Two Stage Indirect/Direct Evaporative Cooling

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Abstract—The performance of two-stage indirect/direct evaporative cooling system is experimentally investigated. For this purpose, a two-stage evaporative cooling experimental setup consisting of an indirect evaporative cooling stage (IEC) followed by a direct evaporative cooling stage (DEC) was designed, constructed and tested. Two air simulators are provided to simulate outdoor design condition in primary and secondary air streams. To achieve comfort conditions and power saving the system has been investigated with related excess water consumption. Considering the evaporative comfort zone, this system can provide comfort condition in a vast region where direct evaporative system alone is not able to provide summer comfort condition. More than 60% power saving could be achieved by this system in comparison with mechanical vapor compression systems and 55% increase in water consumption with respect to direct evaporative cooling systems. This system can complete the gap between direct evaporative cooling systems and mechanical vapor compression systems as an energy efficient and environmentally clean alternate.

I. INTRODUCTION

Evaporativecoolingisanenvironmentallyfriendlyand energyefficientmethodforcoolingbuildingsinhotand dryregions.Indiaasamulti-climatecountrydemandsavarietyofcoolingsystemstoachieveoptimizedenergyconsumption,reduceemission,andprovidesummercomfortcondition.Manytypesofnaturalandpassivemethodswereusedforcoolingbuildings.Allofthesemethodshavebeenworkedbasedonnatural ventilation.Windtowerandshapeofbuildingarethemainelementsinthesetraditionalcoolingmethods,which deviateandconveyoutsideairtobuildings.

Two principle methods of evaporative cooling are commonly used, the direct (DEC) and the indirect one (IEC).DEC is the simplest, oldest, and the most widespread form of evaporative air conditioning. This system typically uses a fan to draw hot outdoor air into a porous wetted medium. The water absorbs heat as it evaporates from the porous wetting medium, and the air thus leaves the DEC at a lower temperature.In fact, dry bulb temperature of the air reduces as it is moistened in thisadiabatic saturation process. The principle underlying DEC is the conversion of sensible heat to latent heat. The wetted medium could be a porous wetted pad consisting of fibers, cellulose papers or a spray of water.

A. 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.

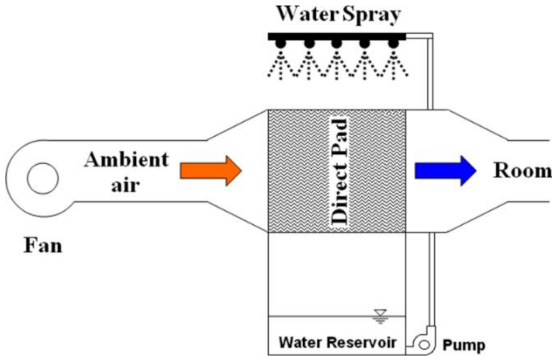

Fig. 1. DIRECT EVAPORATIVE COOLING

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. 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 following equation:

$$\varepsilon = \frac{Tdb - SAT}{Tdb - Twb} \quad \textbf{(1)}$$

Where Td_b is the outdoor dry-bulb temperature, Tw_b is the outdoor wet-bulb temperature and SAT is the supply air temperature 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.

1) ACTIVE DIRECT EVAPORATIVE COOLING SYSTEM

The active direct evaporative coolers are electricity-driven systems, however, it use a fraction of power for air and water circulation. So, it is considered much less energy intensive than other traditional cooling technologies, with energy saving up to 90%. A typical direct evaporative cooler comprises of evaporative media (wettable and porous Pads), fan blows air through the wetted medium, water tank, recirculation pump and water distribution system. The direct evaporative cooling is an adiabatic cooling process, i.e. the total enthalpy of the air is constant throughout the process. The water absorbs the sensible heat from the supply air and evaporates causing the air temperature decreases and its humidity to increase

Theoretically, the supply air could be cooled to 100% effectiveness, but in such process a wet-bulb effectiveness of 70%-80% only is achievable because of short contact time between the two fluids, insufficient wettability of the pads and due to the fact that the circulated water and the supply air will reach an equilibrium point that is equal to the wet-bulb temperature of the supply air. Eventually the system would not be able to cool down the incoming air lower than its wet-bulb temperature. The wet-bulb effectiveness could reach range between 70-95% in most current commercial DEC coolers and mainly as a function of the type and thickness of evaporative media, working climate, and supply air flow-rate.

According to ASHRAE Handbook-HVAC Systems and Equipment (2008) active DEC could be divided according to types of wet media into: Random media DEC, Rigid media DEC and Remote media DEC as shown in figure 2.

Fig. 2. TYPES OF DEC SYSTEM PADS

2) PASSIVE DIRECT EVAPORATIVE COOLING

Passive cooling techniques use natural phenomena, energies, and heat sinks for cooling buildings without the use of mechanical apparatus consume electrical energy. However, small fans and pumps could be required. Passive DEC is relied on the climate which means the techniques applied for hot and humid regions are different from those for hot and arid areas. This technology is able to reduce indoor air temperature by about 9 ℃. The main types of passive direct evaporative cooling building integrated systems are:

(a) The Mashrabiya

(b) Wind Towers

(c) Roof-Pound

B. INDIRECT EVAPORATIVE COOLING SYSTEM

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 evaporative. 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%. 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. 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 two 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.

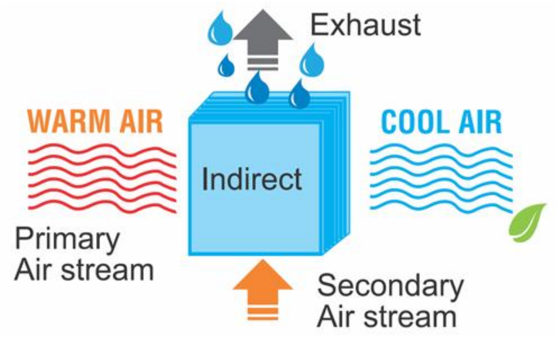

Fig. 3. INDIRECT EVAPORATIVE COOLING

The effectiveness of indirect evaporative cooling can be expressed as:

$$\varepsilon = \frac{t1-t2}{t1-twb\,1} \quad \textbf{(2)}$$

ε = indirect evaporative cooling effectiveness, %

t1 = dry bulb temperature of entering primary air℃

t2 = dry bulb temperature of leaving primary air, ℃

$t$wb1= wet bulb temperature of entering secondary air, ℃

Direct Evaporative Cooling system (DEC) and Indirect Evaporative Cooling system (IEC) are two main groups in evaporative cooling systems. In hot and humid or temperate and humid regions where the DEC and IEC systems do not provide comfort condition, mechanical vapor compression cooling systems are used. Some advantages of evaporative cooling systems in comparison with mechanical vapor compression systems are as following:

(a) Reduction in input power and input current.

(b) Using water as the working fluid which is environmentally friendly

(c) Elimination of CFC gases which are harmful to ozone layer

(d) Ability to induce fresh air into the room.

(e) Base price is low.

Also, some disadvantages of evaporative cooling systems are as following:

(a) Water supply restrictions in an area where there is scarcity of water.

(b) Evaporative cooling systems will have little or no cooling effect in a moist environment.

(c) Due to supply of humid air in the room, the air within the room will get saturated.

(d) Evaporative cooling systems need more frequent maintenance.

(e) Ductwork is required in Evaporative cooling systems.

In both the above cases of Direct evaporative cooler (DEC) and Indirect evaporative cooler (IEC) the minimum temperature to which air can be cooled theoretically is the wet bulb temperature (WBT) of the incoming air. Therefore a combination of above two systems called indirect-direct two stage evaporative cooling is used to improve the performance of the whole system. Such a system reduces the dry bulb temperature (DBT) of incoming air in a heat exchanger before it passes to the direct stage. Such a system can ultimately reduce the temperature of the incoming air below its WBT.

C. INDIRECT DIRECT EVAPORATIVE COOLING SYSTEM

Two-stage indirect/direct evaporative coolers as shown in Figure 4 can cool air to lower temperatures than are attainable with direct (“one-stage”) evaporative coolers, and add less moisture to the indoor air. In these coolers, a first-stage indirect evaporative cooler lowers both the dry bulb temperature (DBT) and wet bulb temperature (WBT) of the incoming air. After leaving the indirect stage, the supply air passes through a second stage direct evaporative cooler. Figure 5 shows the cooling process on a psychrometric chart. First-stage cooling follows a line of constant humidity ratio as no moisture is added to the primary airstream; the second stage follows the WBT line at the condition of the air leaving the first stage.

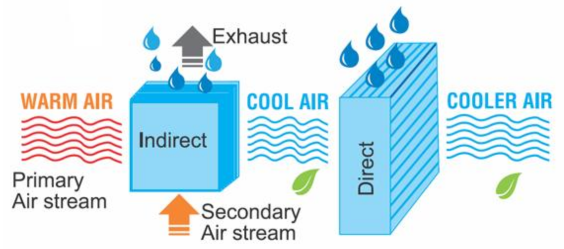

Fig. 4. INDIRECT DIRECT EVAPORATIVE COOLING

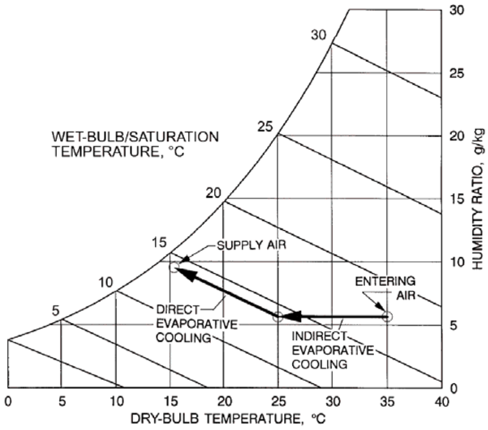

Fig. 5. INDIRECT DIRECT EVAPORATIVE COOLING PROCESS

Different researchers have made the effort to improve the performance of these systems by changes in design, process and materials.

G. Heidarinejad 2009 experimentally investigated the cooling performance of two stage indirect/direct evaporative cooling system in various simulated climatic conditions in Iran. They used plastic wet surface heat exchanger as an IEC unit and 15 cm thick cellulose pad for a DEC unit. They obtained an effectiveness of IEC unit in the range of 55 % -61 % and effectiveness of IEC/DEC unit in the range of 108 % -111 %. They also reported 55 % more water consumption than DEC unit and power consumption as 33 % of mechanical cooling systems.

Jain 2007 developed and tested a two stage evaporative cooler to improve the efficiency by using wooden shave as the packing material. Room return air was evaporatively cooled and used in a heat exchanger to cool the incoming dry air. The effectiveness ranged from 1.1 to 1.2 and this cooler could achieve favourable temperature and relative humidity conditions for storage of tomatoes for 14 days.

Camargo 2005 developed a mathematical model for a DEC and presented their experimental results of the tests using rigid cellulose media with wetted surface area of 370 m2/m3. The effectiveness relation derived in terms of heat transfer coefficient, mass flow rate of air, wetted surface area and humid specific heat is useful in predicting the performance of different pad materials. They concluded that the effectiveness is higher at higher dry bulb temperature and lower air speeds.

El-Dessouky 2004 carried out theoretical and experimental study on small scale evaporative cooling unit using structured packing material of high density polythene with wetted surface area of 420 m2/m3. They used a combination of DEC and IEC and concluded that the efficiency of IEC unit is less than DEC but a combination of both can reduce the temperature of incoming air below its WBT.

Maheshwari2001 compared the power requirements of an IEC unit with conventional packaged air conditioner. They concluded that the best performance of IEC unit coincides with the hour of maximum cooling capacity and peak power demand of conventional unit and it offers maximum reduction in cooling capacity and peak power demand.

El-Dessouky1996 used the concept of pre-cooling the air before DEC without using cooling tower. Structured, sheathy leaf and natural fiber packing was used as cooling media with varying thickness and flow of water. They observed that effectiveness increased with packing thickness and flow rate of water to IEC. Structured packing showed higher effectiveness than sheathy leaf and natural fiber.

Dowdy and Karbash 1987 tested rigid impregnated cellulose media experimentally to determine heat and mass transfer coefficients for evaporative cooling process. They used the sample of rigid cellulose media having wetted surface area of 350 m2/m3 with thickness 305 mm and obtained saturation efficiency between 90 to 94 %.

II. EXPERIMENTAL SETUP

To evaluate performance of IEC/DEC system and in order to investigate effect of operational parameters, an experimental setup was designed and constructed as shown in Fig. 6. Test setup consists of four major modules:

1) A primary air simulator including a centrifugal fan provided with a frequency inverter to adjust flow rate, electrical heating elements, and electrical humidifier. This module adjusts flow rate, temperature, and relative humidity in primary air stream. A straighter was installed to achieve airflow uniformity.

2) Secondary air simulator is similar to primary air simulator in secondary air stream.

3) IEC/DEC unit including a polycarbonate wet surface heat exchanger as IEC unit, a cellulose pad as DEC unit, a water circulating pump and two flow meters and two valves to control water flow rate of indirect and direct evaporative systems. Water is distributed over indirect and direct systems using proper spray nozzles.

4) Control panel for setting steady-state temperature and relative humidity and flow rate of primary and secondary air.

As shown in Fig. 6, temperature and relative humidity (RH) are measured in the following positions:

a) Air temperature and RH before the IEC unit in primary andsecondary flows.

b) Air temperature after the IEC unit in primary flow.

c) Air temperature and RH after the IEC unit in secondary flow.

d) Air temperature and RH after the DEC unit.

III. EXPERIMENTAL PROCEDURE

In Indirect evaporative cooler, hot and dry secondary air enters the heat exchanger from the bottom duct. Water flowingalong the polycarbonate plates in downward direction gets evaporated due to heat of air and takes heat from air as well as plates. As a result the temperature of plates is reduced. Warm and humid secondary air is discharged through the upper duct on the same side. The primary air enters the indirect evaporative cooler horizontally from the primary air simulator due to suction of air in primary fan. The cooling effect produced in secondary channels is transferred to the primary air flowing through the alternate channels and thus primary air gets cooled. The primary air travels in horizontal direction through the IEC and enters the DEC on the opposite side.

In direct evaporative cooler, primary air comes in contact with wetted pad surface. Water on the pad surface getsevaporated by taking heat from incoming air. Thus the temperature of primary air is reduced in two stages first in IEC and then in DEC.

IV. INDICATIVE PARAMETERS

A. WET BULB & DEW POINT EFFECTIVENESS

Wet-bulb effectiveness is a parameter describing the extent of the approach of the outlet product air temperature of the IEC against the wet-bulb temperature of the inlet working air, and can be written as:

$$\boldsymbol{\varepsilon_{wb} = \frac{t_{p,db,in} - t_{p,db,out}}{t_{p,db,in} - t_{p,wb,in}}} \quad \textbf{(3)}$$

Dew point effectiveness is another parameter used for this purpose and defined as the ratio of the temperature difference between the inlet and outlet product air to the difference between the inlet product air's dry bulb and inlet working air's dew point temperature. This reflects the extent of the approach of the outlet product air temperature against the dew point temperature of the inlet working air related to the IEC, shown as follows:

$$\varepsilon_{dp} = \frac{t_{p,db,in} - t_{p,dh,out}}{t_{p,db,in} - t_{p,db,in}} \textbf{(4)}$$

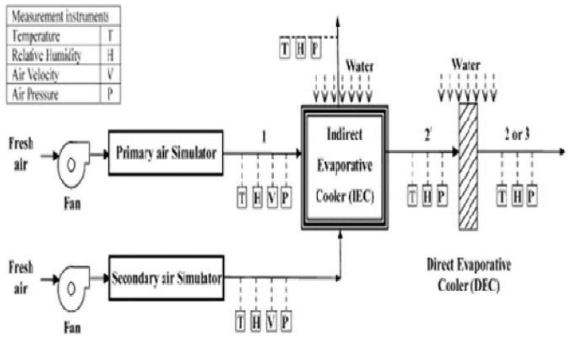

Fig. 6. EXPERIMENTAL SETUP

B. EVAPORATIVE COOLER EFFIECIENCY RATIO

ECER, defined as the ratio of the cooling delivery volume to electrical power related to the IEC, is measured on the condition of intake air dry/wet bulb temperature of 32.8/ 20.6 1ºC and room air temperature of 26.7 1ºC. This could be expressed in the following equation:

$$ECER = \rho_f c_f [t_{room} - (t_{p,db,in} - t_{p,wb,in})] V_{p,out} / W \textbf{(5)}$$

C. COOLING CAPACITY

The cooling capacity refers to the enthalpy change of the product air when travelling across the dry channels of the IEC heat exchanger, and is expressed as follows:

$$Q_{total} = \rho_f V_{p,out} (i_{p,db,in} - i_{p,db,out}) \textbf{(6)}$$

Since the air is cooled at the constant moisture contentduring the dry channels of the IEC exchanger, theenthalpy change of the air could be represented by the temperature reduction of the air during its dry channel flow path. For this reason, the above equation could be rewritten as:

$$Q = c_f \rho_f V_{p,out} (t_{p,db,in} - t_{p,db,out}) \textbf{(7)}$$

D. ENERGY EFFICIENCY

Energy efficiency, known as 'coefficient of performance (COP), is the ratio of the cooling capacity of the IEC to the power consumption of the system. This term can be mathematically expressed as:

$$\eta = \frac{Q}{W} = \frac{c_f \rho_f V_{p,out} (t_{p,db,in} - t_{p,db,out})}{W} \textbf{(8)}$$

If this figure is multiplied by a unit conversion factor of 3.413, the COP is then converted into the energy efficiency ratio (EER).

E. WATER EVAPORATION RATE

The water evaporation rate of an IEC system depends upon a number of its operational parameters, e.g., the inlet air temperature/humidity, airflow rate, treated cooling load, as well as the swellas system's cooling effectiveness. Theoreticallyspeaking, the water evaporation rate is equal to the volume of the moisture increase in the working air during its indirect cooling operation and could be expressed as:

$$V_w = \frac{V_{s,out}\,\rho_{s,f}}{\rho_w}(W_{s,out} - W_{s,in}) \quad \textbf{(9)}$$

F. SECONDARY TO PRIMARY AIR RATIO

In an IEC system, the secondary air, known as the 'working air' is used to cool the primary (i.e., product) air. Ratio of the secondary to primary air-flow is an important measure effecting on the cooling performance of the system. It is claimed that the ratio of the secondary to primary air is usually in the range 0.3–1.0 and during operation, increasing the value of this ratio will lead to increase of the cooling effectiveness. However, this increase will also lead to reduced supply air volume and thus the overall cooling capacity of the system may fall. There will be an optimised figure on the ratio that will enable the maximised cooling capacity of the system and adequate cooling effectiveness. This figure will be determined using the dedicated computer programme under a given geometrical and operational conditions.

G. PRESSURE LOSS

Pressure loss refers to static pressure drop of the air when passing across the dry and wet channels of an IEC heat exchanger.

H. AIR FLOW RATE

Air flow rate refers to air volume flow rate across the IEC heat exchanger channels including dry and wet channels. The air flow rate is usually measured by the unit of m^3/s orm^3.

V. CONCLUSION

The results obtained from experimental two-stage indirect/direct evaporative cooling system shows that, this system has high potential to provide comfort conditions in regions where at present standalone direct evaporative coolers cannot provide comfort conditions. Also in regions with higher wet bulb temperatures, this system can be used instead of mechanical vapor compression systems, which results decrease in electrical energy consumption. Despite wide variety of climatic conditions, it is found that IEC effectiveness varies between 55 and 61% and IEC/DEC effectiveness over a range of 108–111%. The average water consumption of two-stage evaporative cooling system is 55%more than direct evaporative cooling system and power consumption is33% of mechanical vapour compression cooling systems, so this cooling system can be used in various climatic conditions as an environmentally clean and energy efficient system.

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