Performance and Analysis of an Evaporative cooling System : A Review

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Abstract: This paper represents working principles, and performance of evaporative cooling technology under broad range of operating conditions. The effectiveness of evaporative cooling in different application can be discussed in this paper and benefits in terms of power consumption, cost savings and environmental impacts, specifically for the facility required to support conventional air-conditioning and the facility required to support space cooled via evaporative cooling. This paper also discusses desiccant assisted evaporative cooling and heat and mass transfer analysis. The superior cooling of air and ventilation can be provided by evaporative cooling system while consuming less energy and also provides environmental friendly cooling technologies.

Keywords: Evaporative Cooling, Effectiveness, Performance, Energy Saving

1. Introduction

Evaporative cooling is a physical phenomenon in which evaporation of a liquid, typically into surrounding air, cools an object or a liquid in contact with it. Evaporative cooling occurs when air, that is not too humid, passes over a wet surface; the faster the rate of evaporation the greater the cooling. Evaporative cooling effect is provided by the adiabatic evaporation of water. Water used as a coolant and also as the working substance that can meet many air conditioning needs in both residential and commercial applications. It can work more effectively in hot and dry climates and provides 100% fresh and cooled air to the space. In this technology, heat is removed due to forced convective process. It brings the comfort by increasing the humidity in dry climates, improves the air quality, and makes the air more breathable. The most familiar example of this is cooling effect of evaporating perspiration on the human skin. In arid, hot climates body temperature is partially controlled by the rapid evaporation of perspiration from the surface of the skin. In hot climates with high atmospheric moisture, the cooling effect is less because the high moisture contents present in the surrounding air. In both situations, high humid and hot and dry climate condition, however, the evaporation rate is raised as air movement is increased. Both of these facts can be applied to natural cooling of structures.

Evaporative cooling is an environment friendly technology. In this Technology water is used as a working substance which is free from CFC's and it doesn't cause greenhouse gas emission [1].This technology has a very simple function to operate. This technology is suitable for industrial commercial environments and ideal for workshops, ware houses, offices, schools, malls, waiting halls and also for small and large residential buildings. It creates positive pressure which ensures that cooled spaces remains dust free. For comfort cooling, EAC is most suited for arid climate, and desiccant–assisted systems most suitable for commercial applications even in humid climates [2]. Evaporative cooling is a psychrometric process. Psychometry is the study of moist air and the changes in its conditions. The psychometric chart graphically represents the relationship between air temperature and moisture content and is a basic design tool for mechanical engineers and designers. Psychrometry is the study, how to change air-water mixture, from one condition to another. Evaporation is the conversion of a liquid substance into the gaseous state. When water evaporates from the surface of something, that surface becomes much cooler because it requires heat to change the liquid into a vapor. A nice breeze on a hot day cools us because the current of air makes perspiration evaporate quickly. The heat needed for this evaporation is taken from our own bodies, and we perceive a cooling effect. When air moves over a surface of water it causes some of the

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water to evaporate. This evaporation results in a reduced temperature and an increased vapor content in the air. The bigger the area of contact between the air and water the more evaporation occurs, resulting in more cooling and the addition of moisture. In order for water to evaporate, heat is required [3].

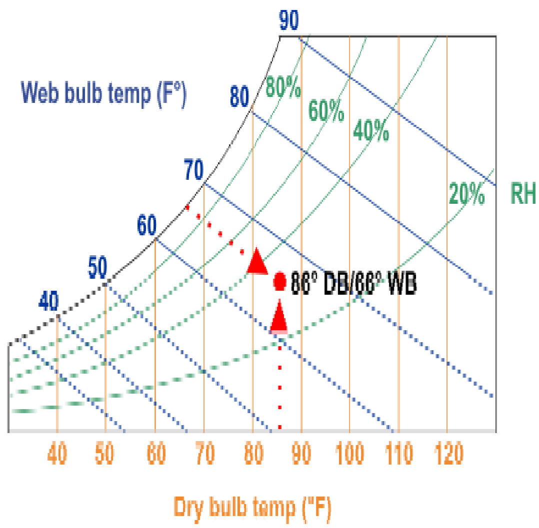

Figure 1. Psychrometric Chart

2. Types of Evaporative cooling

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 vapor, which requires much less energy than refrigeration. When air blows through wet medium, its sensible heat energy evaporates some amount of water and reduces its dry bulb temperature. In evaporative cooling system, the water is consumed by evaporation. The water consumption is determined by the inlet and outlet temperatures, humidity, and air flow rates. When water evaporates, it leaves dissolved impurities; gradually increasing its concentration in remaining water in the cooler. This leads to increase in the deposition of impurities and possibility of corrosion of metal components. The deposits of impurities can block the cooling pads and can reduce the cooling performance of evaporative cooling system. Modern technology has dramatically increased the efficiency and effectiveness of evaporative cooling system. Evaporative air cooling can be categorized as direct, indirect and two- stage system.

2.1. Direct Evaporative Cooling

In direct evaporative cooling sensible heat energy evaporates some water, and reduced the air's dry bulb temperature. Greater the differences in dry bulb and wet bulb temperatures; better is the cooling effect to the space and the temperature of saturated moist air is achieved almost near the wet bulb temperatures.

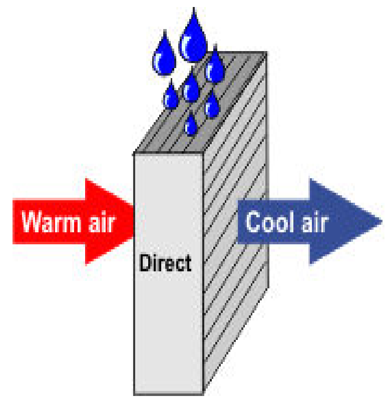

Figure 2: Direct Evaporative Cooling [4]

Direct evaporative cooling, commonly used for residential, commercial, and industrial systems, cools the air by evaporation of water to increase the moisture content of the air. In industrial system mainly uses cellulose pads as evaporative medium. A standard residential system uses evaporative media of shredded aspen fibers, typically 1 to 2 inches thick. These systems have an effectiveness of 55 to 70 percent [5]. When hot and dry air blows through wet medium, the water gets saturated and evaporates. This evaporation of water provides cooling effects. The effectiveness of evaporative cooling system is defined by the types of evaporative media used and it also depends on its thickness. Effectiveness is determined by the performance of evaporative cooling system. It is defined by Equation.1.

$$\varepsilon = \frac{Tdb - SAT}{Tdb - Twb} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (1)$$

Where Tdb is the outdoor dry-bulb temperature, Twb is the outdoor wet-bulb temperature and SAT is the supply air te mperature leaving the evaporative cooler.

Evaporative cooling system design is directly affected by dry bulb, wet bulb temperature, and relative humidity. The main restriction of direct evaporative cooling is air moisture content present in the air. Evaporative cooling systems are of increasing choice because of their lower energy consumption compared to any other refrigerated system, first simplicity in design, low initial cost, and ease of installation, operation, and maintenance. It does not use refrigerants such as chlorofluorocarbons (CFCs), which may cause harmful effects on the human health and the environment. Another attractive feature of evaporative system is that most air contaminants such as dust, dirt, bacteria, and other impurities are washed out in the re-circulated water. When the water evaporates, only pure water is released and air circulation fan supplies 100% fresh and cooled air to the space.

2.2. Indirect evaporative Cooling

In indirect evaporative cooling systems heat and mass transfer takes place and uses an air to air heat exchanger to remove heat from the primary air stream without addition of moisture by means of cooled secondary stream evaporatively [6]. During the heating season, an indirect system's heat exchanger can preheat outside air if exhaust air is used as the secondary air stream. In one configuration, hot dry outside air is passed through a series of horizontal tubes that are wetted on the outside. A secondary air stream blows over the outside of the coils and exhausts the warm, moist air to the outdoors. The outside air is cooled without adding moisture as it passes through the tubes. Indirect evaporative cooling typically has an effectiveness of 60-80% [7]. In indirect evaporative process air moisture content stays constant during temperature decreasing. Due to less energy losses in indirect evaporative cooling process; it results in less effective than direct evaporative, because energy needed in vaporization is taken from the same environment[6].Indirect evaporative cooling systems takes advantage of evaporative cooling effects, but cools without raising indoor humidity. As cooling of the primary air stream takes place by heat transfer across the heat exchanger walls without the mixing of the 2 air streams, the primary air stream becomes cooler without an increase in its humidity. While the greater number of air passes increases the pressure drop and the required fan power, the high effectiveness extends the geographic range where the indirect evaporative cooler can fully meet the cooling demand. In some applications, the greater temperature difference between the secondary and primary air is that the secondary air temperature is lower than the dew-point temperature of the primary air and results dehumidification of the primary air in this cooling process i.e., condensation from primary air, especially in hot and wet climates.

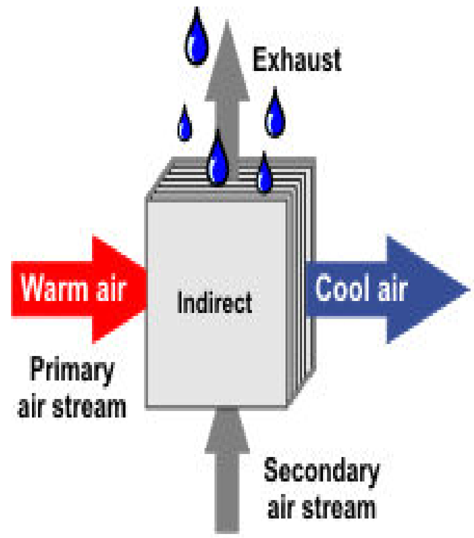

Figure 3. Indirect Evaporative Cooling [4]

The effectiveness of indirect evaporative cooling can be expressed as :

$$\varepsilon = \frac{t1 - t2}{t1 - twb1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

ε = indirect evaporative cooling effectiveness, %

t1 = dry-bulb temperature of entering primary air℃

t2 = dry-bulb temperature of leaving primary air,℃

$twb1$= wet-bulb temperature of entering secondary air,℃

2.3. Two Stage Systems

Indirect cooling is often paired with a second direct evaporative cooling stage, to cool the supply air further while adding some moisture to the supply air. Two stage systems provide cooler supply air at a lower relative humidity than direct evaporative coolers. The first indirect stage cools the supply air without increasing humidity. Since the air is cooled it has a reduced capacity to hold moisture. The air is then passed through a direct stage, which cools the air further while adding moisture. Indirect – Direct systems typically have an effectiveness of 100% to 115%, Indirect – Direct systems used in arid climates can have power consumption as low as 0.22 kW/ton, much lower than compressor-based cooling which can have power consumption on the order of 1 kW/ton. However, in more humid climates indirect-direct systems have less power reduction and energy savings [7].

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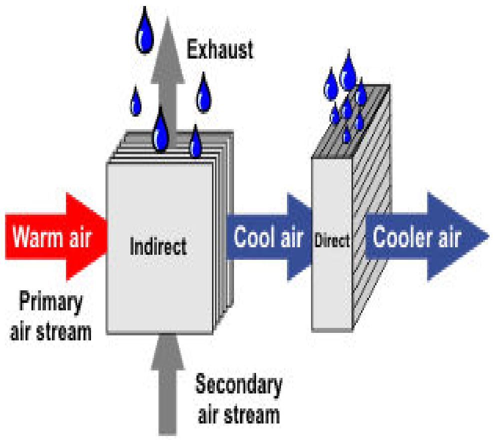

Figure 4. Two Stage Evaporative cooling [4]

The effectiveness of the two-stage evaporative cooling system is improved with an increase in mass flow rate of water. The two-stage evaporative cooling system suffers from high capital cost and pumping costs necessary to operate the extra indirect evaporative cooling system.

3. Applications [3]

In many locations and for many applications, evaporative cooling is all the cooling required to maintain a comfortable indoor environment. In hotter areas or where cooling loads are high, such as in office buildings, one of the most useful applications for indirect/indirect evaporative cooling is supplementing a chiller or DX system. By cooling the air stream before it reaches the cooling coil, an indirect/indirect evaporative unit extends chiller life, cuts energy costs, and provides the chiller needs to function effectively on hot days. The feasibility of evaporative cooling should be examined whenever cooling is required for the purpose other than the comfort of persons. The adoption of the evaporative system depends mainly upon three factors:

- Local climatic conditions
- Types of load
- Availability of water
- Economic involved

Evaporative cooling finds applications in situations where the cooling demand is acute only on a relatively few days during the hot summer. In such locations, evaporative cooling with simple duct work and open natural exhaust facilities results in a system with lowest possible installation cost and operating cost. Evaporative cooling systems are used in many other applications, such as:

- Power plant evaporative cooling towers
- Process cooling water
- Turbine engine air intake cooling.
- Portable cooler applications
- Automobile interior cooling
- Solar powered EAC's
- Exterior spot cooling
- Electronics and optic fiber equipment cooling
- Green house, laundries, and manufacturing process cooling
- Animal housing facility cooling

4. Cooling Performance

The evaporative cooling has a potential to full fill the cooling demands. The evaporative cooling performance depends on characteristics of pads and also the parameters of air and quality of water uses. When air is passes over the porous wet media, its sensible heat energy evaporates some amount of water and reducing the air's dry-bulb temperature. The temperature of saturated air reaches nearly the ambient air's wet-bulb temperature. Relative humidity, air flow rate also plays an important role in performance of evaporative cooling. When mass flow rate of air is increased; the cooling capacity of evaporative cooling system is also increased. In rainy season the performance of evaporative cooling systems decreases due to highly moisture contents present in the air. The cooling effectiveness of evaporative cooling system also depends on inlet velocity of air. The cooling effectiveness decreases with increase in inlet air velocity. High dew point (humidity) conditions decreases the cooling capability of the evaporative cooling systems. In traditional air conditioning system moisture is removed from the air, except in very dry locations where recirculation of air can lead to a buildup of humidity. Evaporative cooling is adding moisture in dry air; dryness may improve thermal comfort at higher temperatures.

4.1. Direct Evaporative Cooling

The effectiveness of DEC affected by many factors such as type of pad material, thickness and surface area of pads, mass flow rates air, velocity of air, direction of air flow and % RH of air passing through the pad. DEC also affected by the quality of water used. The air supplied by the evaporative cooling system is of typically 80–90% relative humidity; very humid air reduces the evaporation rate of moisture from the skin. High humidity in air may further increase the cause corrosion, particularly in the presence of dust. This can considerably shorten the life of electronic and other equipment. It may also cause condensation; this can be a problem for some situations (e.g., electrical equipment, computers, paper/books, old wood). Saturation effectiveness is defined as the difference between the entering and exit dry-bulb temperatures over the wet-bulb depression [2]. Abdollah et al. has found maximum efficiency occur at velocity 1.8 m/s for thickness 150 mm in pad 5090, on other hand the maximum pressure drop occur at thickness 75 mm for pad 7090 and velocity 1.8 m/s. Furthermore the minimum evaporated water is about 0.06 lit/min for thickness 75 mm at 1.8 m/s air speed in pad 7090 [8]. J.K. Jain, D.A. Hindoliya concluded that palash and coconut fibers show great potential for use as wetted media in domestic and commercial direct evaporative cooler. The effectiveness found 13.2% and 26.31% more than that of aspen and khus respectively [9]. Hence the pad selection should be carefully. The pad material should have good heat transfer characteristics and capability of absorbing water and allowing the evaporation process.

Saturation efficiency [10] of cooling media is calculated based on the following relation:

$$\eta = \frac{T1-T2}{T1-Tw} \times 100 \quad \text{…………………(1)}$$

η = Saturation efficiency, T1 = Dry bulb temperature of ambient air, T2 = Outlet temperature of air, Tw = Wet bulb temperature

Cooling capacity [9] is given by

$$Qc = Ma \times Cpa \times [T1 - T2] \quad \text{………….(2)}$$

Qc = Cooling capacity, Ma = Mass flow rate of air, Cpa = Specific heat of air.

4.2. Indirect Evaporative Cooling

IEC technology has great alternative potential as vapor compression system. In this system first the outside air is cooled in an indirect stage and then further cooled in a subsequent direct stage. In the first stage air is cooled without adding moisture and in the second stage moisture is added. This process follows a line along a constant humidity ratio since no moisture is introduced in the indirect stage. Often a direct stage is introduced after the indirect stage, and sometimes several indirect stages can be used to further enhance the sensible cooling effect. [2].A common configuration of indirect cooling that makes use of an air-to-air heat exchanger. The main fan supplies outside air through the dry passages of a heat exchanger into the dwelling, while a secondary fan delivers exhaust air from the dwelling, fresh air, or some combination through wetted passages in thermal contact with the dry passages of the heat exchanger. The cooling performance of an IEC system has achieved significant enhancements which allows as high as 80 – 90 % and wet – bulb efficiency to be obtained while its cooling EER approaches 30 – 80. In a typical heat exchanger for use in indirect evaporative cooling, the static pressure drop of the air in dry and wet channels is found to be in range 60 -150 Pa. and 100 – 500 Pa respectively and ratio of the working product air is in the range 0.3 – 1 [11]. Performance of indirect evaporative cooling can be measured by the ratio of the reduction of the dry-bulb temperature of the dry-side airstream to the initial difference between dry-side dry-bulb and set-side wet-bulb temperature. The performance factor is affected by equipment size and effectiveness, as well as overall air and water quantities [2].The Energy efficiency of IEC is known as coefficient of performance (COP). It is the ratio of the cooling capacity of the IEC to the power consumption of the system. This term can be mathematically expressed as:

$$\text{Energy efficiency } \varepsilon = \frac{Q}{W} \quad \text{…………………… (1)}$$

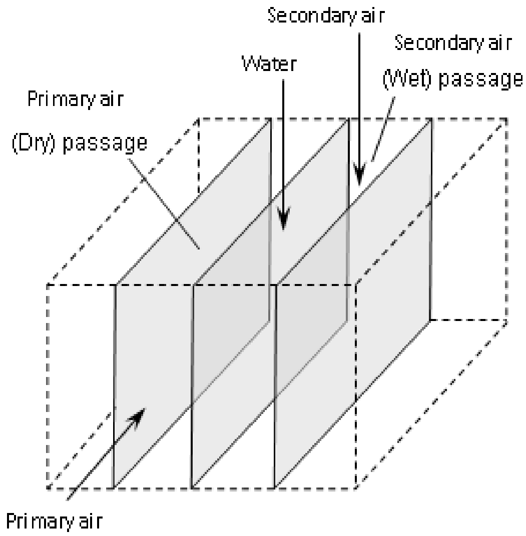

Figure 5. Typical indirect evaporative cooling with cross flow configuration [12]

5. Analysis of Heat and Mass Transfer

Evaporative cooling technology is based on the energy and mass transfer between two streams. During of which both air and water are cooled due to evaporation of water. In a direct evaporative cooler, the heat and mass transferred between air and water decreases the air dry bulb temperature (DBT) and increases its humidity, while in an ideal process the enthalpy would be essentially constant. The temperature of the outside air can be reached near the wet bulb temperature (WBT). The cooling media provides a large water surface in which the air gains moisture and the media is wetted by spraying water. In the indirect evaporative cooling method a wet surface heat exchanger is used where a non adiabatic evaporation takes place. Primary air is cooled sensibly without adding water which flows in dry passages, while the secondary air carries away heat energy from primary air which flows in wet passages. The wet passages surface is wetted by spraying water, so that water film evaporates into the secondary air and decreases the temperature. Therefore heat is transferred from primary to secondary air without introducing moisture into the primary air stream. The air leaving the dry side of the cooler has a lower wet-bulb temperature than the ambient [12]. Evaporative cooling system is one alternative option for mechanical vapor compression air conditioning system. This system usually consumes only one fourth electric power to the mechanical vapor compression system. Evaporative cooling process is one of the most widely used techniques which protect both energy conservation and environment. Evaporative cooling system can decrease the process air temperature by using low energy and theoretically approaching its temperature to wet bulb temperature. The evaporative cooling system is a steady flow device that uses a combination of mass and energy transfer to cool the air by exposing wetted surface to the atmosphere. The air flow may be cross flow or counter flow and caused by mechanical means, convection currents or by natural wind. The air is moved by mechanically driven fans to provide a constant air flow. Chengqin Ren and Hongxing Yang [13] has developed an analytical model for the coupled heat and mass transfer processes in indirect evaporative cooling under real operating condition with parallel and counter flow configuration. Mizushina et al. [14] resented two methods of heat calculation in coolers: one simplified, constant temperature of water praying the tubes was assumed and another, which took into account the variation of that temperature in an exchanger. An experimental study by Facao and Oliveira [15] showed that incomplete wetting might occur with relatively small mass flow rate of spray water. Hasan and Siren[16]Experimental studied that heat and mass transfer coefficients which showed that heat and mass transfer analogy gives lower values of mass transfer coefficients than those found from measurements.

6. Desiccant Cooling

A desiccant assisted evaporative cooling system is used to dehumidify the ventilation air first with the desiccant to a desired state, and then to use evaporative cooling to cool the air to the desired supply temperature [2].The materials which have capability to attract the moisture is called desiccant. The desiccant materials can be either solid or liquid. The attraction of moisture from the humid air is either by adsorption or by absorption process. The adsorption is a process in which the property of the desiccant material remains the same while in the absorption process, moisture is attracted, and the physical characteristic of the desiccant material changes [17]. Desiccant cooling is an alternative option for mechanical vapor compression air conditioning system. In hot and humid regions, effectiveness of DEC and IEC is reduced due to high relative humidity. In these regions latent load is very high and evaporative cooling has no ability to remove these latent loads.[18]The desiccant technology can provide more comfort cooling if the environment is most humid. Desiccant is used first to dehumidify the air at desired state and then EC is used to cool the air to desired supply air temp.[6] Desiccant evaporative technology used for either direct or indirect or two – stage evaporative cooling to reduce the temperature of the system. Desiccants have capability to absorb moisture at different water vapor pressure between surrounding air and desiccant space. In some cases, the desiccant dehumidification and evaporative cooling hybrid system is used only to remove all latent load and part of the sensible load, and additional sensible heat removal terminals, such as dry fan coils and radiant cooling panels, are employed to treat the remaining sensible load [18]. The commonly used desiccant materials are lithium chloride, tri-ethylene, glycol, silica gels, aluminium silicates, aluminium oxides, lithium bromide solution and lithium chloride solution with water.[19]. The desiccant materials have capability of removing air moisture contents by the natural process. The moisture can be removed from the desiccant, either by heating or by reducing the pressure. Heating is the most preferred method in commercial application, however reducing pressure is the preferred one in industrial application [17]. At the lower temperature, the desiccant materials that can be regenerated and can bring comfort, cost, and energy saving [19]. Napoleon Enteria et al. [20] developed desiccant-evaporative air-conditioning system was evaluated using the exergetic method under controlled environmental conditions to determine the performances of the whole system and its components**.** Irfan Uckan et al. [21] developed a desiccant based evaporative cooling system and tested experimentally in this study. In the system studied, the moisture of the fresh air is reduced passing it through a solid desiccant wheel and then its temperature is decreased by the direct evaporative cooler.

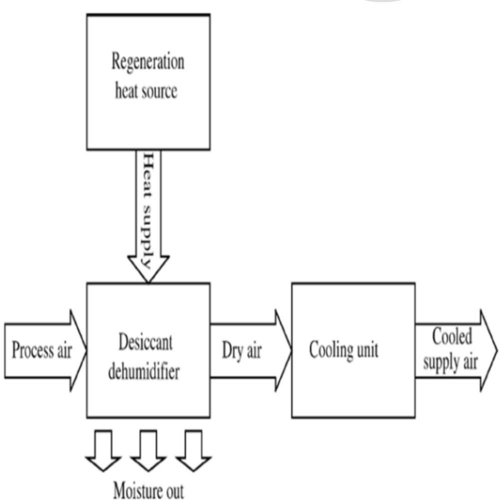

Figure 6. Principle of desiccant cooling [18]

6.1. Solid Desiccant

In solid- assisted desiccant systems, the solid desiccant materials (eg. Silica gel) are used to remove the air moisture content present in the air. There are some kinds of solid desiccant materials: silica-gel, calcium chloride, titanium silicates, zeolite, lithium chloride, organic-based desiccants, polymers, compound, and composite desiccants. The solid desiccant system controlling the moisture present in the air is based on the solid-assisted desiccant materials. In the solid desiccant material, the sorption mechanism is either by absorption or adsorption. Cooling can be obtained by means of heat recovery; evaporative cooling or other means are applied to the system. The most widely used desiccant systems is solid desiccant cooling system. This is due to the simple handling of desiccant materials. A solid desiccant material has higher regeneration temperature than liquid desiccant, new researches made new materials with lower regeneration temperature requirement [18].

6.2. Liquid desiccant cooling

The liquid desiccant (eg. Tri-methylene glycol) is used for controlling air moisture content in liquid desiccant cooling systems. In the liquid desiccant, air moisture can be reduced through the absorption process [17]; due to operational flexibility and capability of absorbing moistures, pollutants and bacteria, the liquid desiccant systems are more likely. Liquid desiccants are regenerated at lower temperature due to lower pressure drops as compared with solid desiccants [19].The dehumidifier (absorber) and the regenerators are generally referred to as contactors. The liquid desiccants can be also used in conjunction with the evaporative cooling systems to form standalone applications. In addition, some liquid desiccants are corrosive, and require proper handling in their application.

7. Conclusions

Evaporative cooling technology is environment friendly which does not emits any green house gases and provides 100% fresh air to the space and remove smoke, odors, smell from the space. Evaporative cooling is more economic, effective and energy saving in hot and dry climates. The performance and effectiveness of evaporative cooling depends upon inlet air velocity, air mass flow rates and moisture contents present in the environment and it also depends on thickness of evaporative media and geographical locations. EC systems have some limitations in high humid regions. In high humid regions the efficiency of EC systems is reduced. With the help of desiccant based cooling system, the moisture content can be removed from air and overcome these limitations of the systems. The desiccant based cooling is the one of the best option for high humid region to control the environmental condition. The effectiveness of desiccant based cooling comparatively high with DEC and IEC.

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