"A Review on Design of Passive Down Draft Evaporative Cooling in Commercial building"

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ABSTRCT

This Paper is focused on the concept and design methodology for a passive downdraft evaporative cool tower application. Passive evaporative cooling is a very efficient cooling application, but is often offset by fan energy. The cool tower concept utilizes pressure differences (stack effect) to move air through the building. To further enhance this air movement, a negatively pressurized atrium creates an additional 'pull' so to correctly define the path of airflow, moving the cooler air into occupied areas that require cooling. There is a common misconception in industry today, that the passive downdraft evaporative cool tower model cannot be explicitly modeled and requires "workarounds". This paper aims to clearly define an explicit workflow, devoid of workarounds. This type of application can be used in many locations, but is especially useful in areas that can be simultaneously hot and dry. The presentation shall analyze the inputs required to simulate this innovative design such as louver intakes, airflow controls and bulk airflow. Finally, certain outputs shall be examined and compared by using this design, with variables such as building energy consumption and thermal comfort of occupants.

Keyword:*PDEC , Evaporative cooling, Energy Efficient, stack effect.*

1. INTRODUCTION

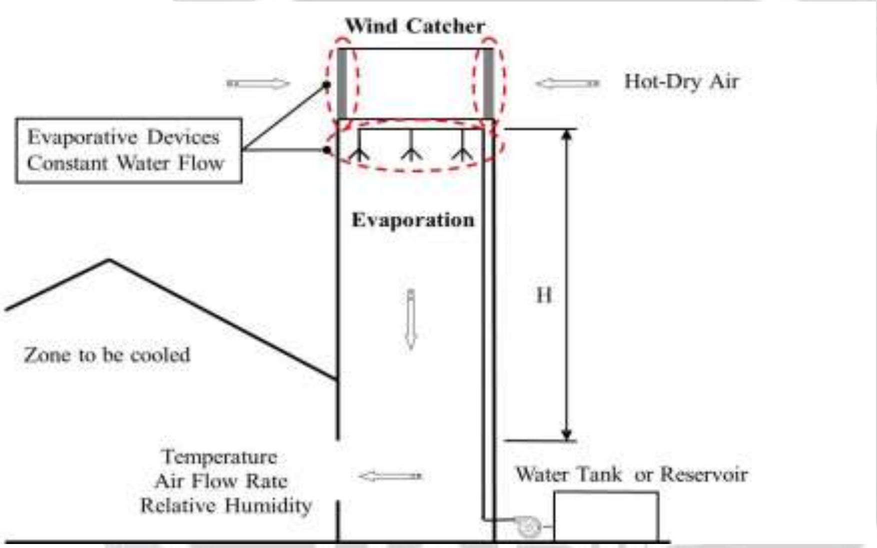
Passive down draft evaporative cooling (PDEC) is a representative term that is defined as a passive and low energy technique for cooling and ventilating spaces in hot, dry climates (Bowman et al., 1998), and it is often described as a reverse thermal chimney (Thompson et al., 1994) as the air flows downward through chimney rather than upward as in a thermal chimney. They are designed to capture the wind at the top of a tower and cool the outside air using water evaporation before delivering it to a space. The air flow in these systems is natural as the evaporation process increases the density of the air causing it to fall through the tower and into the space without the aid of a fan. The principle of PDEC is water evaporation for cooling ambient air, gravity difference for establishing air flow, and momentum transfer from water drops and air (Bowman et al., 1998; Pearl mutter et al., 2008). The main physical phenomenon is thus simultaneous heat and mass transfer.

No specialized terminology on this PDEC technology is currently available. The term "PDEC tower" is a representative term that accounts for this particular type of components. The applications of this technology can be variously named according to their structure, evaporative devices and geographical locations: passive and hybrid downdraft cooling (PHDC) systems, natural draft cooling towers (Cunningham and Thompson, 1986), shower cooling tower (Carew and Joubert, 2006; Givoni, 1994; Mannison, 2003), down-draft evaporative cool tower (DECT; Pearl mutter et al. 1996), and cool tower or natural draft evaporative cooler (Chalfoun, 1997; Givoni, 1993; Thomson et al., 1994.)

Applications incorporating PDEC technology can be categorized into three different types according to evaporative devices: wind tower, a PDEC tower with pad, and a PDEC tower with spray. The cooling performance of these applications is dependent on various factors such as climatic conditions, tower configuration such as the height and cross-sectional area, volume of the water and air, and types of evaporative devices. Physical tower configurations of these systems are similar to each other. However, the cooling capacities of these systems are different, and PDEC towers with evaporative devices are known to be better than conventional wind tower. PDEC towers are thus classified into these three different types in that the cooling capacity and system response to cooling demand substantially change due to the presence of evaporative devices and their types such as wetted pads and sprays.

PDEC tower with evaporative devices

Passive down draft evaporative cooling (PDEC) systems, which have a certain type of evaporative devices such as porous medium and spray, have been developed and integrated with buildings in an attempt to improve the cooling capacity of wind towers. These components are a modified form of wind towers. Overall, PDEC systems are almost the same as traditional wind towers. PDEC towers include an additional evaporative device to accomplish as large of a temperature drop as possible. They typically consist of an evaporative device such as wetted pads or sprays at the top, a shaft, a wind catcher, openings at the bottom, and a water tank or reservoir as shown in Figure 3.5. While the height is an important parameter in cooling power from PDEC systems, most designs tend to achieve most of the temperature drop at the top of the tower (Pearlmutter et al., 1996) due to direct contact between the air and water at the very top. Water is typically transported to the evaporative device by a pump which is the only component that consumes power in these systems. Water flow rate and the size of the water droplets plays a key role in the cooling output of these components, and finer water droplets have been reported to achieve better performance (Cook et al., 2000; Pearlmutter et al., 1996; Santamouris, 2005.)



Significant energy savings is the main benefit of these applications (Givoni, 1994; Lomas, 1999; Cook et al., 2000; Ford, 2002; Santamouris, 2005; Melo et al., 2006). The introduction of outside air and the movement of this air within the space greatly improve thermal comfort and quality of the air in a space (Bowman et al., 2000; Ford, 2002; Givoni, 1994; Melo et al., 2006; Santamouris, 2005). In addition, night ventilation through PDEC towers is feasible, which leads to reduced cooling demand and operating time of the primary cooling systems the following day (Bowman et al., 2000). The air is also cleaned by the water used for the evaporative cooling process (Etzion et al., 1997). Another important advantage is that these systems are able to accomplish greater cooling outputs during afternoon hours that indicate the highest cooling requirements of the day during cooling period since the web-bulb depression increase thus potential cooling outputs ambient temperatures increased rather than the other occupied hours, leading to significant reduction of peak electricity demand. They are also applicable in regions without wind, creating airflow by density difference and momentum transfer from water drops to the air (Bowman et al., 2000; Pearlmutter et al., 2006). In addition, these towers can be incorporated in new or existing buildings with simple construction elements at a relatively low cost (Santamouis, 2005; Melo and Guedes, 2006.)

Climatic dependency is the main disadvantages of PDEC towers with evaporative devices (Bowman et al., 2000; Givoni, 1997; Santamouris, 2005) as it is for many other sustainable building systems. The insufficient cooling capacity of the PDEC systems under certain ambient conditions requires the need for a conventional cooling system (Bowman et al., 2000; Santamouris, 2005). Another deficiency is the lack of studies and models, which allow a more extensive understanding of physical processes involved in PDEC systems and better control of the performance of these systems (Bowman et al., 2000; Lomas et al., 2004.) Studies also noted that the hardness of the water and microbiological contamination could also be a problem (Al-musaed, 2007; Ford, 2002). Noise from the top and water consumption are also a problem in areas with high wind speeds, and the potential for a large volume of water consumption is another main drawback (Ford, 2002; Givoni, 1997; Santamouris, 2005). In a PDEC tower with pad, a high pressure drop and a short life span of the pads were other potential weaknesses (Thompson et al., 1994). Additional issues include: the requirement of a shading device to avoid water loss by solar radiation and the inability to position the pads ideally to capture all prevailing wind directions.

2. LITERATURE REVIEW

Different types of early designs for PDEC towers with spray systems have also been introduced as an advanced form of wind towers. Bahadori (1985) presented a new design of wind tower as illustrated in Figure 2.3 in order to improve the cooling capacity of wind towers. This new design included clay conduits throughout the tower shaft and a water spraying system at the top of the tower. In addition, the first modern application of a PDEC tower with a spray system was introduced at EXPO'92 in Seville, Spain as shown in Figure.1. It was intended to cool outdoor rest areas at the site. The height of the spray PDEC towers reached 30 m high, and fine water droplets up to 14 ㎛ were injected at the top of the tower. The largest temperature drop of 12°C appeared within the first or second meter from the top when the smaller particles were sprayed, whereas temperature gradually decreased with bigger drops (Rodriguez et al., 1991.) These applications showed the possibility of the system as a means of low energy cooling, and were successful in drawing attention to passive cooling strategies. They, however, were inefficient in the cooling of buildings due to a lack of studies that can support advancing the best cooling performance of this particular system.

Figure 1 PDEC towers at Seville EXPO'92

(Source: Website, http://wikipedia.org)

Figure 2Torrenet Research Center

(Source: Website, http://archnet.org)

Initial studies have focused on field measurements in an attempt to advance the overall performance of these systems beyond the early system designs. Pearlmutter et al. (1996) demonstrated the importance of wind catchers and the size of water droplets. The scale model test illustrated that fine water drops accomplished better cooling performance. The study also revealed that the type of wind catcher significantly affected cooling performance (up to 35%). Etzion et al (1997) integrated a large spray PDEC tower, 4m × 4m × 12m, to the top of the atrium in Blaustein International Center for Desert Studies building located in a desert area near Beersheba, Israel. A small fan assisted the flow of air at the top of the PDEC tower. The maximum cooling output was 120kW, and a temperature drop of 14°C were observed. Ford et al. (1998) monitored the performance at the Torrent Research Center in Ahmedabad, India as shown in Figure 2. The PDEC systems achieved temperature drops between 10 and 14°C at the maximum outdoor air temperatures. Electrical energy savings reached 64% in comparison to an equivalent mechanically conditioned building. In addition, almost no occupants felt discomfort in the summer, and overall comfort levels were better than the equivalent air conditioning building. The authors also noted that improvements are necessary to control inconsistent airflow rates and overall performance. In summary, these applications have been shown to have economical environmental benefits and also identified that the main variables such as the type of wind catcher and the size of water drops have a substantial impact on the cooling performance of the spray PDEC tower. It was also shown that they are insufficient in the cooling capacity, inefficient in the use of water, and in need of adequate control algorithms. These studies, however, were limited to a specific condition such as temperature, tower configuration including wind catcher, and water flow rate, leading to a lack of a full understanding of the physical phenomena present in these systems.

Building applications of spray PDEC towers that have appeared as initial studies have proven the potential for these systems. The Interactive Learning Center (ILC) at Charles Sturt University in Australia in 2001 adopted a system as shown in Figure 3 (CADDET, 2002.)Webster-Mannison (2005) reported that the performance was poor at the beginning due to the ineffective design of the wind catcher, so wind deflectors and baffles were installed at the top to correct these problems. This also provided convective night cooling and treated rainfall was utilized as a water source. A maximum temperature reduction of 16.42°C was observed at an ambient air temperature of 42.28°C. This system, however, was unable to meet the cooling requirements for the space, so it was replaced with another cooling system.

Another example of a spray PDEC system is the Malta Stock Exchange (2001) that introduced a PDEC tower in conjunction with convective night ventilation to the central atrium space of this building as shown in Figure 4. The system met approximately 25% of the total cooling loads, and an operating costs reduction and low carbon dioxide emissions were observed.

Figure 3 ILC building in Australia

(Source: http://www.architecture.com.au)

Figure 4 Malta stock exchange building

(Source: http://www.ap.com.mt)

The Center for Global Ecology in Stanford, California adopted a spray PDEC tower in 2004 as shown in Figure 5, which is called a Katabatic Cooling Tower, in order to cool the lobby area. While no data regarding the performance of the system has been reported, the website of the center states that the katabatic cooling tower produces temperature drop of 14.4°C at an outdoor temperature of 29.4°C. Figure 6 shows another example of the application is a PDEC tower incorporated by Prajapati to the Inspector General of Police Complex in Gulbarga, Karnataka in 2005. Preliminary data indicate that temperature drops during a period of March through May were 12 to 13°C, and the simple payback period in comparison with an equivalent air-conditioned building was estimated to be approximately 5 years.

In short, a number of building applications of spray PDEC towers have been implemented during the early 2000s. The performance, however, as an alternative cooling system to a mechanical air conditioning system was insufficient even though overall the concept has improved. No application fully met the cooling demands of the space being conditioned by the PDEC system, and careful control of the PDEC system was needed to produce better cooling capacity. It is thus necessary to improve the understanding of the major phenomena within the tower and to investigate what additional parameters can significantly improve the cooling performance in detail.

Figure 5 PDEC tower in Stanford

(Source: web site http://www.aiatopten.org)

Figure 6 Inspector General of Police

(Source: JitenPrajapati, 2006)

The ESP-r model included several simplifying assumption including a wet bulb depression of 70% and a maximum relative humidity of 70%. Annual simulations for conditions of coupled heat and mass transfer estimated an annual delivered supplementary cooling energy of 508.7 kWh, a total annual water usage of 5170 liters, and a maximum core zone air change rate of 91.5 ACH. Total energy savings of 50% to 83% were observed depending on the internal heat gains and the set-point temperatures. Silva (2005) developed a model that predicts the flow rates and the air temperature as well as the relative humidity, assuming 70% of the wet-bulb depression, which is the difference between dry- and wet-bulb temperatures. The study showed that the ventilation rate is independent of the wind speed. Another finding was that these systems are viable in various regions with low wind speeds. Overall, it did result in low energy consumption and good thermal comfort levels within the space. Melo and Guedes (2006) performed a thermal analysis employing Givoni’s mathematical model for the calculation of temperature and air volumetric flow rate. The annual cost savings and reductions of carbon dioxide emissions were predicted to be approximately 600€ (over US$800) and 3120kg, respectively. The daily water consumption was estimated to be between 20 to 40 liters. In summary, these studies have evaluated the energy performance of spray PDEC towers over a longer time period and shown that PDEC towers are capable of reducing operational costs and pollutants emission. On the other hand, the studies have made overly optimistic assumptions regarding the efficiency of the wet bulb depression, which should vary with outdoor conditions. No studies have properly modeled the conditions of the air delivered to the space from the towers. They also were unable to determine the relative humidity of the air, so the impact on energy performance of actual buildings was inaccurate. As will be seen in this dissertation, more sophisticated mathematical models for PDEC towers are necessary to provide the accuracy necessary to truly evaluate the performance of these systems.

In addition to the energy performance monitoring, various aspects of the system regarding indoor environmental quality have also been evaluated using post occupancy evaluations (POE). Thomas and Baird (2004) conducted a post occupancy evaluation for the Torrenet Research Center buildings in India. They obtained 164 responses from occupants in both the PDEC conditioned and conventional mechanically conditioned (AC) buildings. Generally, occupants in the AC buildings expressed better satisfaction with the indoor thermal environment than occupants in the PDEC buildings, but all occupants in the PDEC buildings gave higher satisfaction scores than the average score from another study of 260 buildings from another study. On the other hand, the comfort level based on temperature and relative humidity of the PDEC buildings were very close to neutral while the AC buildings left occupants feeling cold year round and a bit dry in the summer. In addition, Schiano-Phan and Ford (2008) evaluated the satisfaction of occupants in four different commercial buildings that used PDEC towers. The two buildings that had PDEC towers with pads were the Kenilworth Junior High School, Petaluma, CA and Zion National Park Visitor Center, UT, and the other two buildings with spray PDEC towers were the Sandra Day O’Connor Federal Courthouse, Phoenix, AZ and the Global Ecology Research Center, Stanford, CA. It was observed that the satisfaction of the occupants in spray PDEC tower equipped buildings was very poor in the last two buildings. Conversely, the occupants in the other PDEC tower with pad buildings reported very good levels of comfort. The authors thus concluded that the successful implementation of PDEC towers depended on various aspects such as the overall building strategy, the robustness of control system, the occupants' awareness of the building strategy, and on-site maintenance. In brief, these POE studies proved that these systems help to improve the indoor environmental quality. It was also shown that the implementation of these PDEC towers required a careful design of the building systems and ventilation due to the dependency of the surrounding environment. PDEC towers should thus be integrated as a secondary cooling system and considered as a potential source of significant energy savings and real improvement in the built environment.

Some efforts have been made to advance the performance of the spray PDEC towers. Bahadori et al. (2002, 2008) compared three different passive cooling designs including a wind tower, a PDEC with pad, and a spray PDEC that includes plastic curtains throughout the vertical tower. The temperature drops at the peak outside temperature of 37.2°C were 16°C in the wind tower with spray, 13.1°C in the wind tower with pad, and 3.7°C in the wind tower. The air flow rates measured were 1.1m3/s in the spray system, 0.78m3/s in the pad system, and 1.25m3/s in the wind tower. The overall performance of the new tower designs that included evaporative devices was much better than the conventional wind tower, and the spray PDEC tower with plastic curtain performed best. In addition, Pearlmutter et al. (2008) developed and tested a multi-stage spray PDEC tower that has a secondary air inlet in the middle of the shaft as an improvement over the typical spray PDEC tower application. This study performed a wind tunnel experiment, scale model tests, and airflow analysis using FLUENT. The airflow through the secondary inlet in both the scale model experiment and the full-scale experiment was predicted to be approximately 40% of the total airflow rate. The exiting airflow rate with the aid of a fan was approximately 5.5m3/s, and the spraying water operation increased the airflow rates up to 8.5m3/s. They, however, were reduced to 4.5m3/s without the aid of the fan and to 2 to 2.5m3/s when no water was used (no evaporative cooling). The authors thus concluded that the water sprayers amplified the air volumetric flow up to 50%. In summary, spray PDEC tower system has become the prevalent system design option because it produces better cooling output than the other types of PDEC systems. These studies, however, were unable to accomplish considerable enhancement in the performance of the spray PDEC tower system. Developing a different type of PDEC tower might not be adequate given the current status of this technology as a fuller understanding of the performance of these devices is needed. It is thus necessary that efforts be made to optimizing the performance by first gaining this understanding using more comprehensive analysis of these devices.

3. CONCLUSION

Literature review show that Different studies have contributed to advancing the science of PDEC towers while, in general, the applicability of a PDEC tower as a cooling application in buildings has been proven. The main parameters affecting the thermal performance of this application were also identified. A number of models that can predict the performance of PDEC systems have been developed. Previous studies on PDEC technology, however, do not fully support further improvements of this technology as a cooling application to buildings. A thorough analysis of this technology in various aspects is thus necessary to comprehensively understand the physical phenomena of the down-draft evaporative cooling processes and to detail the potential environmental benefits from a PDEC tower.

The cooling capacity of PDEC towers is insufficient to meet all of the cooling needs of many buildings and difficult to control. Careful design of these systems is critical since the conditions of the air from PDEC towers vary with a number of parameters. None of these studies, however, provides an extensive analysis of the correlation between these main parameters and the performance though studies have identified what parameters have an influence on the performance. This gap leads to difficulty in appropriately designing PDEC towers. As a result, only a few building applications have successfully applied this technology. This is because the influence of the critical variables such as droplet size, tower configuration, and incoming air flow rate has not been properly treated in the previous studies. In addition, attempts at developing different types of PDEC technology have not been successful. Detailed analysis of the physical phenomena and the performance are thus important because it will help identify additional problems and solutions to the performance control issues.

Efficient use of water is critical to successful implementation of the PDEC systems. A tendency that appears in the literature is that these systems use a large amount of water with no careful consideration of saturation of the air as well as loss of the water. This tendency could also cause microbiological contamination. The demand for a large amount of water could also significantly confine the consideration of the system in areas of water scarcity. In fact, the influence of water flow rate has been investigated in the literature. These studies, however, have been performed under very specific conditions of the other main parameters, so that the general adaption of those results to the beyond the conditions studied is inappropriate. It is thus important to understand how water flow rate affects the performance under a variety of conditions. Efforts should thus be made to identify a correlation between water flow rate and different droplet sizes, tower dimensions, and air conditions, so that problems such as excess use of water and possibilities of microbiological contamination can be minimized.

Spray PDEC towers have more potential than the other types of PDEC technology. The traditional wind tower has been improved by adding evaporative devices at the very top of it. As a result, significant improvements in the cooling performance of advanced types of wind towers have been accomplished. The majority of PDEC studies and building applications are on spray PDEC towers since they produce better cooling output and respond faster than the other systems. Many efforts have thus been made to integrate this particular system into buildings while few attempts have been made to integrate the other types. In fact, the PDEC tower with pad has two different possibilities to control the performance: water flow rate and thickness of the pad. Thicker pads, however, increase the resistance against the incoming air, causing lower cooling outputs. On the other hand, spray PDEC towers are more responsive to the variable ambient conditions by adjusting air flow rate, water flow rate, and also possibly droplet sizes. Priority thus needs to be given to spray PDEC towers in that it is able to produce constant cooling capacity when the performance is optimized.

There currently is no existing mathematical model that accurately predicts the conditions of the air at the outlet of PDEC systems. Almost all the mathematical models are only capable of predicting temperature, relying on the wet bulb depression while only Givoni's model includes main parameters such as water flow rate, ambient wind speed, and the height of a tower. These models, however, are unable to deal with the other important variables such as the air mass flow rate and the humidity level of leaving air. In addition, a sophisticated dynamic simulation model is needed so that the impact of spray PDEC towers can be analyzed under various circumstances. Various aspects of this particular system such as improving indoor environmental quality and energy performance should also be analyzed. It is thus critical for the model to include the effects of water droplets and the ratio between tower area and air flow rate, which allowsaccurate predictions for temperature, humidity, and air flow rates, as well as the control of the performance of the system.

Computational domains should include the entire area of the PDEC towers from the spraying system at the top to the bottom opening. Almost all studies shown in the literature do not account for turbulent flows due to the presence of wind catcher as well as wall-bounded turbulent flows, assuming fully developed flows throughout the entire computational domains. Air flow of the incoming air as a result of the wind catcher dominates the overall air flow profile within the tower. Due to turbulent characteristics of the air across the wind catcher, fluid flow through the tower is unlikely fully developed within the range of typical tower heights. No study presents the air flow characteristics in the tower though it is difficult to include all possibilities due to the presence of different types ofwind catchers and outlets. The fluid flows in PDEC towers within the domain are to be reviewed as a solution of performance improvement and control.

Advancement of the modeling of these systems is critical since PDEC applications have been limited to hot arid climates, are difficult to control, and have been found to have insufficient cooling capacity. This study is thus to develop this application as a relevant cooling system in buildings, expand its usage in building, and thus reduce the environmental cost of cooling buildings. To achieve these goals, this study will perform a computational process modeling that helps understand the fundamental physics of the down-draft evaporative cooling processes and examine the relationships between various parameters and the performance, which will allow the significant improvement of the performance of these systems and provide appropriate control strategies. Once the correlations are identified, a mathematical model that includes the influence of the main parameters affecting the performance will be developed. This developed model will be able to determine the accurate conditions of the air at the outlet of the spray PDEC tower so that it can be used in the decision-making process during the design stage andimplemented into a whole building simulation software. In this study, the model will be added to the whole building energy simulation software Energy Plus so that the actual impact of the PDEC systems from both economic and environmental aspects as well as its applicability to different climates can be analyzed. This study will therefore improve the applicability of the PDEC systems inVarious climates and allow the evaluation of the overall effects from these systems on building Energy consumption and environmental impact.

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