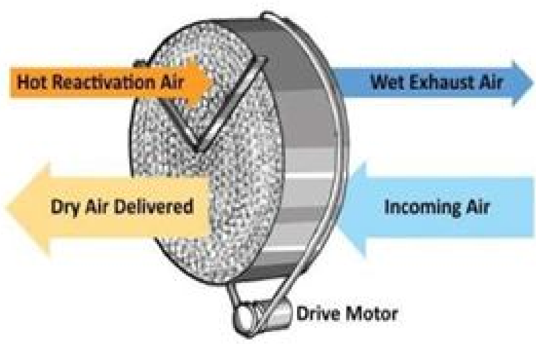

Fig 2: Desiccant Wheel Assembly (R1)

Silica gel was one of the most extensively investigated and promising solid desiccant material which required a regeneration temperature of about 65°C. In this system desiccant material use for regeneration is silica gel; Silica gel is a granular, vitreous, porous form of silicon dioxide made synthetically from sodium silicate. Silica gel contains a nano - porous silica micro-structure, suspended inside of a liquid. Most applications of silica gel require it to be dried in which case it is called silica aerogel.

B. Analytical Method

Todeterminetheperformanceoftheunitvariousanalytical methods areused.

i. Dehumidification & Cooling

It is the process of removing the moisture from the air, which is done by the desiccant wheel present in the unit. When the air passes through the desiccant wheel the granulesofsilicagelabsorbmoisturepresentintheairand gives dry air. This dry air is fed to heat exchanger which coolsdownthisdryair.Themediumintheheatexchangeris cold water which we get from the evaporativecooler.

ii. Regeneration Process

It is the process of removing moisture from the desiccant material so that it can be reused. Desiccant wheel having absorbed moisture is passed through hot region. This hot region can be maintained by small electric heater or small gas burner or heat exchanger containing hot water. The temperatureofthisregionismaintainedat50^{0}c-70^{0}c.When desiccant wheel comes in this region, the moisture entrapped in the granules of silica gel getsreleased.

iii. Load Calculation

Table -1: Load calculation

Load due to		Sensible heat	Latent heat
Walls/ceiling	East	140.78	
	West	486.26	
	North	525.57	
	South	153.73	
	Ceiling	78.33	
	Floor	209.7	
Fenestration	On north wall	226.068	
Wooden door		0.3387	
Infiltration		178.05	534.89
Occupants		285	335
Electrical lights		86.4	
Fans		80	
Total load		2450.326	869.89
Total load		3320.216	

This data was recorded for a room having length 3.835m, width 2.959m and height 2.959m on 20 Mar, 2018 at a day time about 12 noon to 4 pm. Required capacity of indirect evaporative cooler is,

Total load/3500[8]= 0.9486 TR

iv. Amount of Silica Gel required

Amount of silica gel required is calculated by, Q

Q= (CeqD)V(Nt)/(MHF) where
V=(3.14*7.52 *228.6)cu cm
V=40396.954534348cu cm
V=0.04039695cu m
Q= (20*0.1)*(0.04039)*(1*1)/(2*10)=1.6156 kg

D. Actual Working

This unit consists of two zone which are dehumidifying in coolingzoneandregenerationzone.Processairisdrawnby theblowerandthisairisfedtodesiccantwheelwhereallthe moisture present in that air is absorbed by desiccant material present in wheel. Now, this dry air is fed into evaporativecooler.Afterpassingthroughevaporativecooler thereisdropintemperatureduetochangeinsensibleheat. This cooled air is now fed intoroom.

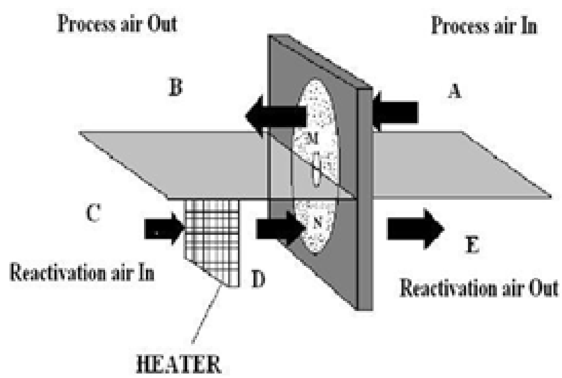

Fig 3: Working of solid desiccant Air Conditioning(R2)

The desiccant wheel is continuously rotating at a speed of 10-20 rph. Now, moisture locked into desiccant material is passed into regeneration zone whose temperature is maintained at 55^{0}c-75^{0}c with the help of small electric heater.Thatpartofdesiccantwheelgetsregenerateddueto the removal of moisture. This moisture is evacuated out of the room by the duct. This cycle isrepeated.

E. Cooling & Dehumidification

It is the process of removing the moisture from the air, which is done by the desiccant wheel present in the unit. When the air passes through the desiccant wheel the granules of silica gel absorb moisture present in the air and gives dry air. This dry air is fed to heat exchanger which cools down this dry air. The medium in the heat exchanger is cold water which we get from the evaporative cooler.

F. Air Cooling

An evaporative cooler (also swamp cooler, desert cooler and wet air cooler) is a device that cools airt hrough the evaporation of water. Evaporative cooling differs from typical airc onditioning systems Which use vapour-compression or absorption refrigeration cycles. Evaporative cooling works by employing water's large enthalpy of vaporization. The temperature of dry air can be dropped significantly through the phase transition of liquid water to water vapour (evaporation), which can cool air using much less energy than refrigeration. In extremely dry climates,evaporative cooling of air has the added benefit of conditioning the air with more moisture for the comfort of building goccupants. A heatexchangeris a piece of equipment built for efficient heat transfer from one mediumtoanother.The media may be separated by a solid wall to prevent mixing or they may be indirect contact. They are widely used in space heating, refrigeration, air conditioning, power- plants, plants, petrochemical, petroleum-refineries, natural gas processing, and sewage treatment. The classic example of a heat exchanger is found in an internal in which a circulating fluid known as engine coolant flows through radiator coils and air flowspast the coils, which cools the coolant and heats the incoming air. Air cooling is a process of lowering air temperature by dissipating heat. It provides increased air flow and reduced temperatures with the use of cooling fins, fans or finned coils that move the heat out of a casing such as a computer case.

III. NUMERICAL ANALYSIS OF HEAT AND MOISTURE TRANSFER IN DESICCANT WHEEL FOR DEHUMIDIFICATION

For this development, we investigated numerical analysis method of heat and moisture transfers in desiccant wheel in order to carry out the optimal design of this desiccant system. In this paper, the heat and water vapor transfer phenomena inside a desiccant wheel were formulated, and the algorithm of numerical calculation for the formulated equations was investigated. Its validity was checked by comparing the calculation results with the results of the repeated adsorption-desorption experiment for a fixed desiccant wheel (the wheel is not rotating), and with the experiment using an actual desiccant machine (the wheel is rotating). With regard to the numerical calculation targeted at the repeated adsorption-desorption experiment, the periodic change in moisture content was accurately reproduced by the calculation. However, with regard to the actual desiccant machine, this numerical analysis could not accurately predict the air temperature after passing through the desiccant wheel, although it could evaluate the amount of dehumidification fairlywell.

A. Transport Equations of Heat & water vapour inside a desiccant element

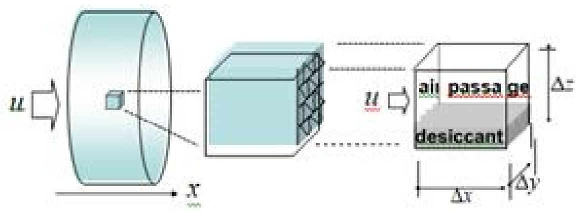

Fig 4: Element ofSolid Desiccant Wheel (R3)

As shown in the Fig. 3, a parallelepiped infinitesimal volume is taken from the wheel and modeled. Considering the balances of water vapor and heat quantity inside this infinitesimal volume, the three transport equations (1), (4), and (5), as shown in Table 1, can be obtained. Equation (2) indicates that the moisture content of a desiccant material changes due to the water vapor transfer on the desiccant material's surface. Equation (3) is based on the assumption of local equilibrium in which the relation between the absolute temperature and moisture content of the desiccant material's surface (adsorption/desorption phase) instantaneously follows the adsorption isotherm. This formulation was conducted with reference to the theory of simultaneous transfer of heat and water vapor proposed by Matsumoto and Hokoiet al. The adsorption isotherm of Equation (3) varies significantly according to materials and so in this study we measured this for the target desiccantwheel.

Table 1. Transport equations of heat and water vapor

Water vapor transport equation in air passage

$$\varepsilon\rho_a \frac{\partial X_a}{\partial t} = -\varepsilon u \rho_a \frac{\partial X_a}{\partial x} + \varepsilon \frac{\partial}{\partial x}\left(\lambda_a' \frac{\partial X_a}{\partial x}\right) - \gamma \frac{\partial w}{\partial t} \quad (\mathrm{kg/m^3s}) \quad (1)$$

Equation of moisture content

$$\gamma \cdot \frac{\partial w}{\partial t} = \alpha' S(X_a - X_b) \quad (\mathrm{kg/m^3s}) \ (2) \qquad w = f(X_a, \theta_a) = f(X_b, \theta_d) \quad (\mathrm{kg/kg_d}) \ (3)$$

Heat transport equation in air passage

$$\varepsilon C_a \rho_a \frac{\partial \theta_a}{\partial t} = -\varepsilon u \rho_a C_a \frac{\partial \theta_a}{\partial x} + \varepsilon \frac{\partial}{\partial x}\left(\lambda_a \frac{\partial \theta_a}{\partial x}\right) - \alpha S(\theta_a - \theta_d) \quad (\mathrm{J/m^3s}) \quad (4)$$

Heat transport equation in desiccant material

$$(1-\varepsilon) C_d \rho_d \frac{\partial \theta_d}{\partial t} = (1-\varepsilon) \frac{\partial}{\partial x}\left(\lambda_d \frac{\partial \theta_d}{\partial x}\right) + L\alpha' S(X_a - X_b) + \alpha S(\theta_a - \theta_d) \quad (\mathrm{J/m^3s}) \quad (5)$$

ε : porosity (-), ρ : air density (kg/m^3), X : absolute humidity (kg/kg'), t : time (s)
x : coordinate along air passage (m), u : air velocity (m/s), λ' : water vapor conductivity {kg/ms(kg/kg')}
γ : density of desiccant material (desiccant mass per volume including air passage) (kg$_d$/m^3)
w : moisture content (kg/kg$_d$), α' : water vapor transfer coefficient on desiccant surface {kg/m^{2}s(kg/kg')}
α : convective heat transfer coefficient on desiccant surface (J/sm^{2}K)
S : Surface Area of desiccant material per volume including air passage (m^2/m^3)
$f(X_a, \theta_a)$: adsorption isotherm (kg/kg$_d$), C : specific heat (J/kgK), θ : temperature (K)
λ : thermal conductivity (J/smK), L : latent heat of vaporization (J/kg)

Suffix a : air d : desiccant material b : desiccant material's surface (adsorption/desorption phase)

B. Measurement of Equilibrium Moisture content of Desiccant Wheel

The experimental apparatus and measuringmethods adopted in this study follows the JIS's method for measuring the equilibrium moisture content of building materials and the Environmental Standards of the Architectural Institute of Japan.

Fig. 4 shows the experimental apparatus. This apparatus is composed of a temperature- controlled bath, an air control unit, which automatically adjusts the mixing ratio of dry air and saturated air to a specified relative humidity and sends air to the measurement chamber, and an air handling unit (AHU), which supplies the air with steady temperature to the temperature-controlled bath. The weight change of the desiccant wheel during moisture adsorption or desorption was gauged by an electronic balance, and the dew-point temperature of the influx/outflux air was measured by a chilled-mirror dew-point thermometer. The temperature inside the temperature-controlled bath was measured by aPT100.
Firstly, a desiccant wheel with a diameter of 150 mm and a thickness of 75 mm was put into an oven, and dried sufficiently at 110 degrees Celsius, and then the reference dry mass was measured. Next, the desiccant wheel was put into the measurement chamber, air with a specified relative humidity of 10% was supplied, and measurement was carried out until the desiccant wheel reached the constant weight (equilibrium state). The relative humidity was increased in a stepwise manner. After the specified relative humidity was increased to 95%, the relative humidity was decreased in a stepwise manner, and the above weight measurement was conducted until the specified relative humidity reached 10% (desorptionprocess).

Fig. 5 shows measurement results of the equilibrium moisture content. Here, the moisture content higher than 45%RH for 70 degrees Celsius condition was not measured because the measuring limit of dew-point temperature was 50 degrees Celsius, and so the humidity limit was 45% in the 70 degrees Celsius condition. This has no problems because the relative humidity of the air inside the actual desiccant wheel never becomes higher than 45 %RH in the high-temperature condition.

Under the 25 degrees Celsius condition, the moisture content during the desorption process was higher than that during the adsorption process, under the medium humidity condition (20%RH-80%RH). This hysteresis phenomenon, which is commonly seen in porous materials, was observed. In addition, when the ambient temperature was set to be 70 degrees Celsius, the moisture content became lower than that under the 25 degrees Celsius condition, for the same relative humidity. This indicates that the relation between relative humidity and equilibrium moisture content varies according to temperature.

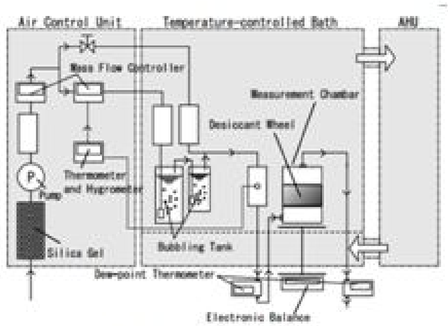

Figure 4. Experimental apparatus for measuring the equilibrium moisture content

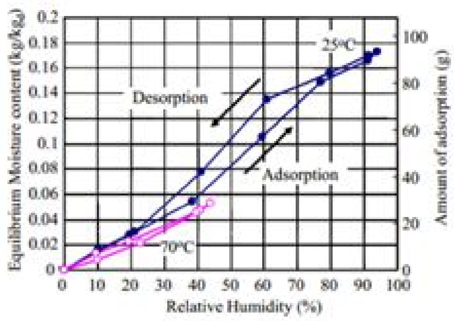

Figure 5. Adsorption isotherm

Fig 5 (R4)

C. Calculation Method considering rotation of the wheel

Calculation method

As shown in Fig. 9, the wheel is segmented into each element in the rotational direction, and the numerical calculation is carried out separately. Each segmented element is rotated, and the flow direction and the influx temperature and humidity are switched on, according to whether it is located at the adsorption side or the desorption side. By averaging the outflow temperature and humidity of all elements located at the adsorption side, it is possible to obtain the temperature and humidity of the air that has been dehumidified through the wheel at each time step. Until this averaged temperature and humidity become steady, the calculation is continued while rotating the wheel.

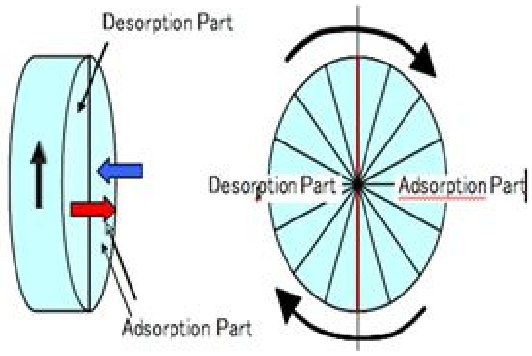

Fig 6. Calculation Method for Solid Wheel (R5)

In order to validate the numerical calculation method considering the wheel's rotation, we compared the calculation results with the experimental results for an actual desiccant machine. The actual desiccant wheel had a diameter of 300/150 mm and a thickness of 100/75 mm. Table 3 shows the experimental condition. For the inflow boundary conditions of the temperature and the humidity at the process side and the regeneration side, the measurement values were used. The air volume was set at 100 m3/h, and the rotation speed was set at 30 RPH.

Fig. 10 plots the calculated result and measured result on a psychrometric chart. The air temperature that has passed through the wheel increased from 30 degrees Celsius to 54 degrees Celsius in the experiment, while the calculated temperature became 49 degrees Celsius, which was about 5 degrees lower than the experimental value. The absolute humidity after passing through the wheel was 0.01 kg/kg' in the experiment, while the calculated one was 0.0093 kg/kg'; these values are almost the same. Namely, the amount of dehumidification was evaluated quite accurately by the calculation. With regard to the discrepancy in temperature in calculation method we did not take the heat transfer among the segmented elements into account but in actual wheels it is considered that there is heat transfer at the boundary surface between the regeneration and process sides. This is expected to be improved by considering the heat transfer at the boundary surface between the regeneration and process sides in the model of the numericalcalculation.

Table 2. Calculation Conditions

Geometry of desiccant wheel	300/150φ×1 00/75 t
Inflow Condition of process air	Temperature 30 K Absolute humidity 14.7 g/kg'
Air volume	100 m^3/h
Rotation speed	30 RPH

IV. CONCLUSION

By using this air-conditioning system we can get the cooling effect without help of compressor. With the help of this system we can say that this type of system gives the cooling effect up to 29 C. This system is work well in warm sunny days and analysis shows that this system will be significantly more economical to own and operate then the conventional AC. In spite of a slightly higher initial cost, this system proves to be more economical, mainly due to its significantly lower operating cost. Because of desiccant wheel load get completely separated there by performance of system improve by certain level as performance of air conditioning is significantly governed by latent load. It can be good option when the humidity level is high. Combining the basic desiccant model with IEC and DEC allows reducing significantly the DBT to 29°C and keeping Rh within the accepted value 59 % considering hot-humid outside climate at 36°C and 70%.

The performance of the desiccant cooling system can be studied more for further improvements. One of these improvements is to combine with the desiccant cooling system a solar air heating system for the DW regeneration.

V. ACKNOWLEDGMENT

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