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Review on Evaporative Cooling Systems

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ABSTRACT

A review of evaporative cooling systems for air conditioning is presented. The concept, applications, and the factors affecting it were reported. The evaporative cooling systems are grouped into three broad categories, namely, the direct evaporative cooling system, the indirect evaporative cooling system and the combined evaporative cooling system. Also, studies aimed at determining the cooling pad selection and modelling of heat and mass transfer, overall energy balance, direct and indirect cooling was reviewed. Generally, evaporative cooling can be specially applied in dry and hot climates and it's a simple and least energy consumptive way of achieving air conditioning.

K**eyword: evaporative cooling, direct, indirect, pads, models, review**

1.0 INTRODUCTION

For the past few decades there's been a significant increase in energy and water consumption due to the increase in cooling demand. In order to respond to this challenge, it became necessary to develop a new low energy cooling technologies (LECT), which will have a better eco-sustainable characteristics and less life-cycle cost than comparable refrigeration systems. Life cycle cost includes all money values such as first cost, energy, water, time value of money, and maintenance costs (Raskovic *et al*, 2008).

Evaporative cooling operates using induced processes of heat and mass transfer, where water and air are the working fluids. It consists, specifically, in water evaporation, induced by the passage of an air flow, thus decreasing the air temperature (Camargo *et.al*, 2003).

Evaporative cooling is a simple, least energy intensive and environmentally benign technique of air conditioning (ASHRAE, 2003).

Almost any climatic region offers some opportunity for the use of evaporative coolers to cool ventilation air. Evaporative cooler achieve air cooling by the evaporation of water which is done by passing air through a water spray or through a packing that is kept wet by constantly circulating water. Evaporative cooling is an adiabatic saturation process in which evaporating water absorbs its heat of evaporation from the flowing air; thus cooling it. Since the vapour holding capacity of air is related to its absolute humidity dry and warm air has the ability to hold more water vapour than humid air, consequently evaporative cooling is more effective in drier climatic regions (Khalid, 2008).

Nigeria weather primarily features a tropical kind of climate where most of the seasons are very humid and damp; the weather of Nigeria is generally quite hot throughout the year (Powell, 2013). Ventilation is important in a greenhouse for many reasons, but during hot weather, it is especially important with cooling. Circulation fans will help to stay the greenhouse uniformly heated, while exhaust fans will thrust out stale air so that fresh air can move in. Suitable ventilation also prevents pest infestations, which can be a difficulty when plants are stressed (Kouchakzadeh and Brati, 2013).

Since, air temperature and humidity are the two major parameters affecting thermal comfort significantly, and only sensible load can be handled by an evaporative cooling system, conventional evaporative cooling system is suitable for dry and temperate climate where the humidity is low (Costelloea and Finn, 2003; Heidarinejad *et al*, 2009). Evaporative pad cooling is the most efficient method for greenhouses cooling under arid conditions (Al-Helal, 2001).

Evaporative cooling has been useful for many other agricultural purposes besides food storage. Evaporative cooling system was created to reduce the temperature of a silkworm rearing house in Thailand. Heat stress is believed to be a cause of low silkworm production, therefore cooling can be an important addition to the silkworm environment. Using a fan to force air through a wetted pad, a 6-13^{0}C drop in temperature was observed along with an increase of 30-40% relative humidity (Lertsatitthanakorn *et al.,* 2006)

This paper present works that was done on various engineering concept of evaporative cooling, factors affecting evaporative cooling, different evaporative system cooling pads, cooling pads selection, evaporative cooling system designs, models formulation and economic evaluation of using evaporative cooling systems.

2.0 ENGINEERING THEORY OF EVAPORATIVE COOLING.

According to Watt and Brown (1997), the concept of using water for air cooling has been around for millennia. While complex evaporative cooling processes and machines have been invented, the basic concept has not changed. Egyptian frescoes portraying large, porous jars of water being fanned to force evaporation and subsequent cooling have shown the prevalence of evaporative cooling since ancient times.

Evaporative cooling is the process by which the temperature of a substance is reduced due to the cooling effect from the evaporation of water. The concept evaporative cooling is that the surrounding air serves as a heat sink where sensible heat is exchanged for latent heat of water (La Roche, 2012). The conversion of sensible heat to latent heat causes a decrease in the ambient temperature as water is evaporated providing useful cooling. This cooling effect has been used on various scales from small space cooling to large industrial applications (Liberty *et al*, 2013).

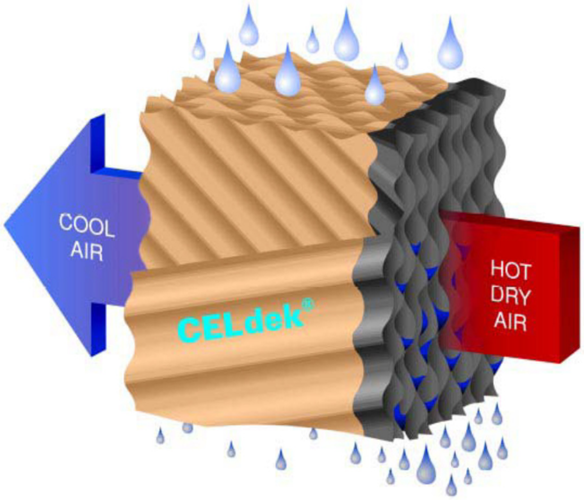

Fig 1: concept of evaporative cooling, describing air flow through a cooling pad (Kinney, 2004)

Similarly, evaporative cooling system is based on the principle that when moist but unsaturated air comes in contact with a wetted surface whose temperature is higher than the dew point temperature of air, some water from the wetted surface evaporates into air. The latent heat of evaporation is taken from water, air or both of them. In this process, the air loses sensible heat but gains latent heat due to transfer of water vapour. Thus the air gets cooled and humidified. The cooled and humidified air can be used for providing thermal comfort (Shah, n.d.).

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. The efficiency of an evaporative cooler depends on the humidity of the surrounding air. Very dry air can absorb a lot of moisture, so greater cooling occurs. In the extreme case of air that is totally saturated with water, no evaporation can take place and no cooling occurs. Generally, an evaporative cooling structure is made of a porous material that is fed with water. Hot dry air is drawn over the material. The water evaporates into the air raising its humidity and at the same time reducing the temperature of the air (FAO, 1995).

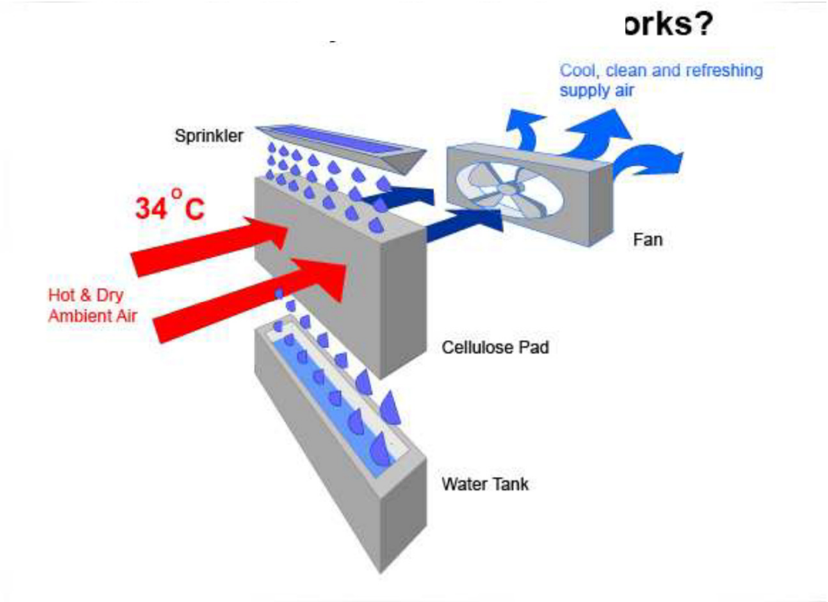

Fig 2: Working of an evaporative cooler (Sreeram, 2014)

Many examples of the application of the phenomenon of evaporative cooling can be found, such as the metabolic regulation of the human body temperature through the evaporation of sweat from the skin, the use of cooling towers or evaporative condensers, the cooling of pools by the evaporation of the water (Gomez *et. al,* 2010).

2.1 FACTORS AFFECTING EVAPORATIVE COOLING.

The cooling effect of an evaporative cooler depends on the rate of evaporation and on conditions within the cooler. Environmentally, temperature and humidity have the most significant impact on evaporation. The temperature must be high enough to allow for evaporation and the relative humidity must be low enough to allow for more water vapour to enter the air. Water quality also has an important role in both evaporation and keeping the system well maintained (Fouda and Melikan, 2011).

Lin and Chang (1997) in their presentation listed the factors that affect evaporative cooling as follows:

- Relative humidity
- Ambient temperature
- Droplet size
- Ventilation rate
- Droplet travel distance

Similarly, Odesola and Onyebuchi (2009) gave four major factors that impact the rate of evaporation. It is important to keep in mind that they usually interact with each other to influence the overall rate of evaporation, and therefore, the rate and event of cooling.

1. **Relative Humidity**: This is the amount of water vapour in the air as a percentage of the maximum quantity that the air is capable of holding at a specific temperature. When the relative humidity is low, only a small portion of the total possible quantity of water vapour that the air is capable of holding is being held. Under this situation, the air is capable of taking on additional moisture, and if other conditions are also met, the rate of evaporation will be higher. On the other hand, when the relative humidity is high, the rate at which water evaporates will be low, and therefore cooling will be low.
2. **Air Temperature:** Evaporation occurs when water absorbs sufficient energy to change from a liquid to gas. Air with a relatively high temperature will be able to stimulate the evaporative process and also be capable of holding relatively great quantity of water vapour. Therefore, areas with high temperatures will have higher

rates of evaporation and more cooling will occur. With lower air temperature, less water vapour can be held, and less evaporation and cooling will take place.

3. **Air Movement:** The movement of air, either natural or artificial, is an important factor that influences the rate of evaporation. As water evaporates from a surface it tends to raise the humidity of the air that is close to the water surface. If this humid air remains in place, the rate of evaporation will start to slow down as humidity rises. On the other hand, if the humid air and the water surface are constantly been moved away and replaced with drier air, the rate of evaporation will either remain constant or increase.
4. **Surface Area:** The greater the surface area from which water can evaporate, the greater the rate of evaporation.

2.2 EVAPORATIVE SYSTEM COOLING PADS

Traditionally, evaporative cooler pads consist of excelsior (aspen wood fiber) inside containment net, but more modern materials, such as some plastics and melamine paper, are entering use as cooler-pad media. Modern rigid media, commonly 8" or 12" thick, adds more moisture, and thus cools air more than typically much thinner Aspen media (Kheirabadi, 1991).

There are different types of cooling pads used my manufacturers based on the need and the type of application. Some of them include Aspen pads, Cellulose pads Glasdek pads. Most of these cooling pads find their applications in poultry farming and greenhouses. Cellulose and Glasdek pads are the commercially used ones for data center applications. Cellulose is made from paper and Glasdek from fiber glass (Sreeram, 2014). Another material which is sometimes used is corrugated cardboard.

Table 1: List of Evaporative Cooling Pads

S/N	EVAPORATIVE COOLING PAD	REFERENCE
1	Aspen	Muazu, 2008; Sreeram, 2014; Bucklin *et al,* 2016
2	Celdek	Kinney, 2004
3	corrugated cardboard	Wikipedia, 2012
4	Cellulose	Sreeram, 2014
5	Charcoal	Kouchakzadeh and Brati, 2013; Douglas *et al.,* 2011
6	Jute material	Mogaji and Fapetu, 2011; Manuwa and Odey, 2012
7	Ceramics	Riffat. and Zhu, 2004
8	Rice Husk	Soponpongpipat and Kositchaimongkol, 2011
9	Clay	Chinenye, 2011
10	Wood shavings	Manuwa and Odey, 2012
11	Recycled High-Density Polyethylene	Soponpongpipat and Kositchaimongkol, 2011
12	Wire-mesh pads.	Setekleiv *et. al*,2008

Mogaji and Fapetu (2011), gave part of the general requirements, the efficiency of an active evaporative cooler depends on the rate and amount of evaporation of water from the cooling pad. This is dependent upon the air velocity through the fan, pad thickness and the degree of saturation of the pad, which is a function of the water flow rate wetting the cooling pad (Wiersma, 1983; Thakur and Dhingra, 1983). Jute type of cooling pad of 0.06 m thickness was selected for an efficient performance of the evaporative cooling system as it has good water holding capacity, high moisture content, % dry basis, high bulk density reported (Manuwa, 1991).

Similar findings have been reported by Igbeka and Olurin (2009) on the dependency upon the air velocity through fan as follows:

- **Velocity of air (v)**

The velocity of air from the suction fan of the evaporative cooling system is determined using Bernoulli's equation as follows:

$$\frac{P_1}{\rho_1} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\rho_2} + \frac{V_2^2}{2g} + Z_2 + headloss \qquad 1$$

where:

P_1 and P_2 = Atmospheric pressure (N/m^2)

ρ_1 and ρ_2 = Density (kg/m^3)

Z_1 and Z_2 = Height (m)
V_1 and V_2 = Velocity (m/s)

Where ρ_1 and ρ_2 are constant for compressible air flow from the fan:

$P_1 = P_2$ and $\rho_1 = \rho_2$, then

$$\frac{P_1}{\rho_1} = \frac{P_2}{\rho_2} \qquad 2$$

Then,

$$\frac{P_1}{\rho_1} - \frac{P_2}{\rho_2} = 0 \qquad 3$$

For the fan, V_1 and Z_2= 0

Then equation (1) is reduced to (4)

$$Z_1 = \frac{V_2^2}{2g} + headloss \qquad 4$$

The head loss at the conical head of the system is determined using equation (5):

$$H_f = \frac{4flV^2}{2gd} \qquad 5$$

Where, f = Frictional factor

g =Gravitational constant m/s^2
L = Length of the conical part (m)
d = Diameter of the conical head (m)
V = Velocity (m/s)
f = 16/ R_e
R_e = Reynolds number = 1516.5
f = 0.0106
L = 0.4 m

$$H_f = \frac{4\ x\ 0.0106\ x\ 0.4\ x\ V^2}{2\ x\ \ 9.81\ x\ 0.206}$$
$$H_f = \ 3.33188\ x\ 10^{-3}V^2$$

Then $Z_1 = \frac{V_2^2}{2g} + H_f \ = V_2^2\ (5.43019\ x\ 10^{-2})$

The datum of the system Z_1 =1 m
So $V_2 = 4.3\ m/s$
The convective nature of the air flow was determined using equation (6):

$$R_{ed} = \frac{V_\infty\ d_{ch}}{v} \qquad \text{(Holman, 1997)} \qquad 6$$

Where, V_∞ = Air velocity (m/s)
d_{ch}=Diameter of the chimney head (m)
v = Kinematic viscosity (m^2/s)
R_{ed} = Reynolds number in tube
From Holman (1997) at 32℃ (305 K)
v = 16.20 x 10^{-6} m^2/s
V_∞ = 4.3 m/s
d = 0.260 m

On substitution, R_{ed} is estimated to be 69025, thus, the air flow through the suction fan is turbulent in nature which justified the required forced convective nature of air flow for an effective evaporative cooling system.

Many researchers showed characteristics of various types of evaporative cooling pads in their works (Dagtekin *et al.*, 2009; Setekleiv *et al.,* 2008; Dai and Sumathy, 2002; Liao *et al.,* 1998; Simmons and Lott, 1996; Koca *et al.,* 1991; Dowdy *et al.,* 1986).

Soponpongpipat and Kositchaimongkol (2011) studied saturation efficiency and pressure drop across wetted pad of recycled High- Density Polyethylene (HDPE) and rice husk as a wetted pad in evaporative cooling system. After comparing to commercial wetted pads, the results showed that rice husk wetted pad gave the average saturation efficiency of 55.9%, while HDPE gave the average saturation efficiency of 29.1%. However, the result of pressure drop across wetted pad of rice husk and recycled HDPE is significantly higher than that of commercial wetted pad.

Kouchakzadeh and Brati (2013), used bulk charcoal an alternative evaporative cooling pad material with a cooling efficiency ranging from 48% to 70%. In 200.14 and 206.22 (kg m^{-3}) bulk densities rising water flow to 0.2 L s^{-1} for each square meter of pad with 5 cm thickness elevated cooling efficiency to 60%, while in 209.58 (kg m^{-3}) charcoal's bulk density, increasing water flow over 0.08 L s^{-1} for each square meter caused reduction in efficiency. In 200.14 (kg m^{-3}) bulk densities rising air velocity over 0.47 L s^{-1} decreased cooling efficiency in any water flow rates, while in 206.22 and 209.58 (kg m^{-3}) bulk densities increasing air velocity to 1.38 m s^{-1}.

Similarly, charcoal has a porous structure that can hold water and is easily available (Douglas *et al.,* 2011). Bulk charcoal placed in various types of evaporative cabinet cooler between the outer and inner metal container walls (Anyanwu, 2004). The charcoal may resist chemical degradation even when exposed to intense weathering in a tropical climate. No changes in quality of finely distributed bulk charcoal over time were founded (Schneider *et al.,* 2011).

The most widely used type of pad material is corrugated cellulose that impregnated with wetting agents and insoluble salts to help to resist rot. These pads are expensive, but when properly maintained they do an excellent job of cooling air. With proper maintenance, corrugated pads should have a lifetime of ten years (Bucklin *et al.,* 1993).

2.3 DIFFERENT EVAPORATIVE COOLING SYSTEM DESIGNS

Due to simple design and energy saving potential of an evaporative cooler, several researchers have dedicated their investigations to the development of different designs of these coolers such as direct, indirect and modified coolers. Basically evaporative cooling can be direct, indirect or combination of direct and indirect (Gomez *et al*, 2010). The combination types are also called hybrid or integrated types (Muazu, 2008).

- DIRECT EVAPORATIVE COOLING SYSTEM

Direct evaporative cooling system adds moisture to the cool air, which also makes conditions more uncomfortable for humans as (air) humidity increases (Maheshwari *et al.,* 2001).

It is used to lower the temperature and increase the humidity of air by using latent heat of evaporation, changing liquid water to water vapor. In this process, the energy in the air does not change. Warm dry air is changed to cool moist air. The heat of the outside air is used to evaporate water. The RH increases to 70 to 90% which reduces the cooling effect of human perspiration. The moist air has to be continually released to outside or else the air becomes saturated and evaporation stops (Wikipedia, 2014).

The underlying principle of DEC is the conversion of sensible heat to latent heat. Through a direct evaporative cooling system, hot outside air passes a porous wetted medium. Heat is absorbed by the water as it evaporates from the porous wetting medium, so the air leaves the system at a lower temperature. In fact, this is an adiabatic saturation process in which dry bulb temperature of the air reduces as its humidity increase (constant enthalpy). Some of the sensible heat of the air is transferred to the water and become latent heat by evaporating some of the water. The latent heat follows the water vapour and diffuses into the air. The minimum temperature that can be obtained is the wet bulb temperature of the entering air (Camargo *et al.,* 2005; Heidarinejad and Bozorgmehr, 2008; Abbouda and Almuhanna, 2012).

Similarly, Watt and Brown (1997) explained the principle underlying direct evaporative cooling is the conversion of sensible heat to latent heat. Non-saturated air is cooled by heat and mass transfer increases by forcing the movement of air through an enlarged liquid water surface area for evaporation by utilizing blowers or fans. Some of the sensible heat of the air is transferred to the water and becomes latent heat by evaporating some of the water. The latent heat follows the water vapour and diffuses into the air.

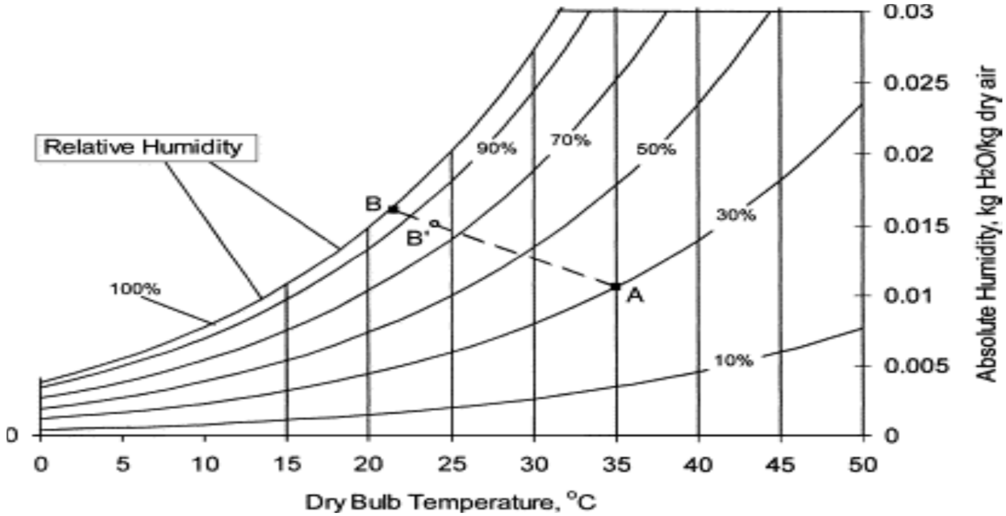

Figure 3: Cooling path for direct evaporative cooler (Muazu, 2008)

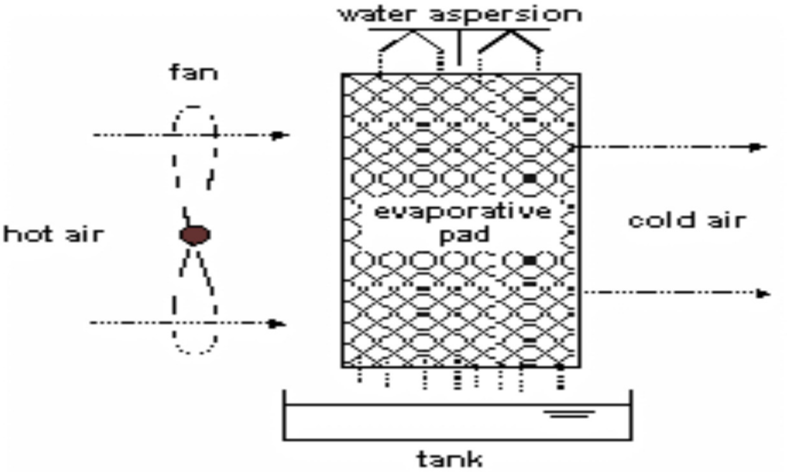

Figure 4: Schematic diagram of direct evaporative cooling system by Camargo *et.al* (2003)

- INDIRECT EVAPORATIVE COOLING SYSTEM

On the other hand, an indirect evaporative cooling system provides only sensible cooling to the process air without any moisture addition. Therefore, it is more attractive than direct evaporative system. However, the cooling effectiveness is generally low, around 40–60% (Maheshwari *et al.,* 2001).

It is a cooling process that uses direct evaporative cooling in addition to some type of heat exchanger to transfer the cool energy to the supply air. The cooled moist air from the direct evaporative cooling process never comes in direct contact with the conditioned supply air. The moist air stream is released outside or used to cool other external devices such as solar cells which are more efficient if kept cool. One indirect cooler manufacturer uses the so-called Maisotsenko cycle which employs an iterative (multi-step) heat exchanger that can reduce the temperature to below the wet-bulb temperature (Wikipedia, 2012).

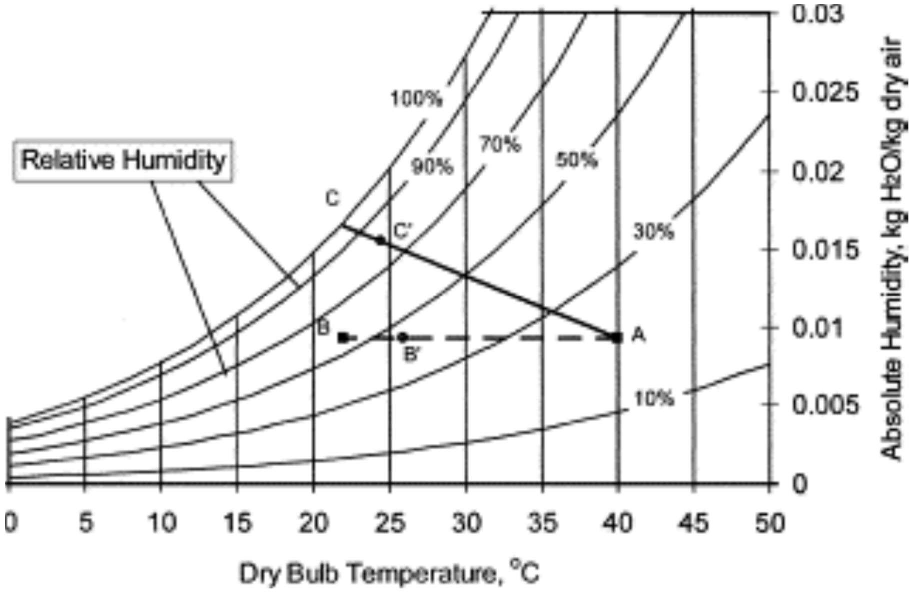

Figure 5: Cooling paths for indirect evaporative cooler (Muazu, 2008)

Indirect Evaporative Cooling systems can lower air temperature without adding moisture into the air, making them the more attractive option over the direct ones. In an indirect evaporative air cooling system, the primary (product) air passes over the dry side of a plate, and the secondary (working) air passes over the opposite wet side. The wet side air absorbs heat from the dry side air with aid of water evaporation on the wet surface of the plate and thus cools the dry side air; while the latent heat of the vaporized water is transmitted into the working air in the wet-side (Zhiyin *et.al*, 2012).

The advantage of this arrangement is that the moisture content of the cooled air remains unchanged (Hsu *et.al,* 1989).

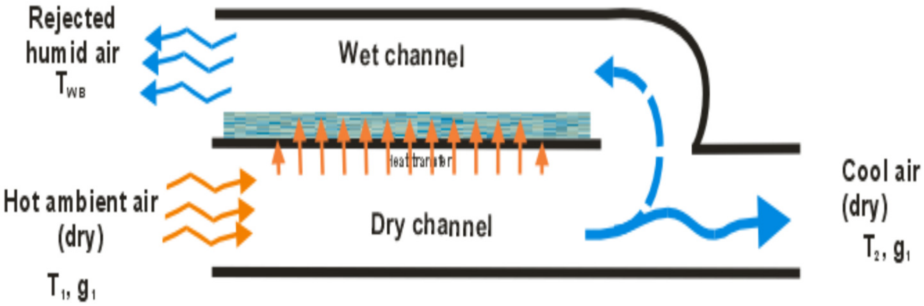

Figure 6: A simple schematic of a sub wet bulb temperature indirect evaporative cooler (Boukhanouf *et.al*, 2014)

- HYBRID (COMBINED DIRECT AND INDEIRECT EVAPORATIVE COOLING SYSTEM)

In the first stage of a two-stage cooler, warm air is pre-cooled indirectly without adding humidity (by passing inside a heat exchanger that is cooled by evaporation on the outside). In the direct stage, the pre-cooled air passes through a water-soaked pad and picks up humidity as it cools. Since the air supply is pre-cooled in the first stage, less humidity is transferred in the direct stage, to reach the desired cooling temperatures. The result, according to manufacturers, is cooler air with a RH between 50-70%, depending on the climate, compared to a traditional system that produces about 70–80% relative humidity in the conditioned air (Wikipedia, 2012)

Depending on the climatic conditions and the application, combining indirect and direct evaporative coolers might be appropriate to increase the cooling capacity (Mazzei, and Palombo, 1999; Abbouda and Almuhanna, 2012). A two-stage air-conditioner combining indirect and direct processes is gaining popularity in places where the higher wet bulb temperatures (i.e. higher ambient humidity) does not permit sufficiently low indoor temperatures supplied from a simple direct air-conditioner.

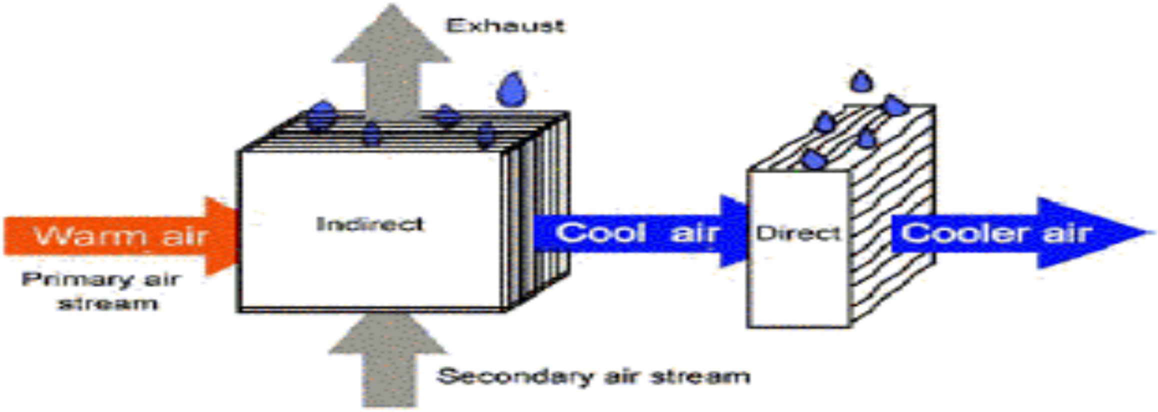

Figure 7: Indirect/direct evaporative cooling system as used by Muazu (2008)

According to Gomez *et.al*, (2010) in the summer, in dry and hot air conditions, the supply air from the indirect evaporative coolers presents a dry bulb temperature over 21ºC and its relative humidity below 50 %. Thus, it can be interesting introducing an additional direct evaporative cooling process that decreases this temperature, though it also increases the air humidity. Usually a high relative humidity in supply air is acceptable, if it is capable to eliminate the sensible loads of the room. To meet this target, two evaporative coolers are connected in series, the indirect system in the first place and then the direct one. The operating characteristics are given by the device installed in each stage. Thus, plate heat-exchangers are commonly used in indirect stages, cooling the secondary air with sprayed water; while in direct evaporative stages the Rigid Cooling Media Pad.

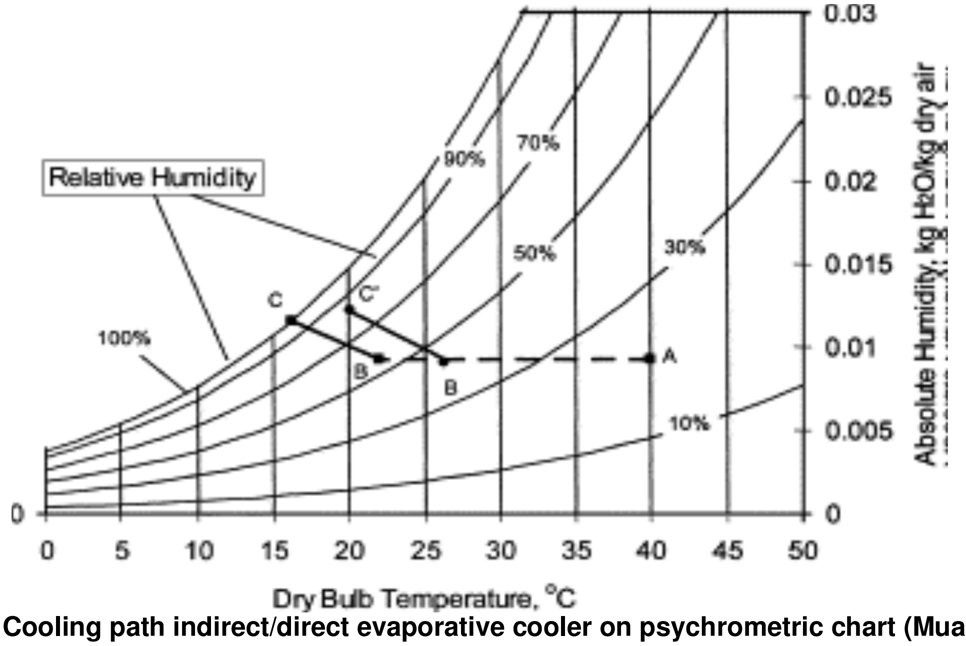

Figure 8: Cooling path indirect/direct evaporative cooler on psychrometric chart (Muazu, 2008)

3.0 MATHEMATICAL MODELLING OF EVAPORATIVE COOLING SYSTEMS.

Landsberg *et al.,* (1979), proposed a theoretical model for the efficiency of evaporative cooling in different physical conditions and Bowen ratios. The limitation of this model is the prior specification of the sensible heat to latent heat ratio rather than its deduction from actual crop behaviour. Moreover, this model was not tested against any experimental data.

More recently, detailed models use complex mathematical formulation and require detailed data about the physical characteristics of the equipment (size and arrangement of heat exchanger tubes) and the thermal phenomena (uniformity of the water distribution, cooling capacity and air velocity across the tubes) occurring within the EFC (Evaporative Fluid Coolers). Detailed models are based on a CFD-type approach (Computational Fluid Dynamics), involving the numerical solution of differential equations for air/spray water flow, energy and water vapour concentration. Computational fluids dynamics is an advanced technique for design in engineering; it is increasingly being used to analyse greenhouse microclimate with respect to structural specifications (Boulard and Wang, 2002; Bartzanas *et al.,* 2004).

After velocity, temperature and humidity fields are generated; transfer coefficients can be calculated as a result. Al though a detailed analysis of air and spray water distribution in the EFC is possible because they have some limitations (Gan *et al*, 2001; Hasan and Gan, 2002). These models and codes also consume considerable computing time and require a certain degree of specialization (Raskovi *et al*, 2008).

There are major assumptions involved in modelling evaporative cooling system; they are summarized as follows (Maclaine-cross and Banks, 1981; Kettleborough and Hsieh, 1983; Zalewski and Gryglaszewski, 1997; Ren and Yang, 2006; Rašković *et al,* 2008):

- the system is in a steady-state,
- no heat transfer to the surroundings occurs, and radiation heat transfer is ignored,
- specific heat capacities, as well the heat and mass transfer coefficients are constant,
- fluids at entry are uniformly distributed in the plane perpendicular to the flow,
- mass and heat transfers take place only in the direction normal to the flow,
- complete surface wetting of the tube bundle is assumed, and
- resistance of the heat transfer from the water layer core to its surface is neglected; temperature of the water at an inter phase surface is equal to an average value; according to Zalewski (1992) the temperature difference, in this case, does not exceed 0,4%.

Works on formulations and modelling of processes involved in evaporative cooling have been concisely described in the following subsections.

A. Mathematical model of heat and mass transfer processes in evaporative fluid coolers

Zalewski (1993) presented a mathematical model of evaporative cooling, based on the heat and mass transfer equations for non-adiabatic evaporation. The mass transfer coefficient is obtained by analogy with heat transfer correlations of fluid flow across tube bundles. A correction for the mass transfer coefficient was suggested as a function of in let air wet bulb temperature.

Similarly, Zalewski and Gryglaszewski (1997) modified the mathematical model of evaporative fluid cooler by using four ordinary differential equations with their associated boundary conditions and some algebraic equations. Figure 8 shows the schematic of the evaporative fluid cooling process modelled by them.

The differential equations used by them are described below:

$$\frac{dx}{dl} = -\frac{\beta_x f_m \; B\{X''(T_w) - X\}}{m_{ps}} \qquad 7$$

$$\frac{dT_p}{dl} = -\frac{B\,(T_w - T_p)}{m_{ps}\; c_p}\left\{\beta_x \; f_m \; C_{pw}\langle X''(T_w) - X\rangle\right\} + \left\{F_t \; \propto_p\right\} \qquad 8$$

$$\frac{dT_w}{dl} = \frac{B}{m_w\, C_w}\left\{\beta_x\, F_m\left[T_w\left(C_w - C_{pw}\right) - r_o\right]\left[X''(T_w) - X\right] - f_t \; \propto_p \left(T_w - T_p\right) + K_z\left(T_f - T_w\right)\right\} \qquad 9$$

$$\frac{dT_f}{dl} = -\frac{K_z\left(T_f - T_w\right)}{m_f\, C_f} \qquad 10$$

The boundary conditions for the equations (7) - (10) are as follows:

$X(L) = X_1$; $T_p(L) = T_p X_1$; $T_w(0) = T_w(L)$ and $T_f(0) = T_{f1}$

Where,

X = air humidity ratio ($kg_w \, kg_{ps}^{-1}$)
L = length, linear coordinate, (m)
β_x = mass transfer coefficient, (kgps m^{-2} s^{-1})
f, f_t, f_m= area ratio

B = length of wall, length of tubes of exchanger, (m)
T = temperature (°C)
$\propto$ = heat transfer coefficient (W m^{-2} K^{-2})
r_o = latent heat of vaporization at 0°C; r_o = 2500800 (J kg^{-1})
h = specific enthalpy (J kg^{-1})
W= mass flow rate of water vapor (kg s^{-1})
Q_k = heat flux through wall (W)
Q_p = heat flux from water surface into air (W)
δ = thickness, (m)
c = specific heat at constant pressure (J kg^{-1} K^{-1})
Subscripts
ps = dry air
pw = water vapor
f = cooled liquid
p = moist air
w = spraying water
1= inlet (initial) value
2= final (outlet) value
s = wall
“ = saturation state

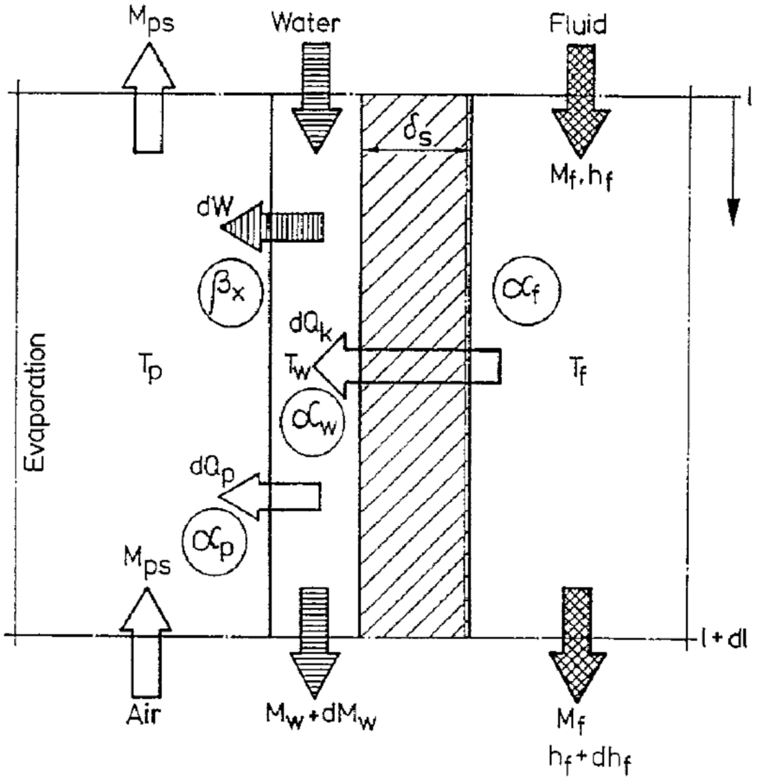

Figure 9: Heat exchange scheme of evaporative fluid cooler as used by Zalewski and Gryglaszewski (1997)

The model heavily depends on the specification of the geometry of evaporative fluid cooler which is mostly not available in manufacturer’s catalogue data. Also, spray water temperature input parameter required by the model is not available in the catalogue data. Along with these, determination of heat and mass transfer coefficient is very difficult. Because of the reasons stated above, the model is not suitable for implementing into the building energy simulation programs.

Similarly, Quereshi and Zubair (2005) gave a comprehensive design and rating study of evaporative fluid coolers. They studied effect of fouling on thermal effectiveness of evaporative fluid cooler and evaporative condenser. They took infinitesimal control volume of evaporative heat exchangers consisting of three subsystems having air, water and process fluid. The results show that effectiveness of evaporative heat exchangers are decreased by more than 50% because of fouling. This caused outlet process fluid temperature to increase by 5%.

A. Mathematical model of the overall energy balance.

The sub-wet bulb temperature evaporative cooler was modelled using common energy and mass conservation laws (Boukhanouf *et al.,* 2014). In the model the dry and wet channel were divided into small elements (finite volumes) to which the energy and mass transfer equations were applied. The overall energy and mass balance at the water film interface between the air flow in the dry channel, the water film on the ceramic surface and the air flow in the wet channel can be expressed as:

$$\frac{\dot{m}_{fw}c_{pfw}T_{fw}}{dA} = U\left(T_d - T_{fw}\right) - \sigma\left(g_{fw} - g_w\right)h_{fg} - \alpha\left(T_{fw} - T_w\right) \qquad 11$$

The governing differential equations were discretised and applied to each finite volume element along the dry and wet channel length. In the computer model, it was assumed that the air properties, heat and mass transfer coefficients are constant in each finite control volume, the water film and the non-permeable membrane thermal resistances were assumed to be negligible.

The initial conditions used in this model include known air properties (temperature and moisture content) for the dry channel and air moisture content for the wet channel. The main design parameters of the system are given in Table 2.

Table 2: Design and modelling parameters in Evaporative cooling systems

Air channel Length	0.64 m
Air channel Width	0.93 m
Air channel Height	0.005 m
Mass low rate in the dry channel	0.03 (kg/s)
Mass flow rate in the wet channel	0.012 (kg/s)
Air flow regime	Laminar
Fan power rating	16-24V, 14 W
Porous Ceramic materials composition	Al_2O_3, SiO_2, Si_3N_4
Porosity	17%
Density	2300 kg/m^3
Thermal conductivity	1.5 W/mK

Computation of the operating parameters of airflow along the air ducts length was performed iteratively until converging conditions were satisfied giving a temperature difference between two consecutive iterations of less than 0.01°C. It was shown that the evaporative cooler can achieve high thermal performance in terms of low air supply temperatures and effectiveness. The structural stability and manufacturing controllability of ceramic materials lend them well to integration into buildings and performing the function of air conditioning in regions with hot and dry climatic conditions.

B. Modelling of direct and indirect evaporative cooling.

In direct evaporative cooling, Heidarinejad and Bozorgmehr (2008) cited lots of works on modelling of direct evaporative cooling, which includes Camargo *et al.* (2005) presentations on the principles of operation for the direct evaporative cooling system for human thermal comfort, and the mathematical development of the equations of thermal exchanges, allowing the determination of the effectiveness of saturation; Dai and Sumathy (2002) investigated a cross-flow direct evaporative cooler, in which the wet honeycomb paper constitutes the packing material and the results indicated that there exists an optimum length of the air channel and the performance can be improved by optimizing some operation parameters. Liao and Chiu (2002) developed a compact wind tunnel to simulate evaporative cooling pad-fan systems and tested two alternative materials. Al-Sulaiman (2002) evaluated the performance of three local natural fibres (palm fibre, jute and luffa) to be used as wetted pads in evaporative cooling.

In the field of indirect evaporative cooling, Maclaine-cross and Banks (1981) analysed the evaporative heat transfer in an indirect cooler. They suggested a simplified analysis model assuming that water film is stationary and continuously replenished with water at the same temperature and saturation line is a linear function of temperature. The resulting decoupled equations describing the wet and the dry passages of the cooler were solved by defining a new independent variable: wet bulb depression which is the difference between dry bulb and wet bulb temperatures. This model then could be used to predict the cooler performance by analogy to dry surface heat exchangers.

Pescod (1979) proposed a simple design method for indirect evaporative cooler using parallel plastic plates with small protrusions. Although the thermal conductivity of plastic is very low, the heat transfer resistance across a thin plastic plate would be less than of the thermal resistance between the air and plate in dry side. Predictions of the efficiencies of Pescod’s wet surface plate heat exchanger were found to be higher than the experimental data. Thus incomplete wetting of plate surfaces was suspected.

There are three different models describing evaporative indirect cooler:

1. Poppe model considering a variable Lewis factor, spray water evaporation rate and modelling over saturation in the secondary air;
2. Merkel model- can be derived from Poppe model by assuming a Lewis factor of unity and negligible effect of spray water evaporation and assuming that the secondary air never becomes over saturated;
3. Simplified model- assuming that the water temperature is constant throughout the cooler.

The models were applied to a cross flow indirect cooler and simplified model was recommended for small units and for initial design purpose (Heidarinejad and Bozorgmehr, 2008; Erens and Dreyer 1993).

The thermal analysis of evaporative fluid cooling unit is inherently complicated because the cooling process involves simultaneous heat and mass transfer processes. For that reason a lot of different numerical models, classified as de tailed or simple (correlation-based), are developed in the past (Facao and Oliviera, 2000).

4.0 ECONOMIC EVALUATION OF EVAPORATIVE COOLING SYSTEMS.

Estimated cost for installation of an evaporative cooler is about half that of central refrigerated air conditioning (Krigger and Dorsi, 2004). Also, estimated cost of operation is 1/8 that of refrigerated air, power consumption is limited to the fan and water pump and because the water vapour is not recycled, there is no compressor that consumes most of the power in closed-cycle refrigeration (Wikipedia, 2012). The refrigerant is water. No special refrigerants, such as ammonia or CFCs, are used that could be toxic, expensive to replace, contribute to ozone depletion and/or be subject to stringent licensing and environmental regulations.

Vegetable and fresh produce storage has proven to be a good application for evaporative cooling. High temperature is an important factor in produce preservation that can be combated by evaporative cooling (FAO, 1989). To lengthen storage life, fresh produce needs to be stored in conditions of high humidity to reduce water loss which evaporative cooling can also achieve (Appropedia, 2016). The financial impact of evaporative cooling in produce preservation can be substantial. For example, in India where post-harvest losses can reach 30% annually, the use of an evaporative cooler can reduce food loss resulting in increased income for farmers and decrease the amount of money spent on food as it can be preserved longer (Jain, 2007).

Certain economic evaluations have estimated a payback period of 1.2 years for an evaporative cooling system depending on the size and quantity of produce sold (Seyoum, 2010).

Evaporative cooling provides an economical means of personal thermal comfort in arid climates. It is used in about 90% of the residences in the West Texas region and approximately 4.5 million residences throughout the United States (Foster, 1999; Paschold *et al*, 2003).

The main advantages of evaporative coolers are their low cost and high effectiveness, permitting a wide range of applications and versatility in the buildings, dwellings, commercial and industrial sectors. They can be specially applied in dry and hot climates, as the minimum cooling temperature for the air depends on it’s the wet bulb temperature. It is convenient sometimes to humidify the air, in which cases the direct evaporative cooling is an interesting solution. On the other hand, conventional air-conditioning systems usually dry up the air for being controlled only by the return temperature level and not by the required humidity levels. When it is not possible to humidify, indirect evaporative systems in a regenerative or recovering configuration are preferred (Gomez et al., 2010).

With these advantages the evaporative cooling system face the environmental, technical and little health difficulties

A. ENVIRONMENTAL DIFFICULTIES

Evaporative cooling is used extensively worldwide, in regions of dry climate such as northern India, South Africa, and Australia (Watt and Brown, 1997).

Orientation of the greenhouse relative to other buildings or structures and in relation to prevailing summer winds influences the efficiency of operation. Fan arrangements and locations of the fans and pads should be determined by greenhouse location and orientation (Bucklin *et al.,* 2016).

The cooling effect of an evaporative cooler depends on the rate of evaporation and on conditions within the cooler. Environmentally, temperature and humidity have the most significant impact on evaporation. The temperature must be high enough to allow for evaporation and the relative humidity must be low enough to allow for more water vapour to enter the air. Water quality also has an important role in both evaporation and keeping the system well maintained (Fouda and Melikan, 2011).

Evaporative coolers can only provide cooling down to 10^0C under optimal conditions. Lower temperatures require different cooling technologies (Holand, 2010; Appropedia, 2016).

B. TECHNICAL DIFFICULTIES

Evaporative cooling differs from common air conditioning and refrigeration technologies in that it can provide effective cooling without the need for an external energy source (liberty *et al*., 2013).

The major problems with evaporative cooling system operation can often be traced to poor initial evaporative air cooler installation and/or supply air design; untrained evaporative air cooler's operators; insufficient maintenance; atmospheric conditions and efficiency of cooling pads.

Cooling pads lose efficiency due to clogging from impurities in the water, algae growth and decay. If the pad material is clogged or decomposed its ability to function as designed is impaired. Air exhausted by the fans will enter the building at the point(s) of least resistance. If a pad area is totally or partially clogged, very little if any air will pass through that portion of the pad. If the pad has holes, the air will move directly through them. This means less contact between air and water and much less cooling. When a pad has decayed, the only alternative is to install a new pad (Bucklin *et al,* 2016).

There is often a problem of perception of the capabilities of evaporative cooling. Some building occupants are so accustomed to the "flip-a-switch" world that they expect to be able to maintain comfort conditions under any conditions (Palmer, 2002).

Compared to the conventional systems, the evaporative cooling systems suffer from the following disadvantages:

1. The moisture level in the conditioned space could be higher, hence, direct evaporative coolers are not good when low humidity levels in the conditioned space is required. However, the indirect evaporative cooler can be used without increasing humidity
2. Since the required air flow rates are much larger, this may create draft and/or high noise levels in the conditioned space
3. Precise control of temperature and humidity in the conditioned space is not possible
4. May lead to health problems due to micro-organisms if the water used is not clean or the wetted surfaces are not maintained properly.

C. HEALTH IMPLICATIONS

Aldous *et al*. (1996) examined the relationship between several home environmental factors and lower respiratory tract illness (LRI) in infants at homes equipped with evaporative coolers. A statistically significant relationship between wheezing LRI in infants living with other children in a house and the use of evaporative cooling was found (24% versus 15% for non-evaporative air cooled homes). This study also found an increased occurrence of non-wheezing LRI for infants as neighbourhood dustiness increased. Unfortunately, no measurements of PM (Particulate Matter) levels were made and the assessment of "dustiness" was based on subjective records provided by the adult test subjects participating in the study. The study suggested that outdoor PM is related to chronic cough, bronchitis, and "chest illness", but not to asthma or wheezing and that evaporative cooling may introduce pollutants other than ambient PM (pollen, fungi, or other particulates) contributing to increased LRI rates.

An evaporative cooler is a common place for mosquito breeding. Numerous authorities consider an improperly maintained cooler to be a major threat to public health (Reddy and Prasanna, 2015).

Improperly maintained evaporative cooling towers can be linked to a number of outbreaks of Legionnaires' disease, due to the conditions in the cooling tower being ideal for the proliferation of Legionella bacteria. There has, however, never been a case of Legionnaire's disease (or Pontiac fever, or other related illnesses) attributed to a properly maintained evaporative cooling tower; Odours and other outdoor contaminants may be blown into the building unless sufficient filtering is in place; Mould and bacteria may be dispersed into interior air from improperly maintained or defective systems, causing Sick Building Syndrome; Asthmatics and allergy sufferers may be advised to avoid improperly maintained evaporatively cooled environments; A sacrificial anode may be required to prevent excessive evaporative cooler corrosion; Wood wool of dry cooler pads can catch fire even by small sparks (Wikipedia, 2012).

5.0 CONCLUSIONS

Many studies have been conducted regarding vegetable storage in Nigeria. One study used a cooler with coconut fiber as the absorbent in a cabinet shaped cooler. During a no-load test, the cooler was able to achieve cooling of 0.1^0C-8.3^0C. When the relative humidity was 80%, it was found that no cooling occurred. Using the cooler, pumpkins were stored 60 hours instead of 12 hours without cooling and tomatoes lasted for 93 hours compared to 32 hours (Anyanwu, 2004).

Another researcher in Nigeria constructed an evaporative cooler out of clay with one cooling pad and a reflective surface on the roof. The cooler reduced ambient temperatures from range of $32\text{-}40^0$C to $24\text{-}29^0$C throughout the day. The cooler has a cooling capacity from 870-1207 W and was able to store tomatoes for 19 days (Chinenye, 2011).

Similar studies from Mogaji and Fapetu (2011) have shown increases in storage life of 14 days over ambient storage conditions.

With refrigerating systems decreases both temperature and humidity with high energy consumption while evaporative cooling decreases less temperature and increases humidity with a considerable amount of energy, which is more suitable for storage of agriculture produce, which does not require very low temperature (Wilson et al., 1995; Nitipong and Sukum, 2011).

A review of evaporative cooling system has been undertaken. From this study, the following are evident:

1. Evaporative cooling can be specially applied in dry and hot climates, as the minimum cooling temperature for the air depends on it's the wet bulb temperature.
2. Materials for the design of an evaporative cooler are cheap and readily available.
3. With evaporative cooling, air conditioning is simple to achieve with the least energy consumption, and safe environmental activity.

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