Evaporative Cooling Technologies: A Review

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ABSTRACT: The function of air conditioning in maintaining the thermal comfort of inhabitants is critical. However, the energy costs for the building have grown prohibitive. However, the most widely used cooling methods, vapor compression systems, are very energy-intensive. This article will examine current advancements in evaporative cooling systems, which have the potential to offer adequate cooling comfort while reducing environmental impact and lowering energy consumption in buildings. An thorough literature study was performed, and the state-of-the-art evaporative cooling systems were mapped out. Direct evaporative cooling, indirect evaporative cooling, and combination direct-indirect cooling systems are all included in this study. Because of its excellent thermal performance, indirect evaporative coolers, which include both wet-bulb temperature and dew point evaporative coolers, have piqued attention. For its increased efficiency and reduced energy consumption, dew point evaporative coolers have shown tremendous promise for development and study.

KEYWORDS: Adequate Cooling, Dew Point, Dry Bulb Temperature, Evaporative Cooling, Effectiveness.

INTRODUCTION

Building cooling energy consumption has risen dramatically in recent decades, raising worries about depletion of energy supplies and contributing to global warming. According to current estimates, energy demand accounts for between 40 and 50 percent of overall primary power use [1]. Evaporation is a natural process for cooling. Perspiration, or sweat, is the most frequent example we all encounter. Perspiration absorbs heat and cools your body as it evaporates. Evaporative cooling is based on the notion that water must be heated in order to transform from a liquid to a vapor. When water evaporates, the heat is transferred to the water that remains in a liquid form, resulting in a colder liquid. Evaporative cooling systems offer cooling for equipment and structures by using the same concept as sweat [2]. A cooling tower is a heat-rejection device that uses water cooling to release heated air from the cooling tower into the atmosphere. The term "cooling tower" is used in the HVAC industry to refer to both open- and closed-circuit heat-rejection equipment. Heat is produced in an HVAC system by the sun shining on the building, computers, and humans. The heat is collected in the air handlers, which are connected to the refrigerant through a series of heat exchangers [3]. The refrigerant is converted from a liquid to a vapor by the heat.

Cooling tower water circulates via a heat exchanger, which condenses refrigerant vapor and transfers heat to the water. The cooling towers' function is to chill the heated water that returns from the heat exchanger so that it may be reused. The heated return water from the heat exchanger is sprayed over the "fill" in the open cooling tower. The fill increases the surface area of the water, allowing more heat to pass between it and the air, causing some of the water to evaporate [4]. The cold water then returns to the start of the operation, absorbing additional heat from the heat exchanger. Cold water or a solution of ethylene or propylene glycol is used to cool a closed circuit cooling tower. Unlike an open cooling tower, the cooling fluid is contained in a coil and is not exposed to the air directly. The exterior of the coil, which holds the fluid that has been heated by the process, is recirculated with cold water [5]. Heat is transmitted from the fluid to the spray water and subsequently to the atmosphere when a part of the water evaporates during operation. The cold fluid in the coil then loops back to the start of the operation, where it is reused. Space air cooling with conventional HVAC systems accounts for the majority of building energy consumption in hot climate nations. In the Middle East, for example, it accounts for 70% of building energy use and roughly 30% of overall consumption. Building air conditioning has become a requirement for people's lives in recent years, and it plays a critical role in maintaining interior comfort levels [6]. As a result, increasing the efficiency of cooling technologies is critical, especially those with promise, such as high performance and low power consumption.

Despite their high energy consumption and poor performance in hot climates, mechanical vapor compression coolers (MVC) are now the most popular. Evaporative cooling systems, on the other hand, are more ecologically friendly since they use less energy and enhance performance as air temperature and humidity rise. a comparison of various cooling cycles' coefficients of performance (COP). The primary disadvantage of evaporative cooling is its significant reliance on the ambient air conditions. Evaporative cooling is driven by the temperature differential between the dry and wet bulb temperatures of the ambient air [7]. This difference is minimal in mild and/or humid climates, resulting in inadequate cooling capability. Evaporative cooling is a heat and mass transfer technique that utilizes water evaporation to cool the air, transferring a significant quantity of heat from the air to the water and lowering the air temperature as a result. Evaporative coolers are divided into three categories: (1) direct evaporative coolers, in which the working fluids (water and air) are in direct contact; (2) indirect evaporative coolers, in which the working fluids are separated by a surface/plate; and (3) combined systems of direct and indirect evaporative coolers and/or other cooling cycles [8]. A categorization of the many kinds of evaporative cooling systems used in buildings. This is the earliest and most basic form of evaporative cooling, in which the outside air is brought into direct contact with water, converting sensible heat to latent heat and so chilling the air.

Ancient civilizations utilized ingenious methods in a variety of configurations thousands of years ago, some of which included utilizing earthenware jars with water contained, wetted pads canvas placed in air channels. In terms of operating power consumption, direct evaporative coolers in buildings range from zero to high power consumption systems. Active DECs, which are electrically powered to function, and Passive DECs, which are naturally operated systems with negligible power usage, are the two types of DEC systems. DEC is only appropriate for dry, hot regions [9]. The relative humidity in wet circumstances may reach as high as 80%. This high humidity is not appropriate for direct delivery into structures because it can cause warping, corrosion, and mildew in sensitive materials. The active direct evaporative coolers are powered by electricity, but they only require a portion of that for air and water movement. As a result, it is considerably less energy demanding than other conventional cooling methods, with up to 90% energy savings. As shown schematically in a conventional direct evaporative cooler consists of evaporative media (wet table and porous Pads), a fan that pushes air through the wetted medium, a water tank, a recirculation pump, and a water distribution system. Direct evaporative cooling is an adiabatic cooling process, in which the total enthalpy of the air remains constant throughout the operation. The water absorbs the sensible heat from the supply air and evaporates, lowering the temperature and increasing the humidity [10].

DISCUSSION ON EVAPORATIVE COOLING

The supply air could theoretically be cooled to 100% effectiveness, but due to the short contact time between the two fluids, insufficient wettability of the pads, and the fact that the circulated water and supply air will reach an equilibrium point equal to the wet-bulb temperature of, only a wet-bulb effectiveness of 70%-80% is achievable. The system would eventually be unable to cool the entering air below its wet-bulb temperature. In most contemporary commercial DEC coolers, wet-bulb efficacy may vary from 70 to 95 percent, depending on the kind and thickness of evaporative media, operating environment, and supply air flow rate. Passive cooling uses natural phenomena, energies, and heat sinks to cool buildings without the need of mechanical devices that use electricity. Small fans and pumps, on the other hand, may be needed. Because passive DEC is dependent on the environment, the methods used in hot and humid regions vary from those used in hot and dry locations. This technique can decrease the temperature of indoor air by approximately 9 degrees Celsius. The mashrabiya is a classic Islamic architectural feature that allows buildings to be naturally ventilated and cooled without using any electricity. Its wooden screens/windows offer shade, provide sun protection, and enable breezes to flow inside the structure for cooling. Figure 4a depicts a mashrabiya system with porous water-jugs to provide evaporative cooling for a home and cooling water within jugs for drinking water. The wind tower, also known as a wind catcher, is a traditional passive cooling method for buildings that has been used in the Middle East and Iran for hundreds of years.

A wind tower's basic construction. The top of a capped tower with one face opening or several face openings is put on the roof of a house. According to the airflow patterns within the tower, wind towers/catchers may be classified as downward airflow towers or upward airflow towers. The pressure differential between the tower's windward and leeward sides drives the downward airflow wind tower, commonly known as a "Passive Downdraught Tower (PDEC)." The tower collects the ambient air that arrives at the top and circulates it around the structure, giving fresh air. Water may be incorporated into the tower geometry in a number of ways, including a water pool at the foot of the tower, porous jars filled with water suspended in the tower airstream, or wetted pads suspended at the top. The temperature differential between the inside of the building and the outside environment drives the upward flowing wind tower. Because of positive pressure on one side of the structure, hot air may be drowned down through subterranean channels or water fountains before entering the building as cooled air, while hot interior air rises upward via the wind tower openings. Roof ponds are a kind of evaporative cooling system that is built into the structure. It may provide a significant contribution to heat mitigation by passively chilling the roof; as a result, the interior air is chilled without adding moisture, lowering energy consumption and heat gain throughout the day.

A conventional roof pound consists of a water pool kept on top of the building's roof in a plastic or fiber-glass container. A detachable cover, a permanent cover, or a fixed floating installation may be used to cover the pond. During the summer, the ambient air flow over the pond causes the water to evaporate, cooling the pond as well as the roof structure, which serves as a heat sink for the inside of the building. The pond is drained and the shaded entrances are closed during the winter. To improve evaporative cooling, roof-pond cooling systems may include a water spraying mechanism. Temperature of the wet bulb The most typical design and flow pattern for an IEC system is a packed unit of flat-plate-stack, cross-flow heat exchanger that can reduce air temperature close to, but not below, the wet-bulb temperature of the intake air. A schematic diagram depicting the principles of operation of a typical HX configuration of a wet-bulb temperature IEC system, which consists of multiple pairs of neighboring channels: wet working (secondary) air passages and dry supply (primary) air passages.

The supply air is sensibly chilled with no extra moisture added into the cooled supply air stream due to heat transfer between the two working fluids through a heat conductive plate. The latent heat of water vaporization is used to transmit heat between the working air and the water in wet channels. This system's wet-bulb effectiveness is between 40 and 80 percent, which is lower than the DEC systems. There are many kinds of IEC systems, which may be divided into plate-type IEC, tubular-type IEC, and heat pipe IEC based on the type of heat exchanger (HX), as described below: IEC based on plate-type HX: The flat-plate-stack heat exchanger with cross- or counter-flow arrangement of the main and secondary airstreams is the most frequently utilized design. A simple plate-type IEC system is shown schematically in Fig. 6a. Several studies assessed energy savings, mathematical modeling of the heat transfer mechanism, and performance assessment. IEC based on tubular-type HX: As illustrated in Fig. 6b, this structure is typically made up of circular tubes. Other tubular forms, such as elliptical and rectangular tubes, have been utilized in the past.

A common configuration is a bundle of round tubes mounted in a cylindrical or rectangular shall, with the primary air flowing inside the tubes and the secondary air flowing across and/or along the tubes in the opposite direction to the primary air, while water is sprayed on the tubes' external surface. Heat pipe HX based IEC: Heat pipe is a light, simple, and thermally conductive device that may be used to transfer heat from primary to secondary air passageways for cooling purposes. It comes in a variety of forms and sizes. The heat pipe may be configured in a variety of ways, including thermo-syphon, cryogenic, rotating and revolving, flat plate, and capillary pumped loop heat pipe. The condenser portion of the heat pipe is utilized in the secondary air (wet) channel, while the evaporator section is employed in the main air (dry) channel, in this heat pipe-based IEC. Only a few studies have been conducted to assess the efficacy of heat pipe-based IEC systems for building cooling. A finned heat pipe was used to increase convective heat transfer between the primary air and the heat pipe, with various methods of heat removal from the condenser sections, including a water sprayer on the condensation section surface, precooling the outdoor air with an air washer before passing through the condensation section, and the use of a porous ceramic water container fitted around the condensation section. In addition, numerous research papers on heat pipe applications in building cooling, which includes HVAC systems, have been published in the literature. A novel design of the heat exchanger of the IEC system was developed to address some of the drawbacks of DEC systems and to improve the efficacy of wet-bulb temperature IEC. The Maisotsenko-cycle (M-cycle) based IEC system combines a cross-flow, multi-perforated flat-plate HX with evaporative cooling, in which secondary air is precooled in the dry channel before being directed to the wet channel for additional heat transfer with the dry channel. As a result, the main air temperature is lower than the wet-bulb temperature and approaches the incoming air's dew point temperature. As a result, it's known as Dew point IEC. Wet-bulb efficacy ranges from 110 percent to 122 percent, with dew-point effectiveness ranging from 55 percent to 85 percent.

Although the M-cycle heat exchanger has a 10–30% greater efficiency than traditional heat exchangers, it still has significant drawbacks: the secondary air is not completely cooled since a large part of it is diverted early into the wet channels, and cross-flow is an undesirable heat exchanger design. The M-cycle based IEC system's dew-point/wet-bulb efficacy was only about 50–60% and 80–90%, respectively, according to experimental testing. Several research investigations were performed to create and alter the M-cycle IEC's thermal process in order to address the aforementioned disadvantages, improve efficiency, and improve thermal performance. Based on the M-cycle of a dew-point evaporative cooling system, a novel counter-flow heat and mass exchanger has been developed. Unlike the cross-flow Maisotsenko-cycle heat exchanger, holes are placed at the ends of the flow channels in this construction. The product air flows through and along the dry channels, losing sensible heat to the wet channels, and part of the cooled product air is delivered to the conditioned space, while the remaining air is diverted to the adjacent wet channels as cold working air, transferring heat latently with the water and sensibly with the product air in the dry channel. Wet bulb efficacy was found to be up to 130 percent and dew-point effectiveness was found to be up to 90 percent. Furthermore, under the same geometrical proportions and operating circumstances, a comparison of cross-flow and counter-flow M-cycle base IEC systems revealed that the counter-flow arrangement produced approximately 20% greater cooling capacity and 15–23% higher dew-point and wet-bulb efficacy. In contrast, the cross-flow exchanger has a 10% better performance, which is owing to the counter-flow heat exchanger's increased power consumption.

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Because DEC has a higher effectiveness but humidity rises indoors while IEC has a lower effectiveness but humidity remains constant, combining the two systems or using other cooling technologies to achieve the best characteristics of both systems, such as cooler supply air with lower relative humidity, higher efficiency, and controlled humidity, could be a viable option. The heat exchanger in the IEC unit, the evaporative pad in the DEC unit, the water recirculation system, the water reservoir, and the blowers are the major components of the IDEC system. The efficacy varies between 90% and 115 percent. The high initial cost and system complexity, on the other hand, are apparent disadvantages. The following are examples of IDEC systems: IDEC with two stages: in this arrangement, the IDEC has two stages: an IEC stage and a DEC stage. The outside air is cooled in the first indirect stage, then passed through a direct stage for further cooling to below the wet-bulb temperature, but with extra moisture added. The efficiency ranges from 90 to 120 percent, while water usage rises by 55 percent. Other IEC-DEC two-stage designs. Three-stage IDEC: This system combines two-stage IDEC with a cooling cycle to create a three-stage IDEC. A solid desiccant dehumidifier with an IEC and/or DEC unit, for example, has a COP of approximately 20. There have been reports of an IEC, cooling coil, and DEC stage in various combinations. An IEC and DEC system for sensible and adiabatic cooling, combined with a desiccant system for dehumidification, may save 54 percent to 82 percent of the energy used by traditional cooling systems. Multi-stage IDEC is a hybrid system that combines two-stage IDEC with several cooling cycles. For example, a two-stage DEC-IEC linked nighttime radiative cooling and cooling coil system is more effective than a two-stage evaporative cooling system, saving 75-79 percent of energy as compared to MVC systems.

CONCLUSION AND IMPLICATION

Evaporation of water as a means of lowering air temperature is by far the most ecologically friendly and efficient cooling technology. A review of evaporative cooling technology that might be used effectively in building air-conditioning was conducted in this article. The innovation brought about by the M-cycle based dew-point IEC system revealed that indirect evaporative coolers have greater efficacy and are more affordable in terms of energy consumption savings. Combined IDEC systems, on the other hand, offer comparable or even better performance, but their system complexity and high initial cost are the main drawbacks. Recent research on indirect evaporative cooling based on the Maisotsenko-cycle has shown significant promise for improving the performance and cooling capacity of IEC systems for building cooling.

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