Review of Energy Efficient Cooling Techniques Based on Various Evaporative Cooling Systems

[1]Ranjeeta Ghosh, [2]Archana Mirashi

[1,2] PVG's College of Engineering and Technology, Vidyanagari, Parvati, Pune – 9

Abstract - This review paper explores the potential of evaporative cooling for reducing the energy consumption due to air conditioning. It also greatly reduces the CFC gas emissions caused in conventional air conditioning making it an environmental friendly alternative for air conditioning. The possibilities of using evaporative air cooling in different combinations and configurations in order to increase the effectiveness have been discussed here. Two- stage evaporative cooling like desiccant based evaporative cooling seems to have good potency for its use in tropical climate. The feasibility of using these systems in various climatic conditions needs to be evaluated.

Keywords - Direct evaporative cooling, desiccant, heat pipe, indirect evaporating cooling

I. INTRODUCTION

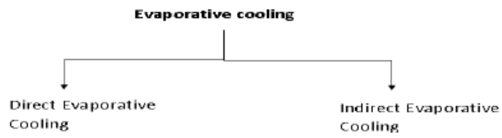
Evaporating cooling technology is re-emerging out as an energy efficient cooling technique to overcome the tribulations of energy crisis and negative environmental impacts due to the CFC emissions released in the conventional air-conditioning systems.

In case of evaporative cooling, evaporation of a liquid (usually water) into gas (water vapour) causes the absorption of heat (latent heat of evaporation). This absorption of heat during the phase change causes the cooling of the surrounding air or an object or a liquid in contact with it. Water is an excellent coolant because it is plentiful, non-toxic, and evaporates easily in most climates. It has been estimated that six gallons (22.7 L) of evaporating water has the same cooling effect as a typical (3.5 ton-hour) home central air-conditioner.

II. EVAPORATIVE AIR COOLING

Evaporative cooling is a process which uses the effect of evaporation for cooling of air. Sensible heat from the air is used to evaporate the water resulting in cooling of the ambient air. The temperature of the product air mainly depends upon the difference in Wet Bulb Temperature (WBT) [1] and Dry Bulb Temperature (DBT), higher the Wet Bulb depression (DT=DBT-WBT) [2], cooler the product air.

Evaporative Cooling is broadly classified into two types as shown below.



A. Direct Evaporative Cooling (DEC)[3][4][5][6][7]

In this, the air temperature reduces due to direct contact of air with water or a wet solid surface or using spray systems.

The outside hot air is blown through a water saturated evaporative pad as shown in fig.:1. As the water vaporizes, heat and mass transfer between air and water takes place. This increases the humidity ratio and relative humidity, where as the enthalpy remains constant as no heat is added or taken out of the air. Thus it is an adiabatic cooling technique in which sensible heat of air is converted into latent heat of evaporation of water.

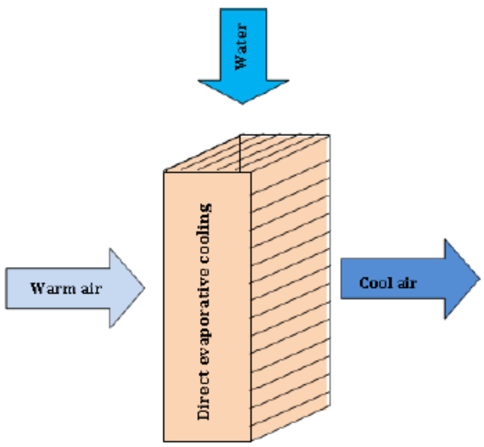


Fig 1 : Direct evaporative cooling (DEC)

Hence, dry bulb temperature (DBT) reduces, but wet bulb temperature (WBT) remains constant as shown in the psychrometric chart in Fig.2. The minimum dry bulb temperature which can be reached in this process is the wet bulb temperature of the incoming air. For an example: Let the dry bulb and wet bulb temperature of incoming primary air be 86^0F and 66^0F respectively. After passing through the wet evaporative pad, water vapour is added to the product air reducing the DBT to

68^{0}F and WBT remains constant (adiabatic cooling)[8]. Since moisture is added to the product air in the process of cooling, the direct evaporative cooling is more suitable for hot and dry climate.

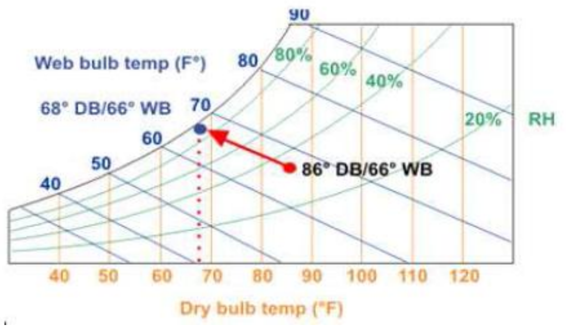


Fig-2: Psychrometric chart Direct Evaporative cooling [8]

B. Indirect Evaporative Cooling (IEC)[3][4][5][6][7]

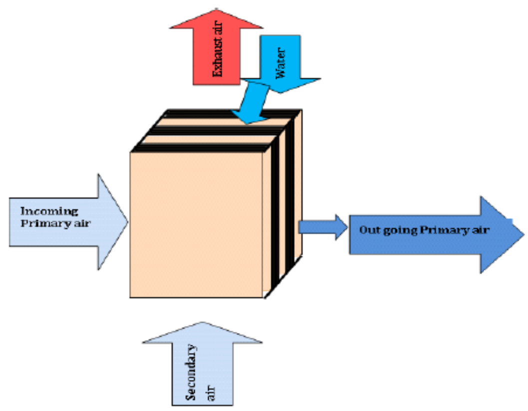


Fig 3 : Indirect evaporative cooling

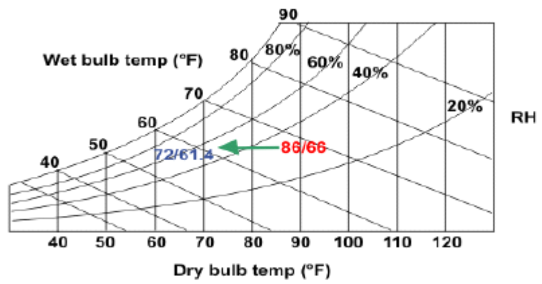


Fig-4: Psychrometric chart for indirect evaporative cooling[8]

Indirect evaporative cooling process involves two air streams, one primary or product air stream and the other secondary or working air stream. The working air stream is cooled by water using direct evaporative cooling and it is passed through the heat exchanger(cross flow[9]) where, it cools the primary air without coming in its direct contact. This reduces DBT and WBT of primary (product) air. Due to the heat transfer between secondary and primary air through heat exchanger, the secondary (working) air becomes hot and moist and is exhausted from the building. For example: Let the dry bulb and wet bulb temperature of incoming primary air be 86^{0}Fand 66^{0}F respectively. After passing through the heat exchanger its DBT reduced to 72^{0}F and WBT reduced to 61.4^{0}F[8].

Here, no moisture is added to the primary (product) air, hence, humidity ratio remains constant whereas the relative humidity increases. The minimum dry bulb temperature of the product (primary) air which can be reached is the wet bulb temperature of the secondary (working) air.

The effectiveness of the indirect evaporative cooling is determined mainly by the efficiency of the heat exchanger. In practice, direct evaporative cooling process typically delivers cooler air than indirect process due to inefficiencies of heat exchangers in an indirect cooling process. But direct evaporative cooling cannot be used in tropical climates as it does not provide comfortable cooling due to the addition of moisture in air.

So the process of indirect and direct evaporative cooling can be combined to improve the quality of the product air and efficiency of the system.

Effectiveness : It is defined as the ratio of actual temperature drop to the maximum possible temperature drop of air when it passes through the cooling system.

$$Effectiveness = \frac{Actual\ temperature\ drop}{Maximum\ possible\ Temperature\ drop} \quad - (1)$$

Evaluation of evaporative cooling system can be done by Feasibility index method (FI). It is defined as

FI = DBT – DT --------------------------------(2)

where DT =DBT – WBT -------------------(3)

It is a fast method to evaluate approximately the potential of the evaporative cooling. This index decreases as the difference between DBT and WBT increases i.e as air relative humidity decreases[3].

FI< 10 is effective for comfort cooling

10< FI<16 is effective for relief cooling

FI>16 is not effective for cooling[3]

In order to increase the effectiveness of evaporative cooling, different combinations of indirect and direct evaporative cooling can be done.

C. Some Combined Systems

i. Indirect-Direct evaporative cooling/ Two-stage evaporative cooling (IDEC)

ii. Indirect-indirect evaporative cooling

iii. Combination of Thermodynamic heat exchanger and evaporative cooling -Maisotsenko cycle or M. cycle

i. Indirect-Direct Evaporative Cooling (IDEC)[3]

This is a two stage process in which the secondary air stream sensibly cools the primary air in the first stage in an indirect process thus reducing both DBT and WBT as shown in Fig. 6. This cooled primary air stream is then further cooled by direct evaporative cooling.

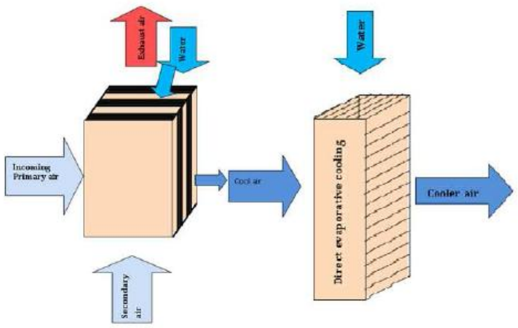


Fig5: Indirect-direct Evaporative cooling (IDEC)

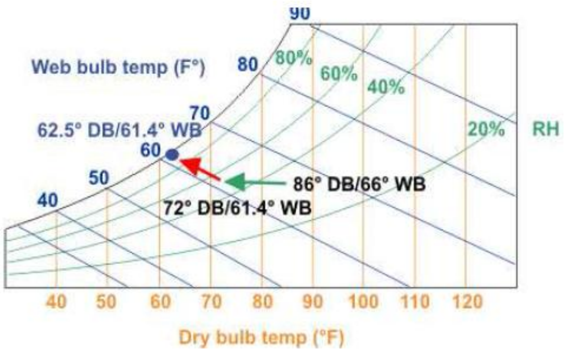


Fig-6: Psychrometric chart for Indirect-direct evaporative cooling [8]

For an example: Let the dry bulb and wet bulb temperature of incoming primary air be 86^{0}Fand 66^{0}F respectively. After passing through the IEC heat exchanger, its DBT is reduced to 72^{0}F and WBT is reduced to 61.4^{0}F. [1] Then this air is passed through DEC system where its DBT is reduced to 62.5^{0}F and WBT becomes 61.4^{0}F[8].

It can be operated effectively in a wider range of climates than the direct or indirect evaporative cooling systems and energy cost is lower than those of conventional vapour compression air conditioners.

The dry bulb temperature of the outgoing primary product air may be brought down below the WBT of incoming primary air. In this case, both Humidity Ratio and Relative Humidity increases.

ii. Indirect-Indirect Evaporative Cooling

Here, the primary air stream is cooled by indirect evaporative cooling in the first stage. Then for the second stage cooling, the cooled excess water from the first stage is used in the wet side of the second stage cooler. Hence in the second stage, the temperature of the air can be reduced below the WBT of secondary air. Here, no moisture is added to the primary air and the additional sensible heat is removed from the primary air stream in the second stage.

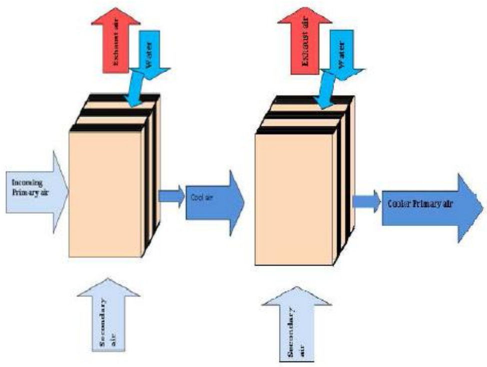


Fig7: Indirect-indirect evaporative cooling

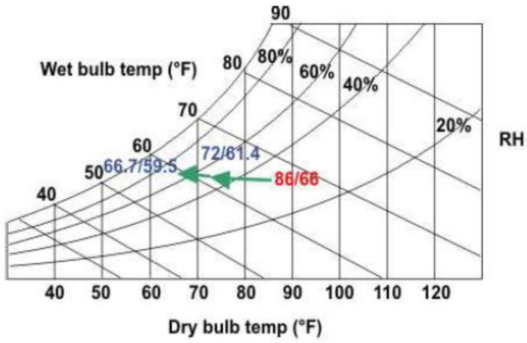


Fig 8: Psychrometric chart of Indirect-Indirect evaporative cooling[8]

For example: Let the dry bulb and wet bulb temperature of incoming primary air is 86^{0}F and 66^{0}F respectively. After passing through the IEC heat exchanger, its DBT is reduced to 72^{0}F and WBT is reduced to 61.4^{0}F [8]. Then this air when passed through another IEC system, its DBT is reduced to 66.7^{0}F and WBT becomes 59.5^0. In this system, the output product air is warmer than that in Indirect-direct evaporative cooling process

Effectiveness in cooling can be further enhanced by combining thermodynamic heat exchanger with evaporative cooling.

iii. Combination of Thermodynamic Heat exchanger and evaporative cooling -Maisotsenko cycle or M. cycle [10][11][12][13]

Maisotsenko cycle is a combination of thermodynamic heat exchanger and evaporative cooling with different airflow scheme. The Maisotsenko Cycle uses wet side and dry side of a plate as shown in Fig. 9 with a different airflow scheme creating a new thermodynamic cycle. This cycle causes the cooling of product air below its wet bulb temperature and towards dew point temperature of the incoming secondary air. The primary air (air-1) enters in the dry channel and is cooled due to indirect cooling and hence its WBT and DBT reduces. The temperature attained by the primary air is equal to the wet bulb temperature of the secondary air.

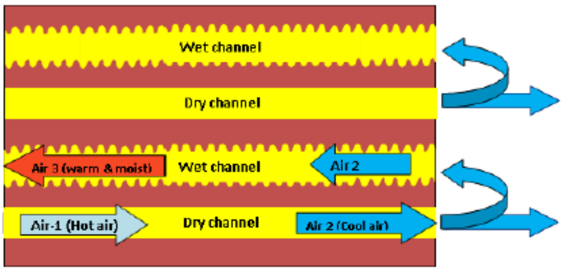


Fig 9: Maisotsenko cycle or M. cycle[10]:

A part of the outgoing product air (air-2) is diverted to wet channel which works as secondary air having lower wet bulb temperature than primary air. The secondary air takes the heat of the dry channel for the evaporation of water and hence, it becomes moist and hot. This moist and hot outgoing secondary air (air-3) is exhausted outside the system.

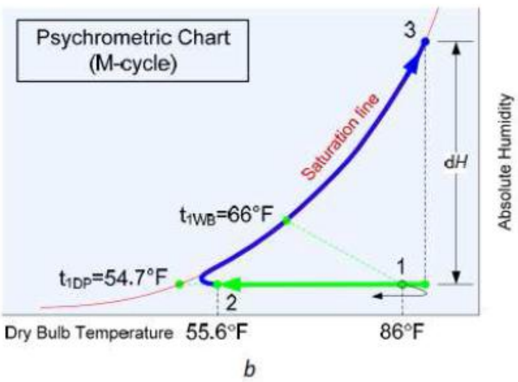


Fig 10: Psychrometric Chart of M-Cycle[10]

As far as cooling is concerned, these systems are very effective and energy efficient, but when it comes to comfortable cooling in tropical climates, moisture has to be controlled in the product air. This can be done by using desiccant systems in combination with evaporative cooling .

III. TWO-STAGE DESICCANT ENHANCED EVAPORATIVE COOLING SYSTEMS [14][15][16]

In desiccant enhanced evaporative cooling, the air is first dehumidified and then sensibly cooled to the necessary level using evaporative cooling. This system is basically open cycle system which uses a desiccant for dehumidification of air. For this purpose, liquid or solid desiccant systems can be used.

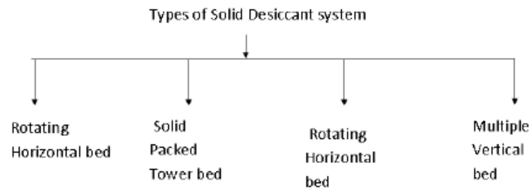
Desiccant: Desiccants are hygroscopic materials which adsorb or absorb the moisture. Thus they can be used for latent cooling in HVAC systems by dehumidification. They can be used in the form of solid (adsorption of moisture) or liquid (absorption of moisture).

The desiccants with a lower vapour pressure when subjected to moist air absorb/adsorb moisture due to the difference in vapour pressure. The extent of dehumidification depends on the vapour pressure difference between the desiccant and the air. As the air gets dehumidified due to adsorption/absorption of moisture, the vapour pressure of the desiccant increases, decreasing the effectiveness in attracting moisture further. So this saturated desiccant needs to undergo regeneration process, where the hot air is passed over the desiccant to reduce its vapour pressure.

Since the vapor pressure of the hot air is lower than the desiccant, the moisture is transferred from the desiccant to hot air stream. The moist hot air is then exhausted from the system into the outdoor air. The regenerated desiccant is now ready to attract moisture and is reintroduced into the process air path.

A. Solid Desiccant Systems

Solid desiccant traps moisture through the process of adsorption. e.g.: Silica gel. Based on the arrangement of solid desiccant beds in the system, solid desiccant systems are broadly classified as given below.



i. Rotating Horizontal Bed[14][15]

It consists of series of shallow perforated trays which rotate continuously between the process and reactivation air.

These trays are filled with dry granular desiccant which adsorbs moisture as the trays rotate through the process air (change from point 1 to point 2 in the equilibrium diagram).

Then the trays are made to rotate into hot reactivation air stream which heats the desiccant, increasing the vapour pressure and releasing the moisture into air (change from point 2 to point 3 in the equilibrium diagram).

The desiccant is then cooled by the process air and this corresponds to the change from point 3 to point 1 in the equilibrium diagram.

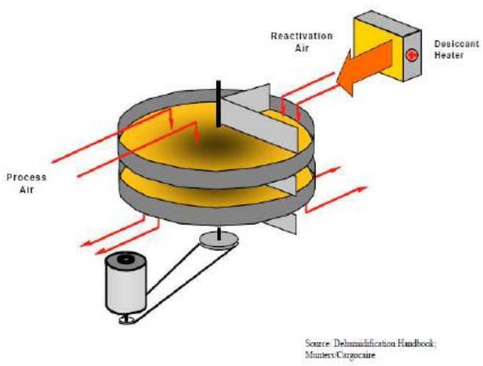


Fig 11: Rotating horizontal bed [14]

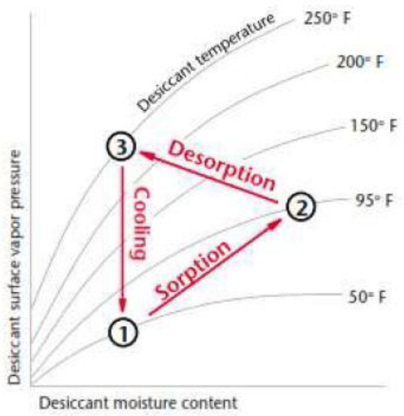


Fig 12 : Equilibrium diagram for Rotating Horizontal bed : [14] [15]

ii. Solid Packed Tower

It consists of vertical tower filled with solid desiccants like silica gel or molecular sieve. When the process air flows through the tower, the dry desiccant adsorbs the moisture from the process air (change from point 1 to point 2 in the equilibrium diagram). The process air is then diverted to a second drying tower. The first tower containing the desiccant saturated with moisture is heated with a small reactivation airstream. This raises the vapour pressure and moisture from the desiccant is released into the air (change from point 2 to point 3 in the equilibrium diagram).

The hot and dry desiccant is then cooled to lower its vapour pressure by cooled (change from point 3 to point 1 in the equilibrium diagram.)

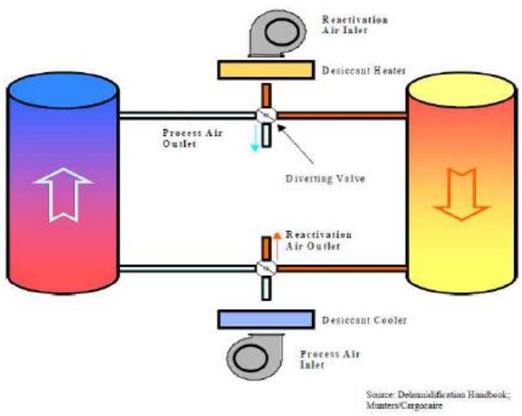


Fig 13: Solid packed tower [14][15]

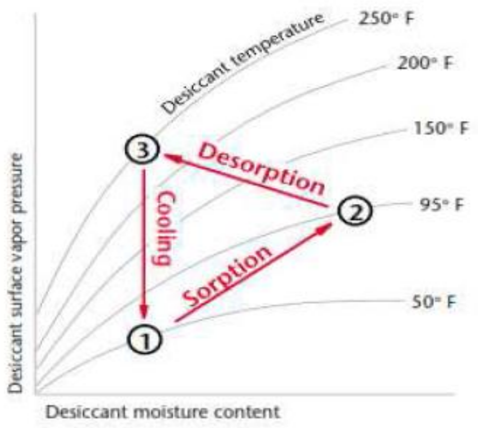


Fig 14: Equilibrium diagram for Solid packed tower: [14]

iii. Multiple Vertical Bed

It is the combination of packed tower and rotating horizontal bed designs with their better features incorporated in the multiple vertical bed system.

The granular desiccant beds are vertically arranged than in flat trays combining the advantages of packed tower and rotating trays. The double tower is replaced by a circular carrousel with eight or more towers which are rotated by ratcheting drive system between process and reactivation air streams.

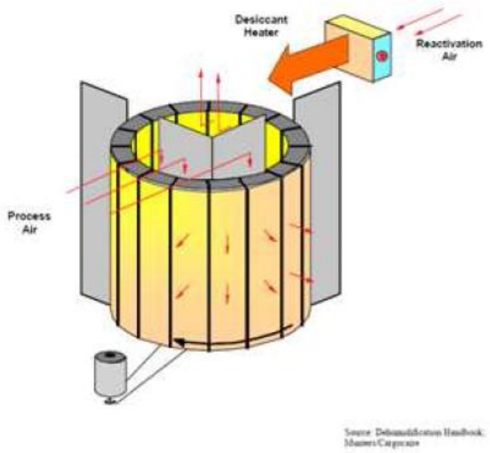


Fig 15: Multiple Vertical bed [14][15]

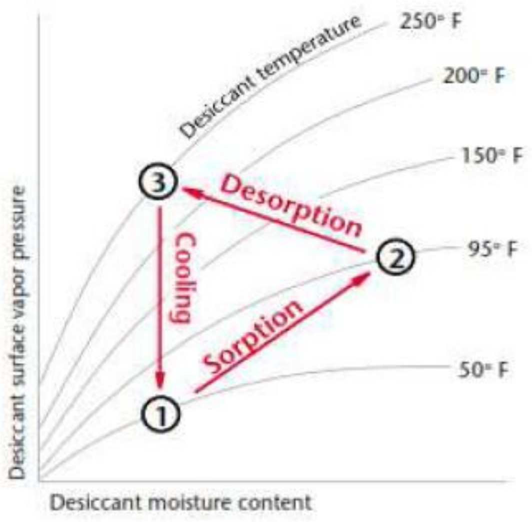


Fig 16: Equilibrium diagram: Multiple Vertical bed: [14]

iv. Rotating Honeycomb

This is also called DEW (Desiccant Wheel) and consists of a semi-ceramic structure which resembles corrugated cardboard and has the finely divided desiccant impregnated into it. This semi-ceramic structure is rolled into the shape of a wheel which rotates slowly between process air and reactivation air.

The process air flows through the flutes formed by the corrugations so that the desiccant in the structure adsorbs the moisture in the air. Thus desiccant gets saturated increasing its vapour pressure (change from point 1 to point 2 in the equilibrium diagram). Then as the wheel rotates into the hot reactivation airstream, the desiccant gets heated releasing the moisture into the reactivation air (change from point 2 to point 3 in the equilibrium diagram) . This hot desiccant then rotates back into the process air there by cooling the desiccant to collect more moisture (change from point 3 to point 1 in the equilibrium diagram)

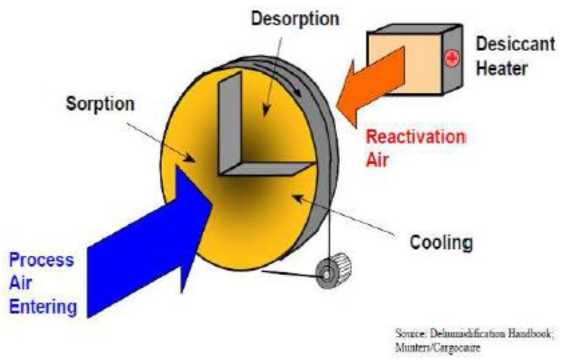


Fig 17: Rotating Honeycomb[14][15]

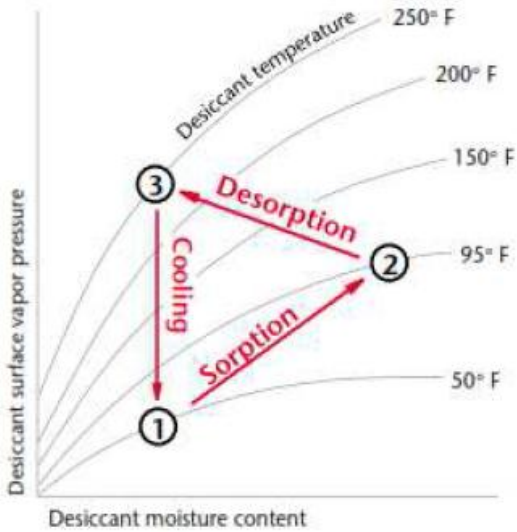


Fig 18: Equilibrium diagram: Rotating Honey comb: [14]

B. Liquid Desiccant System

i. Liquid spray tower

The spray tower dehumidifier unit sprays the liquid desiccants like Calcium Chloride or Lithium Chloride into the air to be dehumidified called the process air. The desiccant after absorbing the moisture falls into the sump. The liquid is sprayed back into the air absorb the moisture further and eventually becomes saturated (change from point 1 to point 2 in the equilibrium diagram.) This saturated liquid desiccant should be regenerated. This is done by circulating the part of the solution through heater. The hot desiccant is sprayed into a second airstream called the reactivation air. The large vapour pressure forces the moisture out of the desiccant into the air (change from point 2 to point 3 in the equilibrium diagram.)

As the desiccant returns from the regenerator back into the sump, it is concentrated and hot with high vapour pressure. To cool down the desiccant, a part of the liquid is drawn out of the sump and is passed through the heat exchanger which is connected to a cooling tower or any other cooling system (change from point 3 to point 1 in the equilibrium diagram.)

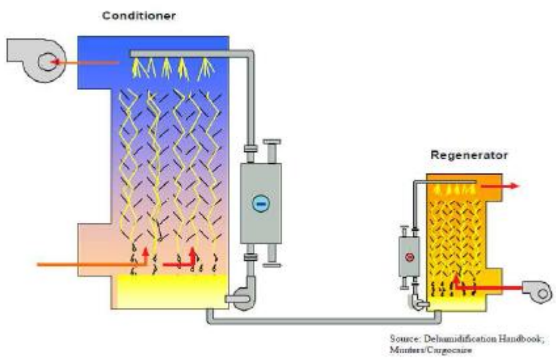


Fig.19 Liquid spray towers[14][15]

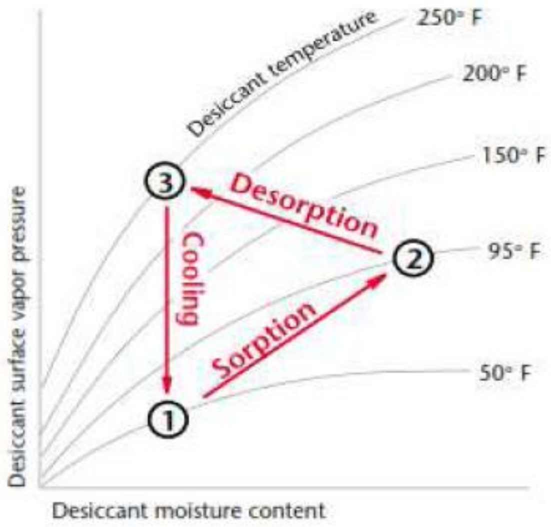


Fig 20: Equilibrium diagram of Liquid spray tower[14]

C. Solid Desiccant Enhanced Evaporative Cooling System[17]

This system consists of two subsystems, viz., desiccant dehumidification system and regenerative evaporative cooling system. Here, primary air is first dehumidified in the desiccant dehumidification system and then it is further subjected to direct evaporative cooling.

A typical solid desiccant enhanced evaporative cooling with regeneration system is as shown in Fig.21

The process air (1) when is passed through section I of a desiccant wheel, its moisture is removed and the air temperature is increased due to adsorption heat effect. This dry and hot air (2) is cooled sensibly by indirect evaporative cooling using cross flow heat exchanger (CHE 1) (2-3). Then the process air (3) is passed through section II of desiccant wheel where its moisture is further removed. When passed through another cross flow heat exchanger (CHE 2) (4 - 5), it is sensibly cooled further. To get conditioned air, the direct evaporative cooling (5-6) may be used.

Regeneration

It has two air paths (7-8-9-10-11) and (7-8-12-13-14) which works simultaneously in section III and IV. The regeneration air cycle is as follows. The air streams are humidified (7-8-9), (7-8-12) increasing the vapour pressure after passing through DEC and cross flow heat exchanger (CHE 1& CHE 2). The warm air stream is then further heated (9-10 & 12-13) by heater and is passed through section III & IV of desiccant wheel to regenerate desiccant and exit at points 11 &14 respectively.

Now this regenerated desiccant with low vapour pressure is ready for further dehumidification cycle. This system gives comfort cooling as the output product is conditioned air. The solid desiccant has a disadvantage that it requires a higher regenerating temperature mostly in the range of 60-115oC against a lower regenerating temperature in liquid desiccants in the range of 40-70oC. This allows the use of low grade heat like solar energy or waste heat. Also, the liquid desiccants have a better capacity to absorb moisture than solid desiccants [31]. Hence, solid desiccant systems may be replaced by liquid desiccant systems

D. Liquid Desiccant Enhanced Evaporative Cooling[18][19][20][21][22][23]

In liquid desiccant enhanced evaporative cooling, the dehumidification process is carried out by using liquid desiccants like Lithium Chloride or Calcium Chloride. In this process, vapour pressure difference between desiccant and air plays a vital role. The concentrated desiccant first gets diluted due to absorption of water vapour from air. The dehumidified hot air is then passed through different types of heat exchanger, where it is sensibly cooled.

A typical liquid desiccant enhanced evaporative cooling with solar regeneration system is as shown in Fig.21. The hot and humid air (a) is passed through a liquid desiccant dehumidifier (b), where concentrated liquid desiccant absorbs water vapour from the air. Here, the air and liquid channels are kept isolated by semi-permeable micro porous membranes, which allow only the water vapour to pass through it and hence eliminate the carryover of the liquid desiccant into the supply air. When the vapour pressure of the air exceeds the vapour pressure of the liquid desiccant, then the water vapour reaches the desiccant through the membrane and air gets dehumidified and heated. The dehumidified hot air then is passed through a heat exchanger (c) which uses chilled water from a cooling tower, where it is sensibly cooled. This air is passed through indirect evaporative cooler for further cooling. The cold and dehumidified air is delivered to the room (f) via fan (e). The humidified dilute desiccant from Desiccant humidifier (b) must be thermally regenerated for further use[18].

Regeneration/ Reactivation of liquid desiccant

Dilute desiccant from the dehumidifier (b) is preheated in the solution-solution heat exchanger (i) by using heat from the hot concentrated desiccant and is stored in a tank (p). The preheated dilute desiccant is then pumped to a plate heat exchanger (k) where it is further heated by hot water from the hot water tank (m) connected to solar heater (l). This hot dilute desiccant is made to flow through the regenerator (j) where it releases water vapour to the air stream due to the vapour pressure difference. The concentrated hot desiccant from the regenerator stored in a tank (o) and then pre-cooled in the solution-solution heat exchanger (i). The exchanger (h) and cooled by water from the cooling tower (g).solution is then pumped into plate heat This cooling helps in increasing the vapour pressure difference between air and concentrated desiccant which ensures higher dehumidification[18].

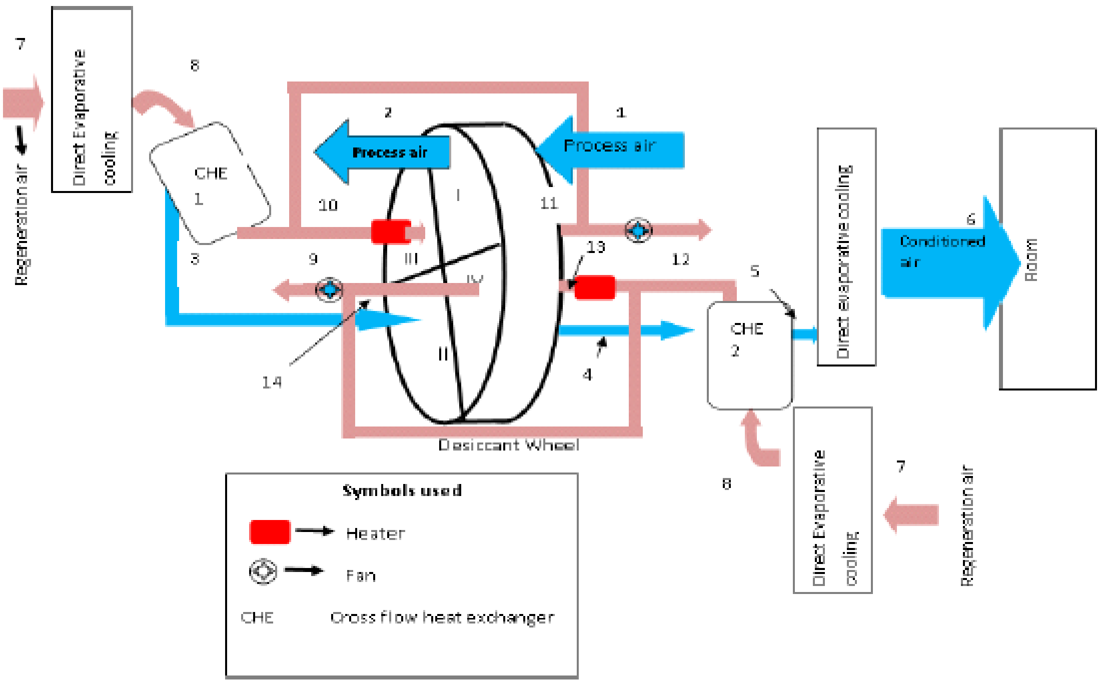


Fig 21: Solid Desiccant enhanced evaporative cooling system

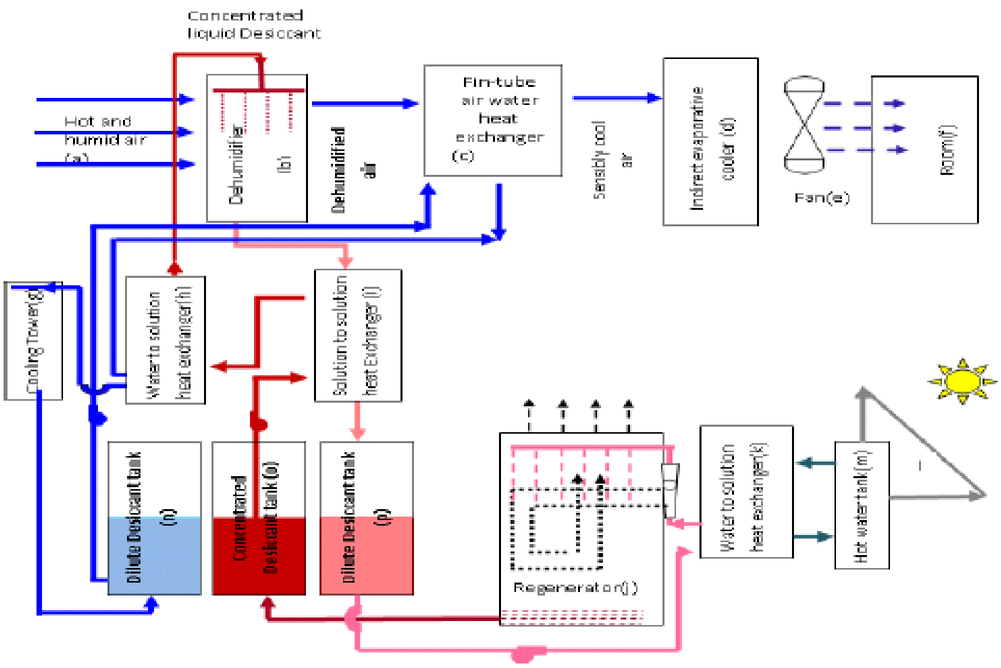


Fig 22 : Liquid desiccant enhanced Evaporative cooling with solar regeneration

IV. INDIRECT EVAPORATIVE COOLING USING HEAT PIPE [8][23][24]

Heat pipe is a heat transfer element with closed evaporator section and condenser section having extremely high thermal conductivity.

It mainly consists of sealed hollow tube whose inside walls are lined with capillary structure or wick. Here, the heat transfer takes place through latent heat of phase change of the working fluid inside the sealed vacuum tube.

The working fluid with sufficient vapour pressure at desired operating temperature saturates the pores of the wick/ capillary structure. In a state of equilibrium between liquid and vapour, when heat is given to a heat pipe, the liquid in the wick evaporates as the evaporating fluid fills the heat pipe's hollow center diffusing through the length of heat pipe.

Wherever the temperature is even slightly below that of the evaporation area, condensation of the vapour occurs.

As the vapour condenses, it gives up the heat acquired during evaporation. Capillary action within the wick transfers the condensate to the evaporator section (heat source) and completes the operating cycle.

In a typical gravity heat pipe, the upper end of the heat pipe releases heat as the working medium is condensed into the liquid. The condensed liquid with the pull of the gravity returns to the hot end along the inner wall of the heat pipe. It will be heated and vapourized again thus transferring the heat from one end to the other end successively.

Thermal resistance of the heat pipe is very small resulting in larger heat transfer capacity at a smaller temperature difference.

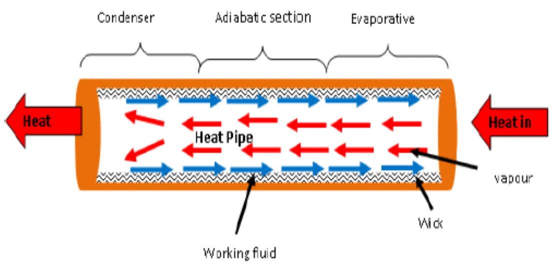


Fig 23: Heat Pipe

Indirect Evaporative Cooling Using Heat Pipe[8][24]

In this heat pipe based IEC, the condenser section of heat pipe is introduced into the secondary air channel and evaporator section is introduced in the primary air dry channel as shown in Fig. 24[24]

The porous ceramic filled with water is used to produce coolness in the condenser section of heat pipe. When the outside air passes through the pores of the ceramic it causes water to evaporate creating cooling effect.

The primary air stream is cooled when it passes across evaporator section of the heat pipe as its heat is absorbed by the working fluid for its evaporation. The vapour then condenses at the condenser section by giving up its heat to the water in the ceramic. The heat pipe used acts as a heat exchanger and transfers the coolness to the primary air.

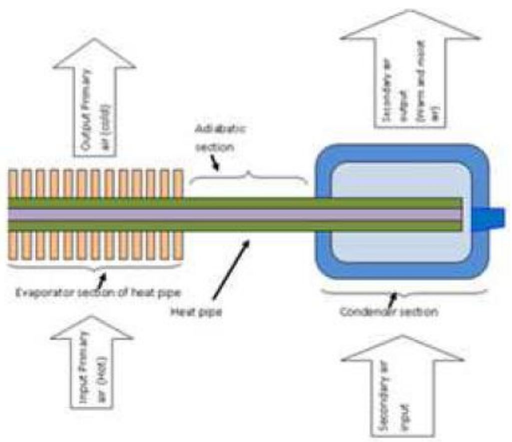


Fig 24 : Heat Pipe based Evaporative cooling system

V. CONCLUSION

Evaporation as a basic mechanism with water used as a refrigerant is proving out to be the most environmental friendly way of cooling and conditioning the air.

Evaporative cooling has shown to have a good potential in energy saving. The effectiveness of the evaporative cooling systems can be enhanced by using it in different configuration/combinations as discussed in the review paper. But complexity of the system and the initial cost are the major constraints.

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