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Simulation Study of Desiccant Dehumidifier: A Review

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Abstract: *Traditional cooling systems based on vapor compression are ineffective in humid climates due to their inability to remove moisture below the dew point of the conditioned air, which involves additional effort in the form of an electrical power supply to run vapor compressors. A solid desiccant cooling system reduces powerusage while simultaneously providing fresh and clean air. It is important toexamine and analyze the performance of desiccant dehumidifiers using the Different pattern in the desiccant wheel that will help to develop a more efficient cooling system. Like ahoneycomb, triangular, sinusoidal.To study different type of material used in desiccant wheeel to adsorp the air moisture. Study different simulation technique used in desiccant.*

Keywords: Dehumidifier; desiccant materials; solid desiccant cooling; Computational fluid dynamics (CFD)

I. INTRODUCTION

Today's rapid technological development has altered the human working environment, leading to an increase in the use of vapor compression-based cooling systems. A desiccant cooling system receives heightened attention as it consumes low-density energy resources such as solar energy and local heating water. The system has benefits in terms of indoor air quality, environmental impact, global warming, and energy efficiency.(CHUNG et al., 2010). India is a tropical land with high daytime temperatures of 29–34°C and relative humidity of 70%–90% throughout the year. India is a tropical country. For the interior environment, the temperature and relative humidity of ASHRAE Standard 55 are suggested at between 23–26°C and between 30–60%, respectively. Climate systems in India are frequently utilized to satisfy the ASHRAE standard. The number of climate control systems used rose from 13,000 in the 1970s to more than 250,000 in the year 1991, to over 1.5 million by 2020. The number was predicted to increase in the future.

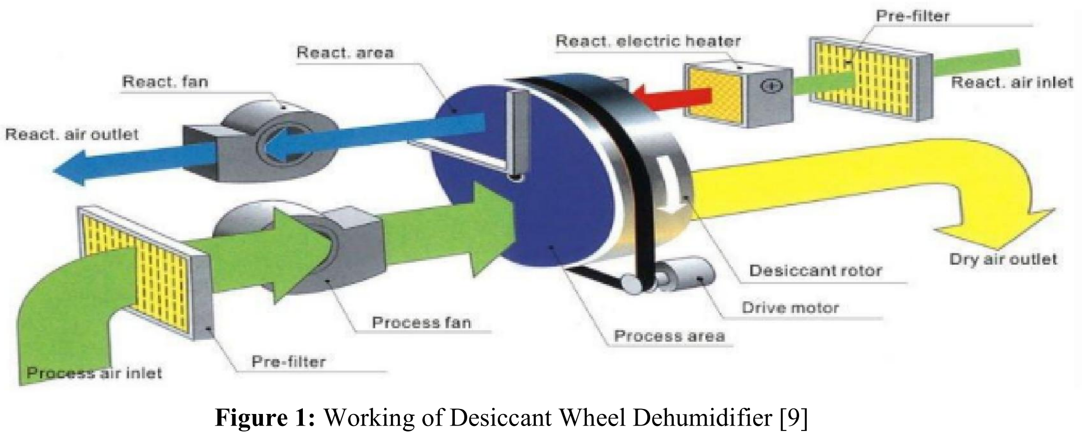

Figure 1: Working of Desiccant Wheel Dehumidifier [9]

increased need for air conditioning, however, has resulted in huge electricity usage. Air conditioning also fulfills the crucial role of moisture management, apart from sensitive cooling. The cooling process and air dehumidification normally are powered by a cooling spool in traditional air conditioning machines. India's high humidity leads to a somewhat high dehumidification burden. As a result of the overcooling process, the conventional approach requires a huge quantity of energy to reduce humidity. Recently, modern air conditioning incorporated independent dehumidification load handling and sensible cooling capacities, which lower its power demand. It is generally integrated with the air conditioning system for the comfort of residential buildings and workplaces requiring around 60%–70% humidity and hospital operating rooms, which require around 50–60% humidity(Rambhad et al., 2021**).** solid desiccants are mostly used in desiccant cooling systems; silica gels, lithium chloride and molecular sieves. Different methods of dehumidification- In Air bypass control method a portion of the return air is bypassed from the cooling coil. This gives less reheat requirement. In Heat pipe system method, precooling of mixed air and reheating of conditioned air can be achieved by introducing a heat pipe between the above air streams. This is also an energy saving device. In Air reheat system method, by selecting the dew point temperature of the coil and reheating the conditioned air to achieve the desired temperature and humidity. This method was widely adopted earlier. It is an energy inefficient method and many countries have banned this method. In Desiccant cooling systems moisture in air is removed by a desiccant that absorbs the moisture when air passes through it. These desiccants can be either solid or liquid. They can be used efficiently to overcome the latent part of the cooling load. Desiccant technology for moisture removal is appropriate where sensible heat ratio (SHR) is low as in high humid locations and applications where precise humidity control is required.(Halid et al., n.d.)

In desiccant wheel dehumidifier, the desiccant material usually a silica gel or some type of zeolite, is impregnated into a supporting structure. This looks like a honeycomb which is open on both ends. Air passes through the honeycomb passages, giving up moisture to the desiccant present in the walls of the honeycomb cells. The wheel constantly rotates through two different air streams. The first stream, namely the process air, is dried by the desiccant. During this process the heat of absorption is released to the air. The second air stream, called reactivation or regeneration air, is heated. It dries the desiccant. The regeneration air can be heated by solar collectors, electric heaters, gas burners, or waste heat sources.

The wheel, where an air-to-air heat and mass transfer takes place at a low rotation speed, is the most crucial component of the desiccant cooling system. Therefore, mathematical modeling of the desiccant wheel plays an important role in enhancing the overall system performance. The optimum wheel speed and thickness, and the operating parameters such as the air flow rate, the relative humidity of the inlet air and the regeneration air temperature on the wheel performance have all been examined.(Chung, 2016)

1.1Type of Material used in Desiccant Wheel

Generally, the materials which have the ability to attract and hold other gases or liquids are termed as sorbents. These sorbents are mainly used in chemical separation processes and are used for absorbing gases or liquids other than water Vapour. Desiccants are a subset the sorbents, which specifically have affinity for water. This process of absorbing and holding water vapour by the desiccants may be defined as either absorption or adsorption depending on whether the desiccant material undergoing chemical change on attracting moisture (absorption) or not (adsorption).Materials like wood, natural fibres, clay sand various synthetic materials can also attract and hold water vapour ,but they have less holding capacity. Generally, a desiccant attracts between 10 to 1100% of its dry mass of water vapour depending on the moisture content available in the surroundings and the type of desiccant material used. Desiccants continuously attract moisture, even from the dry air, until it reaches equilibrium with the environment. Moisture is removed byheating the desiccant material to temperatures from 50° to 150° C and exposing to are generation air stream. After the desiccant is completely dried, it should be cool ends that it can attract water vapour again (Chua, 2015)

Solid desiccants are generally classified into following classes.

A. Silica Gel

Silica gel is silicon dioxide (SiO2 xH2O), a naturally occurring mineral that is processed and purified in to granular or beaded form with amorphous micro-porous structure and heat of adsorption nearly equals 2800kJ/kg .(Srivastava & Eames, n.d.)

B.Zeolites

Zeolites are alumina silicate minerals of alkali and alkaline earth metals like sodium, potassium and calcium. They have crystalline lattice which are wide open that makes ease of holding water vapour like in a cage and have porous structure to accommodate the alkali and alkaline earth metal ions. Water vapour can be removed by heating the material, leaving unchanged alumina silicate skeleton with a void fraction ranging from 0.2 to 0.5. After heating, the size of apertures of the skeleton ranges from 3 to 8 A0 for further adsorption of water vapour. Generally, zeolites will be contacted with aqueous solutions of appropriate cations (practically 0.1M) at a temperature of 60-70°C at solid to liquid (S/L) weight ratios ranging from 1/20 to 1/50, for caution exchange. Clinoptilolite, analcime, Natrolite, Heulandite, Phillipsite and Stilbite are some of the common zeolite minerals. These zeolites are also used in some of the industrial chemical processes like gas separations, ion exchanges, water treatment and catalysis. (Zheng et al., 2014)

C. Activated Alumina

Activated aluminas are hydrides and oxides of aluminium, generally prepared by thermal dehydration or activation of aluminium tri-hydrate or gibbsite. The structural characteristics of alumina can be controlled either by temperature and duration of the thermal process or by the gases used for producing them. Activated alumina, like silica gel, has greater capacity for water vapour than zeolites and surface acidity is the important property for adsorption as well as catalysis. Because of this surface acidity, Lewis acid sites are abundant on alumina and for fully hydrated alumina, Bronzed acid sites (OH groups that don't proton) are present. This activated aluminahas surface area ranging from 150 - 500 m2/g and heat adsorption capacity as high as 3000kJ/kg. (Swapnil et al., 2019)

D. Magnesium Sulfate

Magnesium sulfate is an in-organic salt (chemical compound) and contain magnesium, sulfur and oxygen, with the formula MgSO4. It is often encountered as the empathydrat sulfate mineral epsomite (MgSO4·7H2O), commonly called Epsom salt. Anhydrous magnesium sulfate is frequently used as a drying agent. The anhydrous form is hygroscopic (readily absorbs water from the air) and is therefore difficult to weigh accurately; the hydrate is often preferred when preparing solutions (for example, in medical preparations. Anhydrous magnesium sulfate is generally used as a desiccant in organic synthesis due to its great affinity for water. During work-up, an organic stage is saturated with magnesium sulfate until it no longer forms clumps. The hydrated solid is then removed with filtration or else decantation. Other inorganic sulfate salts such as sodium sulfate and calcium sulfate may also be used in the same way. (Panaras et al., 2011)

E. Molecular Sieve/Synthetic Zeolite

Molecular sieve also known as synthetic zeolite can adsorb moisture strongly hence considered for different moisture removal and AC application. Zeolite prepared from fly ash has shown significant potential for solar cooling application. Composites desiccants are developed from synthetic zeolite and silica gel to obtain favorable adsorption characteristics under lower and higher relative humidity which enables deep dehumidification .(Al-Alili et al., 2015)

F. Calcium Oxide

Calcium oxide (CaO) is calcinated or recalculated lime having a dampness adsorptive limit of at the very least 28.5% by weight. The distinctive highlights of calcium oxide (otherwise called Quick Lime) are: it will adsorb a considerably more prominent measure of water at low relative mugginess than different materials.It is powerful in holding dampness

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at high temperatures; and it is moderately modest when contrasted with numerous different desiccants**.** (Panaras et al., 2011)

G. Calcium sulphate :

Calcium sulphate ($CaSO_4$), better referred to monetarily as Diorite, is an economical option accessible in reasonable bundling shapes. Calcium sulphate is made by the controlled drying out of gypsum, going about as a universally useful desiccant designed for the most part for research centre utilize. It is synthetically steady, non-breaking down, nontoxic, non-destructive, and does not discharge its adsorbed water when presented to higher surrounding temperatures. The ease of calcium sulphate must be weighed against its similarly low adsorptive limit: it adsorbs just up to 10% of its weight in water sulphate. Calcium sulphate additionally has recovery attributes that tend to restrict its helpful life. Albeit accessible, it isn't typically sold in bundle frame(Jia et al., 2007)

H. Composite Desiccant Material

Composite materials are generally formed by the impregnation of hygroscopic salts into the pores of the host, i.e., a porous desiccant material in this case. The hygroscopic salts (nitrates, sulphates and haloids etc.) possess high water adsorption characteristics but they are unstable at higher humidity ratios due to lyolysis, so porous desiccant materials with stable characteristics like silica gels, activated carbon, mesoporous silicates and natural rocks are used as host material(Simonova et al., 2009)

I. Liquid and Polymer Desiccants

Liquid desiccant has been used in many DAC systems and yield decent COP. common liquid desiccant are lithium chloride, lithium bromide (LiBr), Calcium Chloride ($CaCl_2$), and triethylene glycol. The liquid desiccant can be regenerated at lower temperature (60 to 75 °C) which gives an opportunity to utilize low grade waste heat. Polymer desiccant enables 2-3 times higher absorption ability as compared to silica gel and the result are more exciting when operated on higher relative humidity conditions and low regeneration temperature (Daou et al., 2006; Mei & Dai, 2008)

J. Bio Desiccant and Activated Carbons

Many hydrophilic desiccants are produced from biomass with an appropriate water vapour adsorption ability. In a study dry coconut coirs gave interesting performance with lower heat of adsorption as compared to silica gel. Biomass is also used for activated carban production (Narayanan et al., 2011)

Usually the activated carbons are considered as hydrophobic substance but with some treatment it can absorb water vapours at higher relative pressure. Studies shows that activated carbon can yield 2-3 times higher water vapour adsorption as compared to silica gel Bentonites clay(Sultan et al., 2015)

K. Mesoporous Silicate-Based Composite

A new family of ordered mesoporous silicates, prepared by hydrothermal formation of SGs in the presence of long-chain surfactant templates, have attracted intensive attention since the discovery of MCM-41 and FSM-16in1990s. Then, a variety of mesoporous silicates with different pore sizes have been developed, such as MCM-48, MCM-50, KIT-1, SBA-15 and so on (Simonova et al., 2009)

L. Binary Salt Impregnated Composites

The research works mentioned above were based on the composite desiccants with single salt impregnations. Recently composite desiccants with double hygroscopic salts impregnation became more prominent in research. Synthesized two composite desiccants by permeatingLithium chloride+ Lithium bromide and$CaCl_2$+$CaBr_2$ into silica pores and found that the water vapour can be desorbed at 70°C by increasing the chlorine salt concentration in the binary salts. These binary salts impregnated composite desiccants were found to be having higher water adsorption characteristics when compared to single salt composite desiccants and low regeneration temperatures less than 100°C. The water adsorption characteristics of these composite desiccants mainly depends on the concentration and categories the of salts, fabrication processes and pore distribution of host material. By varying these above characteristics, composite desiccants with desired and required adsorption characteristics can be synthesized (Jia et al., 2007)

M. Liquid Desiccant

Liquid Desiccants are generally strong ionic salt solutions whose behaviour can be controlled through varying their concentration, temperature or may be both. The control of temperature is handled by coolers or heaters, whereas concentration is handled by heating the desiccant to remove water vapour into the atmosphere or a scavenger airstream. In air washer, when air is passed through it, the dew point of the air supplied approaches the water temperature with which the machine is supplied. In this process, more humid air gets dehumidified and less humid air humidified. In the same way, the air is brought into contact with the liquid desiccant solution (Chua, 2015)

The selection of liquid desiccants depends on many parameters like density of energy storage, thermo-physical properties, vapour pressure, availability, regeneration temperature, boiling point temperature, cost, etc. and of all the above parameters, vapour pressure of the surface is of main concern. Some of the commonly used liquid desiccants, because of their low surface vapour pressure at low temperature and high concentration, are calcium chloride, lithium chloride, and lithium bromide and triethylene glycol(Ahmed et al., 1998)

N. Calcium Chloride

Calcium chloride is an ordinary ionic halide which serves calcium practical in watery arrangement and at room temperature it is a strong (Mei & Dai, 2008)

Calcium chloride can serve as a source of calcium ion in an aqueous solution, as calcium chloride is soluble in water. This property can be useful for displace ions from solutions. Calcium chloride have a very high enthalpy change of solution. A considerable temperature rise accompaniesits dissolution in water. The anhydrous salt is deliquescent. It can accumulate adequate water in its crystal lattice to form a solution. Drying tubes are frequently packed with calcium chloride Lithium Chloride (Ahmed et al., 1998)

Kelp is dried out with calcium chloride for use in producing sodium carbonate. Adding solid calcium chloride to liquid can remove dissolved water. These hygroscopic properties are additionally connected to keep a fluid layers on the outside of the roadway, which holds dust down. Lithium chloride is an ionic salt that is widely used in air-conditioning systems. It has better hygroscopic properties and amazing solubility of about 83g/100 ml at 20°C in polar solvents. It has a boiling point temperature of 1382°C with 2.068 g/cc density. The crystallization line of $LiCl\text{-}H_2O$ solution is an increasing mass fraction of LiCl and reducing water content.(Daou et al., 2006)

O. Lithium Bromide

Lithium bromide is another lithium salt that is widely used as desiccant in air-conditioning applications. It is generally produced by treating lithium carbonate with hydrobromic acid and it can also be produced as a precipitate in water by treating lithium hydroxide with hydrobromic acid. It generally forms many crystalline hydrates comparative to other bromides of alkali metals. It is quite soluble in water, methanol, ethanol, ether and also slightly in pyridine. It has a boiling point temperature of 1265°C with a density of 3.464 g/cc (Daou et al., 2006)

It generally forms many crystalline hydrates comparative to other bromides of alkali metals. It is quite soluble in water, methanol, ethanol, ether and also slightly in pyridine. It has a boiling point temperature of 1265°C with a density of 3.464 g/cc (Thoruwa et al., n.d.)

Almost all materials can adsorb and hold water vapor. There are however some, of the so-called desiccant materials, in which said capability is particularly relevant; among these are e.g. activated carbon, activated alumina, silica gel, lithium chloride, and calcium chloride. The mostAdsorption of water vapor involves two different processes: chemical sorption and physical adsorption. The first process is permanent, and cannot be reverted by regenerating the silica gel, while the physical adsorption is a reversible process, driven by the intermolecular forces of attraction called Van Der Wall forces, that hold water molecules on the surface of the pores. Thus, it is the physical adsorption that plays a crucial role in the dehumidification process involving desiccant wheels. An important characteristic of a desiccant material is its adsorption isotherm, which determines its water vapor adsorption capacity as a function of temperature and vapor pressure. (Rambhad et al., 2021).

Developed new adsorbent for the desiccant cooling system. The adsorption isotherm of the zeolite 13X, silica gel, DH-5, and D-H7 were also investigated. For cooling cycle, DH-5 and DH-7 were suitable because their ability to provide higher cooling capacity 2.2 and 1.3 times as compared to silica gel and zeolite 13X.(Yaningsih et al., 2018)By individually examining the effect of each parameter, the guidelines for developing a new adsorbent can be obtained.

II. TYPE OF GEOMETRY

The desiccant rotor consists of multiple channels of the matrix on the rotation axis of the desiccant rotor. The desiccant material is coated on the surface of the rotor structure; many types of airflow passages, like triangular, sinusoidal, hexagonal, sinus-soidal, and square shapes, are

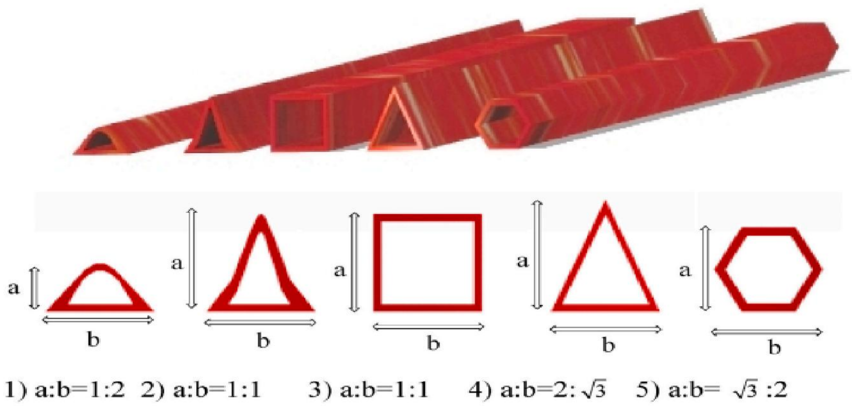


Figure 2 : Rotary desiccant wheel geometries [3]

used as a matrix in the desiccant rotor. They have found that different geometries performed differently, resulting in a different outcome under variable environment.(Bhabhor & Jani, 2021)

2.1 Wheel Speed

The desiccant wheel is the key component of a desiccant cooling system, and the optimum rotation speed is one of the most important factors that can improve the performance of the wheel. The rotation speed should not only be low enough for complete regeneration, but also be high enough to keep the adsorbent far from equilibrium. This conflict yields the optimum rotation speed. The existence of an optimum rotation speed, at which the humidity of the product air becomes minimized, has already been reported(Chung, 2016)

At the same process and regeneration air inlet conditions, process air outlet humidity depends on the wheel velocities. First, it is clear that at low speed the desiccant material remains for a long time in the process area, and its dehumidification capacity is exhausted before the material comes into contact with the regeneration air. Increasing the rotating speed, the adsorption capacity is better exploited, and water content in outlet process air reaches a minimum. If, however, we continue to further increase the speed, desiccant material comes to not use all its adsorption capacity because the time spent in the process area is too short concerning the adsorption time constant. In such a case, the process is dominated by heat transfer and the dehumidification rate decreases(Rambhad et al., 2021).

2.2 Working of the Wheel

While the wheel is rotating, it is also traversed by two different airflows in opposite directions: these are the process airflow and the regeneration one. Process air at ambient temperature, flows throughthe process area, where a part of the water vapor contained in it, is adsorbed by the desiccant material of the wheel.

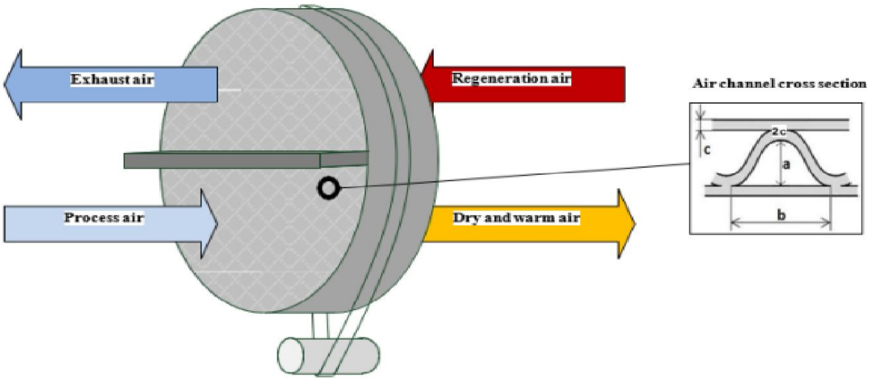


Figure 3 : Schematics of a desiccant wheel [18]

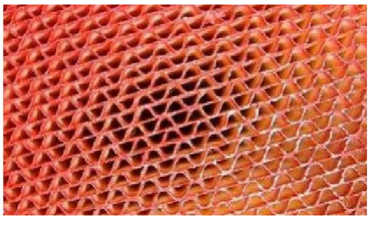
Regeneration air flows through a usually smaller area, called the regeneration area. Before the regeneration air passes through the wheel, it is heated up. During the regeneration process, water contained in the wheel is extracted from the desiccant by the airflow, and the desiccant is regenerated. The wheel rotation brings the desiccant material alternatively in the process area and the regeneration one. Passing through the regeneration area, the desiccant material is brought back to the condition it had when last entering the process area, and the adsorption/desorption cycle can start again. The adsorption capacity is thus intuitively foreseen to be a function of desiccant material, the angular speed of the wheel, process, and regeneration areas ratio, geometry of the wheel, and of course temperature, humidity, and velocity of the airflows. Therefore, the choice of the desiccant material plays a crucial role in the design of the wheel and significantly affects the performance of the whole air conditioning system(Rambhad et al., 2021)

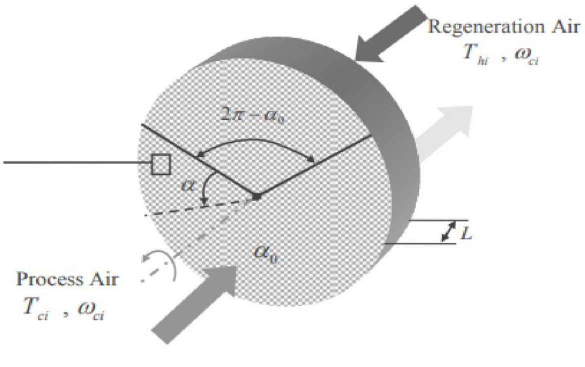
III. GOVERNING EQUATIONS

A rotary desiccant wheel is a cylindrical rotating wheel of length L and radius R which is divided into adsorption section (Angle fraction α0) and regeneration section (Angle fraction 2π-α0). The regeneration and adsorption section are in the counter flow arrangement. Generally, the wheel contains parallel small channels and desiccant material typically constructed in its wall of usually sinusoidal or hexagonal cross-section. The desiccant percentage content f in thickness is usually about 70-80 (%). To simulate a desiccant wheel, assume a single channel as shown in Figure 2 which rotates continuously with speed of N(rpm) between adsorption and regeneration section. The channel cross-section and perimeter are Aduct, Pduct respectively.

$\Theta = \text{mod}\ (\ \Theta_0 + 2\prod\omega t/3600, 2\prod\ )$ (1)

where mod is modulus, a symbol of the mathematical calculation for remainder after division. Herein, the elementary volume is located within the adsorption section if h is less than 2α∏; otherwise, it is located within the regeneration section(Heidarinejad et al., 2009)





(A) (B)

Figure 4: (A) Honeycomb Structure on Desiccant Wheel [18] (B) schematic of desiccant wheel. [10]

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The following assumptions are considered:

- No chemical reaction takes place in channels.
- The air flow in channels is incompressible.
- Heat and mass transfer along desiccant wheel and surrounding are negligible.
- The channel flow is laminar and fully developed.
- The specific heat and thermal conductivity of dry desiccant material are assumed constant.
- The concentration and porosity of sorption through channels are homogeneous.
- Heat and mass diffusion in radial direction are negligible.
- The rotary speed is uniform and low enough to neglect the effect of centrifugal force.

Heat and mass conservation equations for an unsteady-state wet air stream in a narrow duct are mathematically described in the following:

$$\frac{\partial \rho_g c_{pg} T_g}{\partial t} + \Psi \frac{\partial \rho_g c_{pg} T_g}{\partial \theta} + u_g \frac{\partial \rho_g c_{pg} T_g}{\partial z} = \Phi T + \Phi TM \ (2)$$

$$\frac{\partial \rho_g Y_g}{\partial t} + \Psi \frac{\partial \rho_g Y_g}{\partial \theta} + u_g \frac{\partial \rho_g Y_g}{\partial z} = \Phi M \ (3)$$

Where ΦT , ΦTM , and ΦM are source terms caused by heat and mass transfer between wet airflow and sorbent felt, respectively.

They are given as follows:

$$\Phi_T = \frac{h_t (T_f - T_g)}{f_v/f_s} \ (4)$$

$$\Phi TM = \frac{\rho_f h_m c_{pg} T_g (Y_f - Y_f^*(T_g, Y_g))}{F_v/F_s} \ (5)$$

$$\Phi M = \frac{\rho_f h_m \left(Y_f - Y_f^*(T_g, Y_g)\right)}{\frac{f_v}{f_s}} \ (6)$$

In the above equations, fv /fs is the ratio of volume to surface area and is equal to D/4. The ratio of f_v/f_sreflects the basic characteristics of flow passage shape. hm=ht/$\rho_f c_{pf} L_e$, and ht is determined by the Nusselt number ($Nu_D = h_t D/K_g$). The Le is the Lewis number. For air and water vapor mixtures, Le is 0.894. An air stream inside the small channels of the desiccant wheel is considered a fully turbulent flow (i.e., ReD > 2300). A classical expression for computing the local Nusselt number for fully developed turbulence in an internal flow may be obtained from the Dittus–Boelter equation. The equation is of the form found in Incropera and DeWitt: $Nu_D = 0.023Re^{0.8}{}_D prn$, where n = 0.4 for adsorption (Tf > Tg) and 0.3 for regeneration (Tf < Tg).

Unlike in the air channels, heat and mass transfer in the desiccant is dominated by both thermal conductivity and diffusivity. Thus, the equations of energy and mass conservation for the desiccant are described as follows:

$$\frac{\partial \rho_f c_{pf} T_f}{\partial t} + \varphi \frac{\partial \rho_f c_{pf} T_f}{\partial \theta} = \frac{\partial}{\partial z}\left(k_f \frac{\partial T_f}{\partial z}\right) + \Psi_T + \Psi_{TM} (7)$$

$$\frac{\partial \rho_f Y_f}{\partial t} + \varphi \frac{\partial \rho_f Y_f}{\partial \theta} = \frac{\partial}{\partial z}\left(D_s \frac{\partial \rho_f Y_f}{\partial z}\right) + \Psi_M \ (8)$$

where Ψ_T,Ψ_{TM} , and Ψ_M are source terms caused by heat and mass transfer between air flow and desiccant felt, respectively. They are given as follows:

$$\Psi_t = \frac{h_t}{\frac{\delta}{2}}(T_g - T_f)(9)$$

$$\Psi_{TM} = \frac{\rho_f q h_m}{\frac{\delta}{2}}\left(Y_f^*(T_g, Y_g) - Y_f\right) (10)$$

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$$\Psi_M = \frac{\rho_f h_m}{\frac{\delta}{2}}\left(Y_f^*(T_g, Y_g) - Y_f\right)(11)$$

3.1 Thermoproperties Model and Equilibrium Isotherm

The density, thermal conductivity, and specific heat of the fluid mixture in the process stream are given by the following equations:

$$\rho_g = (1 + Y_g)\rho_a \ (12)$$

$$k_g = \frac{\rho_a k_a + Y_g \rho_a k_v}{\rho_g} \ (13)$$

$$c_{pg} = \frac{\rho_a c_{pa} + Y_g \rho_a c_{pv}}{\rho_g} (14)$$

The properties of sorbent can be described as a function of desiccant porosity. Therefore, the density, specific heat, and thermal conductivity are given as follows:

$$\rho_f = (1 - \varepsilon_f)\rho_d + \varepsilon_f \rho_g \ (15)$$

$$k_f = \frac{(1 - \varepsilon_f)\rho_d k_d + \varepsilon_f \rho_g k_g}{\rho_f} \ (16)$$

$$c_{pf} = \frac{(1 - \varepsilon_f)\rho_d c_{pd} + \varepsilon_f \rho_g c_{pg}}{\rho_f} \ (17)$$

Since most heat and mass transfer between airflow and desiccant occur only on the solid surface of a desiccant particle, the effect of the diffusivities of combined ordinary and Knudsen diffusion is small compared with the surface mass diffusion. Therefore, in Eq. 6, only the surface mass diffusion is considered. The diffusioncoefficient, Ds, can be evaluated using the following expression(Majumdar, 1998; Niu et al., n.d.).

$$D_s = \frac{D_o}{\tau}\exp\left(-0.974e - \frac{3q}{T_f}\right) \ (18)$$

The system equation governing the dynamics of sorption has to be solved along with the equilibrium sorption isotherm of the desiccant, which is given by Majumdar (Majumdar, 1998)and is simplified as follows:

$$y_f^* = a_1 + a_2 T^2 + a_3 RH^2 + a_4 RH^3 + a_5 T^3 RH^2 + a_6 T^3 RH^3 \ (19)$$

Where, $a_1 = 0.0329$

$$a_2 = -4.113e - 6$$

$$a_3 = 1.05e - 5$$

$$a_4 = 6.586e - 7$$

$a_5 = 7.894\text{e-}11$

$$a_6 = 6.747e - 13$$

The relative humidity ratio is given by,

$$RH = 264.0727 Y_g / \exp\left(\frac{17.2694(T - 27\ 315)}{T - 34.85}\right)(20)$$

3.2 Boundary Conditions and Gross-Parameters Process

As discussed earlier, a desiccant wheel is a rotating cylindrical porous-medium wheel, where two air streams are blown in counterflow through an adsorption section and a regeneration section. Each elementary volume in the desiccant wheel alternates periodically between the adsorption and regeneration processes. The transient angle location of each elementary volume is described by Eq. 1.

Therefore, boundary conditions for airflows are given by,

If $0 \le \theta < 2\pi\alpha$

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Then, $T_{g,z=0}$, $T_{a,in}$, $Y_{g,z=0}$, $Y_{a,in}$
If $2\pi\alpha \leq \theta < 2\pi$
Then, $T_{g,z=L}$, $T_{r,in}$, $Y_{g,z=L}$, $Y_{r,in}$(21)
For boundary conditions for the desiccant felts, assume the surface of the desiccant is coated with a layer of insulating material. Hence, the boundary conditions are given by,

$$\frac{\partial T_f}{\partial z}|_{z=0} = \frac{\partial T_f}{\partial z}|_{z=L} = \frac{\partial Y_f}{\partial z}|_{z=0} = \frac{\partial Y_f}{\partial z}|_{z=L} = 0 \ (22)$$

In addition, the overall values of the temperature and moisture content of supply air are evaluated, after the outlet of each section in the desiccant wheel, using the following expressions:
If $0 \leq \theta < 2\pi\alpha$

$$T_{a.out} = \frac{1}{2\pi\alpha}\int_0^{2\pi\alpha} T_g(\theta, L)d\theta$$

AND

$$Y_{a.out} = \frac{1}{2\pi\alpha}\int_0^{2\pi\alpha} Y_g(\theta, L)d\theta(23)$$

If $2\pi\alpha \leq \theta < 2\pi$

$$T_{r.out} = \frac{1}{2\pi(1-\alpha)}\int_{2\pi\alpha}^{2\pi} T_g(\theta, 0)d\theta$$

AND

$$Y_{r.out} = \frac{1}{2\pi(1-\alpha)}\int_{2\pi\alpha}^{2\pi} Y_g(\theta, 0)d\theta \ (24)$$

These boundary conditions are based on the impermeable surface of the desiccant wheel. The gross process ignores the effect of the profile of moisture and density along the wheel. These simplifications are considered in order to avoid the complexity of the system, and the result is reasonably accurate.(Gao et al., 2005)

3.3 Performance Criteria of a Solid Desiccant Wheel

A solid desiccant wheel is designed for the purpose of producing a low humidity environment, and its performance is expressed in terms of thermal effectiveness, Ɛt, dehumidification efficiency, ƞD□, and moisture removal rate,ṁw . The thermal effectiveness as expressed in Equation (25) is defined as the ratio between the temperature of the process(Kamsah et al., 2016)
air and the maximum available temperature difference across the wheel.

$Ɛ_t = (T_{2`} - T_1) / (T_3 - T_1)$ (25)

The dehumidification efficiency measures the deviation of actual desiccant wheel performance from the idealized isenthalpic behavior and is described in Equation (26).

ƞD□ = $(\omega_1 - \omega_{2`}) / (\omega_1 - \omega_{2,ideal})$ (26)

While the moisture removal rate of the process air is derived from the mass balance analysis on the wheel and is shown in Equation (27).

$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_{2`})$
$= \rho A_c V(\omega_1 - \omega_{2`})$ (kg/s) (27)

where T and ω are the temperature and specific humidity of the air, respectively. While ρ, A_c, V and are the air density, air velocity and cross sectional area of the ducting pipes, respectively. During the analysis, several assumptions are adopted as follows:

1. The wheel experiences a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process.
2. Dry air and the water vapor are ideal gases.
3. The kinetic and potential energy changes are negligible.
4. The air flow is a one dimensional flow.

3.4 Commercially Available CFD Method

In order for one to solve the CFD equations of computational fluid dynamics first their numerical data must be generated. This is done by a method so-called discretization. In the discretization method, each term within the equation describing the fluid flow is written in a way the computer can be programmed to solve the equations. There are various methods for CFD numerical discretization. In this section of the thesis three of the universally used methods will be introduce, namely: (1) the finite difference method, (2) the finite element method and (3) the finite volume method(White, 2013).

Commercially available widespread CFD codes use one of three basic methods:

1. Finite differences method (FDM) (Structured meshes)
2. Finite volumes method (FVM) (Unstructured meshes)
3. Finite elements method (FEM) (Structured meshes)

A. The Finite Differences Method (FDM)

The finite difference method is one of the earliest methods to be used in numerical solution. This method is thought to have been developed by Euler in (1768)which was used to develop numerical solution for differential equations by hand. This method was then adapted for CFD simple codes. In theory the finite difference methods can be applied to any type of mesh system. However this method is more commonly applied to structured meshes since it requires a mesh having a high degree of uniformityThis method has a set of finite points, so-called nodes, and the Navier-Stokes equations are enforced at these points. The equations take the shape of templates which describe velocity and pressure values at one node to the values at neighbouring nodes. Creation of the templates needs that the nodes be attached in a arranged finite mesh, so that each node recognize its neighbour's see figure(White, 2013)

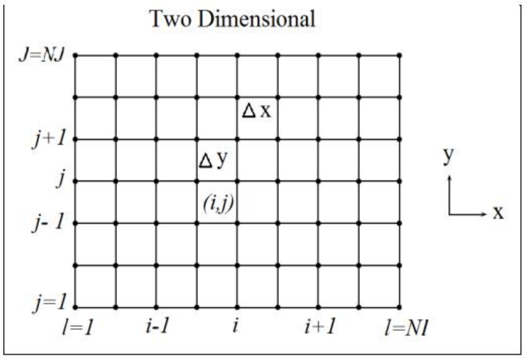

Figure 5: Illustration of a two dimensional equally distributed mesh for the finite difference method[24].

B. Finite Volumes Method (FVM)

The finite volume method was developed by researchers such as McDonald and Mac Cormack (1971) and (1972)for the solution of two dimensional time- dependent Euler equations and was later extended to three dimensional flows by Inouye and Rizzi. The advantage of the finite volume method is that it is not limited to one mesh method because it works with control volumes and has the capacity to accommodate any type of mesh. Including unstructured meshes allows it to have a large number of options for the definition of shape and location of control volumes. This method offers greater flexibility for handling complex geometries. Another attractive feature is that this method requires no transformation of the equation in terms of body fitted coordinate system as shown in figure.6 (White, 2013)

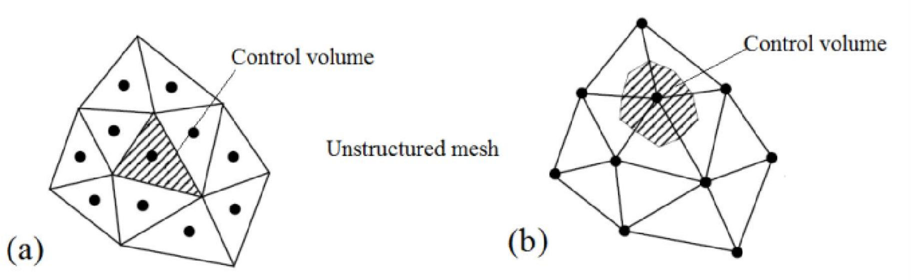

Figure 6 : (a) Mesh and dual mesh of cell FVM (b) Mesh and dual mesh of vertex FVM[24].

C. Finite Elements Method (FEM)

The finite element is one of the earliest use was by Courant (1943)for solving a torsion problem. The method was then refined significantly in the 60's and 70's, mostly for analysing structural mechanics problem. FEM analysis of fluid flow was developed in the mid- to late 70's. One of the advantages of this method it has a high accuracy on coarse mesh it can also be used for diffusion dominated problems (viscous flow) and viscous, free surface problems. Disadvantages of this method slow performance for large simulation problems and is not well suited for turbulent flows simulation modelling figure.7

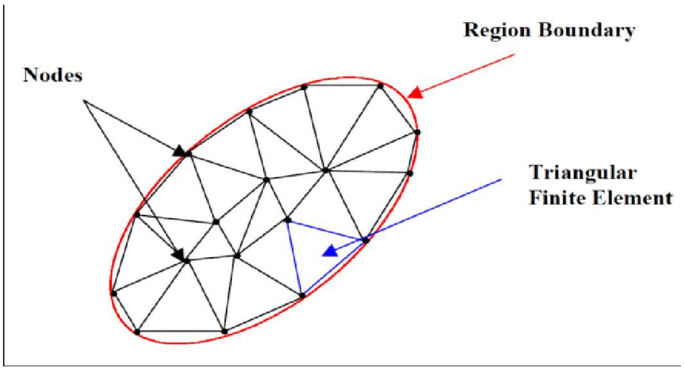

Figure 7 : Two-dimensional region subdivided in finite elements[23].

3.5 The three main CFD Elements

Enclosed in all CFD software codes are three main elements: (1) a pre-processor, which is used to input the flow parameter and the boundary conditions of the intended model. (2) A flow solver, which is used to solve the governing equations of the flow data subject to the setting provided. (3) A post-processor, which is used to manipulate the data and show the results in graphical and easy to read layout.

A. Pre-processing

All the tasks that take place before the numerical solution process are called pre-processing. This includes problem assessment, meshing and generation of a computational model. Problem assessment is the first stage in using CFD in this stage the engineer considers the flow problem, the second stage is meshing. Where the engineer create the geometry of the domain that needs to be analysed. Then the problem domain is sub-divided into smaller cells, also known as volumes or elements(White, 2013)

B. Solver

When a mesh is completed with its grid density and all other complications resolved, the actual computational part of the CFD can be started. At this point the completed geometry can be imported into the solver and the CFD simulation is

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started. Again, a series of steps are to be performed; first, the boundary conditions on the system need to be set and next the process iteration parameters need to be set. With the boundary conditions defined the simulation can be performed. The final step in obtaining the desired data is the post-processing of the data in which the desired data sets are taken from the simulation(White, 2013)

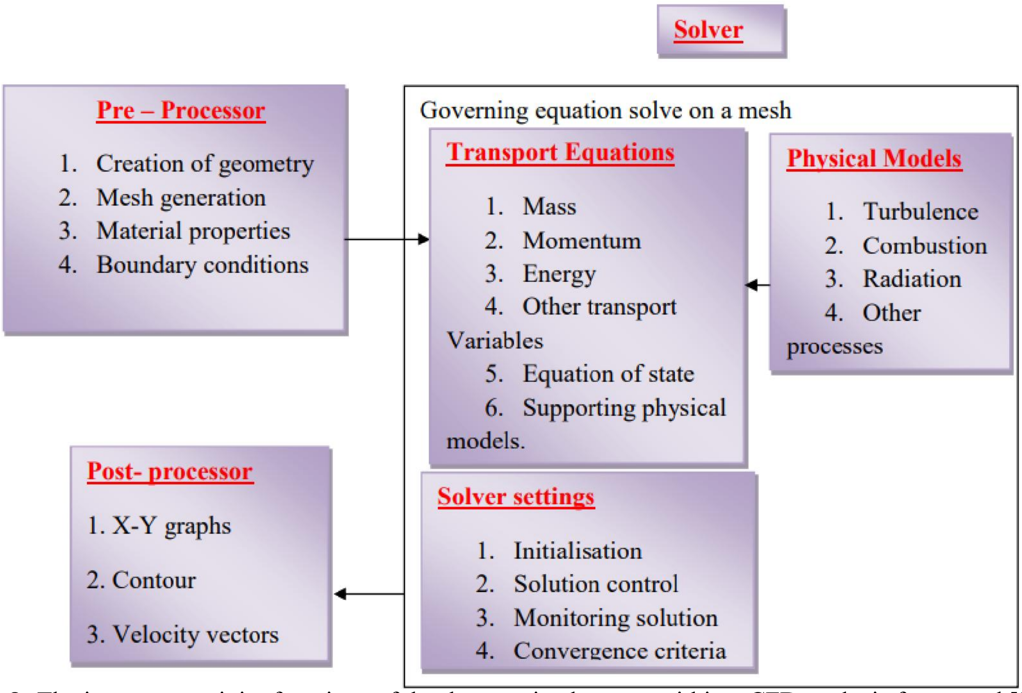

Figure 8: The inter connectivity functions of the three main elements within a CFD analysis framework[24].

C. Post-processing

The post-processing program is used to evaluate the data generated by the CFD analysis. When the simulation has converged the last data set is stored as a final solution. This data set has a record of the status of all elements in the model, temperature, densities, pressures, flow aspects etc. To be able to interpret the data it needs to be ordered and reduced to comprehensible sizes. This displaying of the data is called post-processing and makes it possible to compare the different simulations with each other and with external data. There are as many ways of displaying the data as there are data points so it is important to select the data representation that is required for the desired data comparison. Some of the standard visualization options available are contour plots and velocity vector plots. Contour plots will give a plot in a defined collection of control volumes which can be a plane or a volume, ofcontours of another variable. For example a plane can be defined as a constant x-coordinate plane (y-z plane); we can then make a contour plot showing temperature contours in this plane.

In the same plane a velocity contour plot can be made showing absolute velocities of the fluid in the defined plane. Other variables that can be used for contour plots are magnitude of velocity components turbulence components and local pressure. Velocity vector plots can be made to get an insight into the flow patterns in the overall geometry or detailed at specific locations. The density and magnification of the velocity vectors in the specified field can be manually changed to get a most optimal picture.

The field density has a maximum limitation, the amount of elements in the model. Besides these qualitative data export methods it is also possible to export the numerical data in many different forms. Direct export of selected data sets is facilitated for a number of external applications. It is also possible to export data in Parasolid format for further manipulation. Another method for exporting the numerical data is the two-dimensional plot function in which two data sets can be plotted against each other. This function is useful when, for example, radial velocity or temperature profiles need to be compared. From different simulations, identical plots can be created and a direct comparison of the numerical data is possible(White, 2013)

3.6 Imposing Boundary Conditions Inlet and Outlet :

The boundary conditions take into account numerous elements that affect the behaviour of fluids and help to visualize them through 3D simulation. Some of these elements consist of mass transfer, heat flow, and changes in gas to liquid and liquid to gas phases. Boundary conditions contribute to the understanding of what results are possible at the inlet and outlet of a model(White, 2013)

External Faces

1. Flow inlet and exit boundaries: pressure inlet, velocity inlet pressure outlet, outflow.
2. Wall repeating and boundaries: wall symmetry
3. Internal zones: fluid
4. Internal face boundaries porous media material like-silica gel etc;

3.6 Commercial off the Shelf CFD Simulation Software Packages

These are CFD packages developed and supported by commercial organizations the leading general purpose products are:

- Cosmos Flow Simulation
- Comsol Multiphysics
- Star-Cd
- Fluent
- Cfx

IV. CONCLUSION

The present article, the progresses related to desiccant cooling technology have been discussed along with advantages offered by this technology. The recent developments in different desiccant materials have also been presented.The absorbed water vapour is usually removed from the desiccant by regeneration in which desiccant is exposed to a regeneration airstream having temperature between 50 and 150°C.we use the Zeolite,DH-5,DH-7 instead of using silica gel for better a adsorption rate.

Nomenclature

- Cp-Specific heat (kJ/kgK)
- D-Characteristic length (m)
- Do-Constant for surface diffusion
- Ds - Effective diffusitivity (m^2 /s)
- fv/fs -Ratio of volume to surface area (m^3 /m^2)
- h_t - Heat transfer coefficient (w/m^2K)
- h_m- Mass transfer coefficient (w/m^2K)
- k - Thermal conducitivity (w/mK)
- Le - Lewis number
- Nu_D- Nusselt number
- Pr - Prandtl number
- q - Adsorption heat (kJ/kg_{water})
- Re_D- Reynolds number
- t - Time (s)

- T - Temperature (K)
- Y_g - Humidity ratio ($kg_{moisture}/kg_{dry\ air}$)
- Y_f^* - Equilibrium sorption isotherm ($kg_{moisture}/ kg_{desiccant}$)
- Y_f - Moisture content of desiccant ($kg_{moisture}/ kg_{desiccant}$)
- U_g- Velocity (m/s)
- z - Z coordinate (m)

Greek symbols

- α-Adsorption section angle fraction
- τ-Tortuosity factor
- θ-Angle coordinate
- θ_o-Initial angle coordinate
- ρ-Density (kJ/m^3)
- ω-Rotational speed (rph)
- $\emptyset$-Rotational speed (Rad/s)

Subscripts

- a Adsorption or air
- d Dessicant
- f -Felt
- g -Wet air
- in - Inlet
- m - Mass transfer
- out - Outlet
- r - Regeneration
- t - Heat Transfer
- v - Water vapour

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