ADVANCES IN THE APPLICATION OF PASSIVE DOWN-DRAFT EVAPORATIVE COOLING TECHNOLOGY IN THE COOLING OF BUILDINGS

BY

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DISSERTATION

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ABSTRACT

A passive down-draft evaporative cooling (PDEC) tower is a component that is designed to capture the wind at the top of a tower and cool the outdoor air using water evaporation. While several different types of this particular system exist, PDEC tower with spray was studied in that it is flexible, efficient, and prevalent. Sustainable feasibility has been known as the main benefit of PDEC towers, leading to significant energy savings, improvement of indoor environmental quality, and reduction of environmental cost. In contrast, PDEC towers have not been considered in some circumstances as an alternative to conventional air conditioning systems due to strong climatic dependency, insufficient cooling capacity, and huge water consumption when they could be successfully integrated. In addition, suitable methods that can resolve problems associated with PDEC towers and improve the performance of this particular system have not been presented in the literature. This study was thus designed to present the solutions that overcome these problems with PDEC towers so that they can be widely used in many types of buildings and climatic regions.

Computational process modeling was carried out to understand fundamentals of down-draft evaporative cooling processes. This study developed a computational model using a commercial CFD code FLUENT, and this model was validated against experimental data. The model then explained physical phenomena occurring within the effective area of PDEC towers, so that conditions of the air were accurately predicted in different weather conditions as well as PDEC tower conditions. In addition, parametric study with this computational model defined critical factors that significantly impact the cooling performance of PDEC towers, and the importance of various factors. As a result, a practical design guide to droplet size and tower height was presented, which is applicable to most circumstances where PDEC towers could be integrated.

Regression analysis using general-purpose statistical software Minitab was then followed to formulate mathematical models that provide accurate conditions of PDEC air flows. Two dependent variables, temperature and velocity, were considered. An individual sample was created by the computational model developed in this study. Correlation analysis determined independent variables that have significant relations with each dependent variable. A preliminary

sampling process collected reasonable numbers of samples dealing with wide ranges of weather conditions and PDEC tower conditions. Additional samples were added using forward sampling methods so that minimum number of samples, which explain certain relations between dependent and independent variables at the lowest cost, can be appropriately determined. As a result, linear relations between dependent and independent variables were found and mathematical forms of regression equations obtained was presented.

Dynamic simulations, using a whole building energy simulation program EnergyPlus, employing new mathematical models developed in this study were performed to investigate actual impacts of PDEC towers in various situations. A short-term simulation analysis demonstrated problems with current PDEC towers operation, as well as impacts to indoor thermal environment. Various alternatives to typical PDEC towers operation were analyzed, so that water flow control in conjunction with primary cooling system was determined as a reliable solution that overcomes those problems defined in this study. In addition, energy performance and various impacts to indoor thermal environment were analyzed in a long-term simulation. Consequently, PDEC towers are considered as a feasible component in various types of buildings and climates.

The findings using the methods in this study demonstrate that typical PDEC towers are inefficient in energy performance and indoor thermal environment. The cooling performance of PDEC towers should thus be properly controlled to be an energy-efficient system. In addition, PDEC towers can be considered as a secondary cooling system that meets a portion of cooling loads in a space in order to accomplish low-energy goals as well as a comfortable indoor thermal environment. Furthermore, the performance of PDEC towers is strongly dependent on each critical parameter described in this study. Efforts should thus be made to find the most efficient design conditions for main parameters corresponding to the local environment. Moreover, PDEC towers are viable in various climates rather than a hot-dry climate, achieving almost the same level of energy savings with lower water consumption.

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CHAPTER 1: INTRODUCTION

1.1 Background and Purpose

Almost all world energy outlooks present a significant increase in energy consumption over the coming decades. U.S. Energy Information Administration (EIA) highlighted that "World marketed energy consumption increases by 49 percent from 2007 to 2035 in the reference case. Total energy demand in non-OECD countries increases by 84 percent, compared with an increase of 14% in OECD countries." The first global-scale outlook on energy end-use technologies published by the World Energy Council (WEC, 2004) represents that the world's energy consumption is expected to double by 2030, and the reliance on fossil fuels such as coal, oil, and natural gas is also expected to significantly increase. It also represents concerns on global warming as well as renewable energy use by 2030, despite the introduction of energy-efficient technologies in both areas.

Building sector including both residential and commercial buildings is the greatest source in energy consumption. Buildings consume more than 30% of the total energy end-use in the world (WEC, 2004). According to the Buildings Energy Data Book 2009, building sector consumed 39% of U.S. primary energy in 2006. In addition, electricity is the fastest growing energy source of the primary energy used in this sector, representing 72% of the total. The share of renewable energy of the total primary energy consumption in US buildings in 2006 was 0.58%; moreover, the growth of renewable energy is expected to be proportional to the overall growth in energy demand, leaving renewable energy production at 0.61% of the total by 2030. It is thus necessary to expand use of renewable technologies that contributes to overall energy consumption as well as electricity reduction.

Alternatives that achieve low energy and high performance building are needed in order to address the world energy problems. The demand for air conditioning in buildings has been radically increased all around the world, causing an increase of energy consumption as well as a greater environmental impact such as global warming (Santamouris, 2005), even though substantial improvements have been made in the efficiency of air conditioning systems. Accordingly, rising energy costs and a mandatory rising desire to reduce carbon dioxide emissions has led to a focus on renewable energy sources as well as technologies. Furthermore, many developing countries are distributed in lower latitudes where the demand for cooling is high, and their economic growth will greatly increase this demand (WEC, 2004). Therefore, the demand for energy-efficient, alternative technologies for space cooling has been growing as a solution for the environmental cost of air conditioning is sought.

Passive cooling technologies in buildings are a critical issue in that they enhance the sustainability of buildings, achieving economic and environmental benefits while still providing the necessary conditioning. Conventional air conditioning systems are typically associated with concerns of indoor air quality due to re-circulated air, production of pollution by the use of refrigerants and power plant, and high electricity demand especially in the summer peak hours (Santamouris, 2005; Gert et al, 1999.) As a result, alternatives to air conditioning systems are strongly needed so as to resolve these disadvantages. On the other hand, low energy technologies have been widely developed, and many studies have proven substantial improvements of these passive cooling technologies in economical competiveness as well as environmental effectiveness in the cooling of buildings (Bom et al., 1999; Givoni, 1991; Santamouris, 2005, Giabaklou and Ballinger, 1996).

Evaporative cooling is expected to achieve significant energy saving among various low energy technologies while limited to hot arid areas. This technology is commonly used for cooling buildings in hot arid regions as it requires less energy and costs than many other cooling applications (Givoni, 1991; Santamouris, 2005; Nahar et al., 2003). It is one of the oldest means for comfort cooling and has been used to cool spaces since the ancient Egyptians around 2500 B.C. in hot arid climates (Watt and Brown, 1997). There are several types of commercial applications employing evaporative cooling technology such as evaporative cooler and cooling tower, and their efficiencies have been greatly improved, reaching close to 90% in industrial products (Santamouris, 2005). As a result, an improved form of evaporative cooling such as passive down draft evaporative cooling (PDEC) technology, and its applications have been emerged as a viable alternative to traditional mechanical cooling, which have led to the achievement of the low energy goal and an improved indoor environment.

The performance of passive cooling systems needs to be improved and shown to be valid for other climates. The main drawback of PDEC systems is that they have not been proven in climates other than hot arid climates. The application of PDEC technology is economical, sustainable, and multi-functional. To date, however, PDEC applications have been limited to hot arid climates, are difficult to control, and have been found to have insufficient cooling capacity. The relevant studies and experimental data found in the literature do not provide enough information to support improvements in this technology. 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, improvements in the performance and control of PDEC systems are critical. This study is thus intended to understand fundamentals of evaporative cooling processes within PDEC systems, identify main parameters affecting cooling performance of these systems, provide the way to evaluate for decision-making process at the design stage, and verify capability in various climates.

1.2 Scope and Method

A PDEC tower with spray will be investigated in this study since this type of PDEC tower is the most efficient and capable as a cooling application in buildings. While a wind tower is a fully passive application, it is insufficient in cooling capacity that a space requires. A PDEC tower with pad is also less efficient in control, wind catching, and cooling output than a PDEC tower with spray. A wind tower and a PDEC tower pad are thus unlikely to be integrated with buildings without significant improvements in their performance as well as configurations. In contrast, the efficiency of catching wind and controlling the thermal performance of a PDEC tower with spray is much better in that various types of wind catchers as well as water drops are applicable. This application can thus promptly respond to variable weather conditions. In addition, experimental data and performance evaluation that have previously been conducted are mainly available to this type. With these benefits, this study will focus on PDEC tower with spray system.

Computational analysis using a commercial code is more feasible in this study than an experiment. An experiment is suitable to understanding complex phenomena and to validation of a numerical analysis. It, however, is difficult to control the conditions of variable parameters such as outdoor weather conditions, water droplet sizes, and the tower configurations, and also expensive to be performed. A number of cases are expected to be conducted in order to verify critical correlations between relatively larger number of dependent parameters than many other components and the cooling performance of PDEC systems. The investigation of influences of each parameter under the same conditions in an experiment is thus a very difficult task, which is required for understanding physical phenomena of this type of system. On the other hand, a computational approach allows extensive analyses on influences of dependent parameters without economical and seasonal limitations. A few computational models for a PDEC provide basic approaches to the solutions. These models can be utilized as a simple model using FLUENT that is valid to treat the main physical phenomenon simultaneous heat and mass transfer and fluid analysis based on the finite volume method. This simple computational model then will be developed as a complete model after appropriate validation and verification of convergence.

Correlations between dependent variables and the thermal performance of the system will be identified so that it expands capability and provides possibility in performance control. In fact, evaporative cooling is one of popular alternatives to mechanical air conditioning systems, and enough background information and theories are available in the literature. However, almost no study adequately accounts for physical phenomena within this component. Most importantly, extensive efforts to understand physics of this type of direct evaporative cooling have not been made, while many studies have proven the significance of dependent parameters. They are critical to improve and control the performance of the system as it is able to provide quicker response along outdoor air and wind conditions, which always varies. Since the performance of this application substantially changes with many dependent parameters such as tower configuration, weather conditions, and water droplet size, identification of correlations between these parameters and the performance will maximize the benefits, thus minimize the deficiencies such as water consumption and performance control.

A mathematical model is necessary in order to provide overall design capability and means of further analysis in dynamic energy simulation. A few mathematical models are available in the literature, leaving the accuracy and uncertainties are in question. Among these models, a semi-empirical model developed by Givoni (1993) is the only model valid for PDEC tower with spray. It is critical for the model to account for all critical parameters affecting the cooling performance of the system. This model, however, does not include both the effects of the diameter as well as the temperature of water drops and of wind catchers while including influences of the wet bulb depression, tower height, and water flow rate while. In addition, dynamic energy simulation can only be valid when a mathematical model is available, which can adequately reflect all critical influences from the PDEC tower with spray system. Therefore, mathematical models will be developed once computational analysis verifies such relationships among various parameters. This model includes all critical effects of dependent parameters especially the size of water droplet and air flow rates, which have never been captured in the literature. It will thus predict air conditions at the exit of the tower such as dry bulb temperature, relative humidity, and velocity thus air flow rates, so that indoor thermal environment can be estimated.

The actual impact of the component as a low energy solution will be analyzed. The overall performance and possibilities as a cooling application of buildings are to be investigated in detail as it supports significant improvements in not only cooling performance but the other aspects. To figure out overall benefits of a cooling system, dynamic simulations using a whole building energy simulation software EnergyPlus will investigate energy performance and environmental benefits that these applications can accomplish. Comparisons between PDEC systems and mechanical air conditioning systems in indoor thermal environment, energy consumption, and pollution prevention will be presented. These dynamic energy simulations should be able to account for the impact of the PDEC applications in terms of energy savings, environmental benefits, improvements of indoor environment over equivalent air conditioning systems or other renewable technologies. Mathematical models developed based on computational analysis will be implemented to EnergyPlus so that results of these dynamic simulations can demonstrate overall performance of PDEC tower with spray systems.

This dissertation is intended to advance a passive down-draft evaporative cooling (PDEC) system and to extend their applicability, which is currently limited in a specific climatic condition such as hot-dry. In this chapter, the review of the needs of low-energy system and overall scope and methodologies of this study are presented. Chapter 2 describes findings in the literature review such as the status of these systems as well as their characteristics, and defined key barriers to be resolved so that they can be used in the cooling of buildings. Chapter 3 reviews theoretical backgrounds to understand evaporative cooling process and classification of various types of PDEC towers. Chapter 4 presents a computational modeling process such as governing equations to be solved, description of physical models, and validation against an experimental data. Chapter 5 describes a parametric study using the computational model developed to demonstrate critical parameters impacting the performance of these systems and their significance to the performance. Chapter 6 gives an overview of regression analysis to determine independent variables among a number of parameters defined in the previous chapter, and to formulate mathematical models that provide accurate predictions of PDEC air conditions. Chapter 7 investigates problems with current PDEC systems and their impacts to building performance, and offers one of the possible solutions that could resolve the problems. Chapter 8 explains that how PDEC systems play a role to achieve low-energy goals in different types of buildings as well as climates. Finally, chapter 9 gives findings in this study and future study that would be useful to advance these systems further.

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CHAPTER 2: LITERATURE REVIEW

A simple type of PDEC (passive downdraught evaporative cooler) technology, wind towers, has been widely used since ancient Egypt. These components have been advanced in order to improve the cooling performance of traditional wind towers by installing evaporative cooling devices such as pads or sprays (Baradhori, 1985; Cunningham and Thompson, 1985.) Different studies have investigated these advanced types of PDEC technology and shown that they accomplish better cooling performance and response to the cooling demands in a space than wind towers. Due to the complexity of the physical processes, studies have focused on field measurements and computational analysis as there are not any available exact analytical solutions to solve the complex phenomena involved.

2.1 PDEC Towers with Pad

2.1.1 Applications of PDEC towers with pad

A new design for wind towers, a PDEC tower with pad, has been developed and tested in order to enhance the performance of conventional wind towers. Cunningham and Thompson's test building (1985) in Tucson, Arizona (Figure 2.1) is likely the first modern application of a PDEC tower with pad while Bahadori (1985) introduced the early concept design of the system at nearly similar time. The PDEC tower had vertical wetted cellulose pads (CELdek) and a plywood X-shaped baffle at the top. The results of the field measurements demonstrated that the air flow rate at the exit was determined by the pad area and thickness but that further analysis was necessary. This study showed the great potential of these modified wind towers as a cooling alternative in hot-dry climates. The data, however, was taken under calm wind and hot-dry conditions which is arguably the best conditions to show the improved cooling performance over a simple window tower. It also did not include influences of the other important variables such as water flow rate and tower configuration.

This system has been implemented in actual buildings and simulated to investigate energy performance of the system during the design stage. Chalfoun (1997) designed two applications of the PDEC tower with pad system and integrated it into an office building. The thermal performance of both applications were estimated using a thermal simulation program for modeling a PDEC tower with pad system called CoolT that developed by the University of Arizona's Environmental Research Laboratory in Tucson Arizona. One application at the Botswana Technology Center (BTC) in Gabarone in Southern Africa, classified as semi-desert, was expected to achieve a 24% reduction in cooling load. The other application at the Ministry of Municipal and Rural Affairs (MOMRA) in Riyadh, Saudi Arabia, classified as a hot dry area, was expected to perform better on hot dry days.

It is interesting to note that the early design approach of integrating PDEC towers included the use of energy simulation for this type of system. The model that was used for these cases, however, did not account for the overall performance of the system. It has made some optimistic assumptions such as no wind blowing condition and a wet-bulb depression of 70%, which is the difference between dry- and wet-bulb temperatures. As a result, the same cooling performance of PDEC towers was approximated at different water flow rates at the time step, leading to inaccuracy in the results. In addition, the model was not capable of modeling air mass flow rate that the tower should treat since it varied with pad area and its resistance. The model should represent variable conditions of these parameters since they substantially affect the performance of the system.

In addition, another successful application of this type of PDEC tower has been installed at Zion National Park's Visitor Center in Utah. Torcellini et al. (2005) evaluated the passive cooling strategies of this building such as the PDEC tower with an evaporative pad and natural ventilation through clerestory windows as shown in Figure 2.2. Dynamic energy building simulations using a whole building energy simulation software DOE-2 estimated that the PDEC tower with pad system and natural ventilation achieved 93% of the cooling energy of the base cooling system during a two year period, and the estimated annual water consumption was approximately 420,000 liters. This study also indicated that solar shading at the top to prevent water consumption by solar radiation, relief dampers to control the air flow, and sizing an appropriate water storage tank to minimize waste of water would improve the performance of the system. This study made efforts to minimize uncertainty such as calibration of weather data and real time measurements during the specific period of the study. The actual overall performance of the system, however, is likely to be different since the predictions were based on a specified air condition at the outlet of the PDEC system due to the lack of relevant mathematical models.

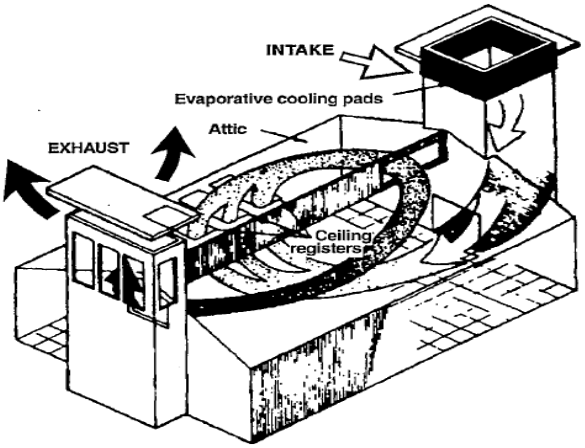

Figure 2.1 ERL's test house
(Source: Cook et al., 2000)

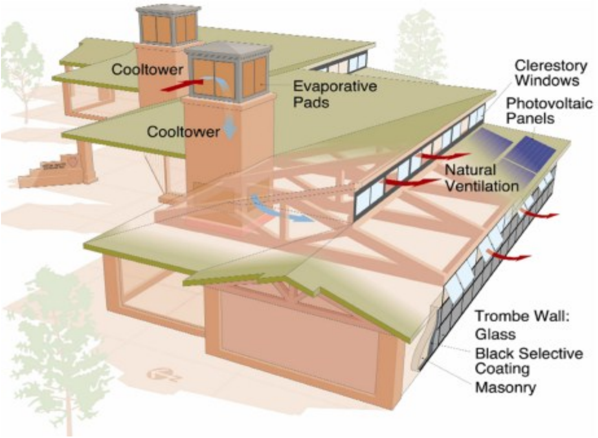

Figure 2.2 Zion National Park's Visitor Center
(Source: Torcellini et al., 2006)

2.1.2 Modeling of PDEC towers with pad

Givoni (1993) developed a semi-empirical model that predicts outlet air conditions such as temperature, flow rate, and velocity. The author formulated a simple equation, which assumed a wet bulb depression of 0.87 in the prediction of the air temperature at the exit. This equation was then expanded to include the effect of wind speed in the prediction of the temperature and volumetric flow rate of the air leaving the tower. The model was validated against experimental data for a 48 hour period in the Cunningham & Thompson's tower described in the previous section. The data collected was confined to particular conditions such as low mass flow rate, small tower size, and hot-dry air inlet conditions. This was necessary for the model to include important variables such as water flow rate, characteristics of the pads, and the physical tower configuration and predict accurate outlet conditions. The model was also able to predict the moisture content of the air leaving the tower.

Thompson et al. (1994) developed a mathematical model for evaluating the performance of a PDEC tower with an evaporative pad. This model was based on density differences throughout the shaft for the system. A summation of the density and wind forces provided a basic relation for obtaining the air flow rate. The model corrected densities as a function of incoming air temperature and tower air temperature. It also included a pressure loss through the evaporative pads by employing pressure loss coefficients given in the literature. With the inclusion of all these parameters, the study approximated the outlet air conditions such as the efficiency of the pads, the velocity, and the temperature drop using four different thicknesses for the pad. This model was employed in a simulation program, CoolT, which is intended to design a PDEC tower with an evaporative pad. Its applicability, however, was confined to the case where no wind was present and assumed that the air velocity through the pads was 1/3 of the outdoor air velocity in the calculation of the density correction. In addition, it was unable to predict the humidity level of the air leaving the PDEC tower, so water consumption could not be accurately determined.

2.2 PDEC Towers with Spray

2.2.1 Applications of PDEC tower with spray

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 2.4. 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 μm 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.

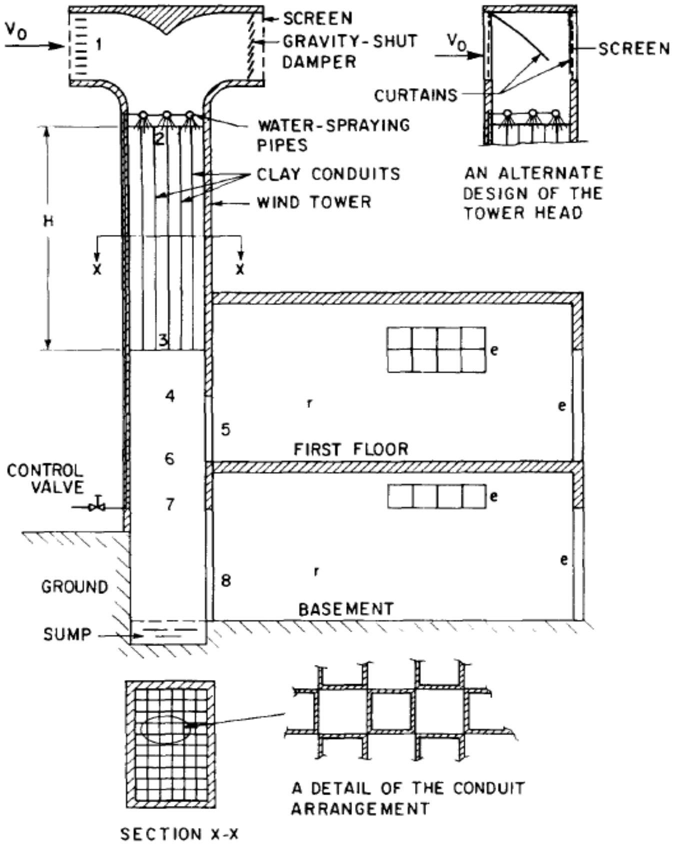

Figure 2.3 An early design of PDEC tower with spray (Source: Bahadori, 1985)

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 2.5. 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.

Figure 2.4 PDEC towers at Seville EXPO'92
(Source: Website, http://wikipedia.org)

Figure 2.5 Torrenet Research Center
(Source: Website, http://archnet.org)

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 2.6 (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 2.7. The system met approximately 25% of the total cooling loads, and an operating costs reduction and low carbon dioxide emissions were observed.

The Center for Global Ecology in Stanford, California adopted a spray PDEC tower in 2004 as shown in Figure 2.8, 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 2.9 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 2.6 ILC building in Australia

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

Figure 2.7 Malta stock exchange building

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

Figure 2.8 A PDEC tower in Stanford

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

Figure 2.9 Inspector General of Police

(Source: JitenPrajapati, 2006)

Recent studies have utilized dynamic simulation in an attempt to evaluate the overall energy performance of the spray PDEC tower over longer time periods. Robinson et al. (2004) conducted a dynamic thermal analysis using the whole building energy simulation tool ESP-r. 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 1.1m^3/s in the spray system, 0.78m^3/s in the pad system, and 1.25m^3/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 5.5m^3/s, and the spraying water operation increased the airflow rates up to 8.5m^3/s. They, however, were reduced to 4.5m^3/s without the aid of the fan and to 2 to 2.5m^3/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.

2.2.2 Modeling of spray PDEC towers

Due to the complexity of the physical phenomena involved, only a few analytic models have been developed. Bahadori (1985) provided the theoretical analysis to investigate the performance of PDEC systems against conventional wind towers. The fluid flow through the systems was analyzed using a pressure-based iterative calculation at a number of vertical nodes along the tower height, assuming constant air density. The author then employed generic equations regarding the convective heat transfer coefficients for the case of a fluid flowing in a tube, as well as the total heat transfer rates. The author defines the mass transfer at each specified node along the tower height using the Lewis relation for the mass transfer coefficient and a mass balance equation, assuming an effectiveness of evaporation of 60%. With this analytical model, the performance of the evaporative based designs was analyzed. This study, however, made assumptions such as constant density through the tower and a wet bulb depression of 60% rather than solve for the variation of these parameters. The conditions, therefore, of the air at the exit including such parameters as temperature, relative humidity, and velocity were inaccurate.

Different studies have formulated empirical models based on the performance measurements of the earlier studies. Givoni (1994) developed the only mathematical model for a spray PDEC tower, which included the effects of water flow rates. In fact, almost all the other mathematical models include only a wet bulb depression for the prediction of temperature. In this study, the air temperature leaving the tower was expressed as a function of the outdoor dry-bulb temperature, the outdoor wet-bulb temperature, the effective tower height, and the water flow rate injected into the tower. The author also formulated equations for modeling volumetric air flow rate and the air velocity at the exit. The considerable contribution of this model is determining the effect of the water flow rate on the temperature and the flow rate of the air exiting the system. Kang and Strand (2009) implemented this model in a whole building energy simulation program, EnergyPlus, so that overall cooling performance of the spray PDEC tower can be determined. The highlight of this study was that it used psychrometric relationships to determine the humidity level of the exit air by assuming an ideal direct evaporation process. It was also capable of modeling the performance when the water flow rate was unknown. This study showed that the effective use of water was one of the key factors in that water flow rate has a strong influence on the cooling performance of spray PDEC tower systems. While careful design process is required, this system could be extended to be useful in climates other than hot-dry areas since its sustainable features were viable in almost all climates.

In summary, Givoni's model was considerable as it was able to account for the impact of the water flow rate. Some limitations, however, were observed in this model. The equations were formulated from data measured for 4 days in October at a particular condition such as low height of the tower (from 1m to 3m) and high water flow rates (up to 14.4 l/min). The model was also unable to accurately predict the moisture content of the air and needed to include other important parameters such as droplet size and air mass flow rate. Due to these limitations, the predictions of the Givoni model and thus the EnergyPlus model that was based in part on Givoni's work could also be inaccurate. Consequently, a sophisticated mathematical model that is able to accurately assess all the benefits of the system under various conditions is necessary.

Computational modeling has become popular since it is possible to vary the conditions of the air and water as well as physical tower configuration. Bowman et al. (1997) investigated the applicability of PDEC technology in Europe and provided some design guidance. This study described the physical modeling techniques for predicting building performance with spray PDEC tower systems. The authors then developed a simple numerical model that was validated against a CFD model. This model, however, assumed a fully developed flow, so that only half of the effective tower area was included. The computational domain should include at least whole area of the tower since the turbulent fluid flow through the wind catcher is unlikely fully developed within the domain. In addition, the model treated the water injected as a volume fraction. In fact, this method is typically used in high-mass flow where the physical amount of the smaller mass fluid is greater than 10% in almost all computational analyses.

In addition, Cook et al. (2000) presented a study performing computational modeling of the air flow in a hypothetical office building with spray PDEC towers. A commercial CFD code CFX was utilized. The continuous phase of the air flow was modeled by conservation equations in mass, momentum, enthalpy and water vapor. The standard k-ε model was chosen for turbulent flows. The dispersed phase of the water was modeled using Lagrangian particle tracking so that each particle's trajectories can be determined by calculating the mass, momentum, and heat transfer from the particle to the continuous phase. This study presented a computational technique for modeling the down-draft evaporative cooling process. The model can be used in a computational analysis using a CFD code in that the solutions of both phases and their coupling were adequately treated. The validation of the computational model, however, was not given. Conditions of the air leaving the PDEC system must be validated to provide some assurance that the method proposed is accurate.

In addition, Elmualim (2006) utilized the commercial code CFX to evaluate the performance of wind catcher. The CFX model estimated pressure coefficients as well as air flow around wind catcher. Pressure coefficients predicted by this computational model were then validated against data obtained from a wind tunnel test. Air flow rates were also predicted using simple explicit and implicit calculations. The characteristics of air flow around catcher with the variation of the wind direction were investigated. It was seen that the performance of wind catcher was strongly dependent on the direction and speed of the wind. This study presented appropriate processes for modeling validation and computational technique. The conditions, however, between the computational domain and wind tunnel test were expected to be different. The airflow passed through the square straight duct considered to be the wind catcher. The airflow in an actual tower is typically induced in a perpendicular direction as a result of the wind catchers, so that the wind pressure at the opening may vary with wind direction. The inclusion of different types of wind catcher would also be necessary to investigate the impacts of wind direction and speed on the capturing efficiency of the air.

While numerous studies have published numerical models for evaporative cooling, few attempts have been made to model the down-draft evaporative cooling process. Belarbi et al.

(2006) proposed a cellular approach for estimating evaporation time and thus sizing spraying system in PDEC towers. Figure 2.10 illustrates a diagram of the calculation process of this approach. This approach assumed that the water spray was formed by bubbles in multiple layers, and considered the spray as a pile of rigid spheres. The evaporation then occurred from the outermost half sphere toward to innermost layers as shown in Figure 2.10. The model indicated that the evaporation time was not a function of droplet size when the distance between droplets was over 600 ㎛. The authors thus concluded that an appropriate model was necessary when the distance was less than 600 ㎛. This approach, however, required an input specifying the bubble size enclosing the water drops despite the fact that an accurate definition of the bubble size is extremely difficult to determine. It also included vapor concentrations of the air within the bubble without consideration of its interaction with the majority of the air mass outside the bubble. This approach could be used for quasi-steady evaporation if all the inputs are clearly identified though the computational domain should include unsteady particle evaporation. Another limitation of the model was that the results were likely different when different droplet sizes were applied. The model, therefore, is not generic enough to estimate the performance of PDEC towers under other conditions.

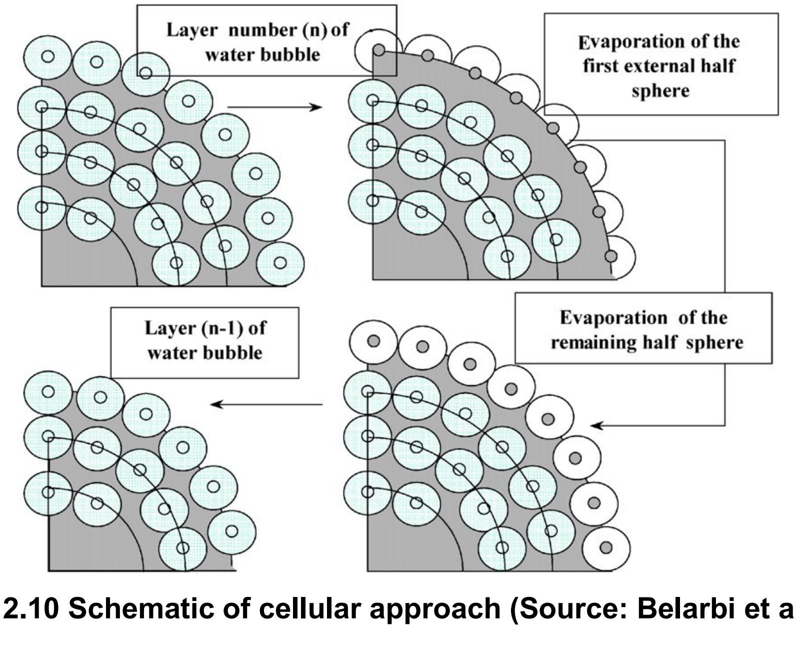

Figure 2.10 Schematic of cellular approach (Source: Belarbi et al., 2006)

2.3 Summary

This chapter describes a brief summary of studies involving PDEC technology. The status of PDEC technology and its applications integrated into buildings have been reviewed in the literature. 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 problems and lessons have been defined in the literature and are summarized below.

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 allows accurate 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 of wind 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 and implemented into a whole building simulation software. In this study, the model will be added to the whole building energy simulation software EnergyPlus 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 in various climates and allow the evaluation of the overall effects from these systems on building energy consumption and environmental impact.

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CHAPTER 3: THEORETICAL BACKGROUND

3.1 Evaporative Cooling

According to the Evaporative Air Conditioning Handbook (Watt and Brown, 1997), simultaneous heat and mass transfer occurs between substances when the temperatures and vapor pressures are different in direct evaporative cooling. In the case of mixtures of air and water, which is the most common evaporative cooling process, these phenomena occur when the gaseous phase of water, i.e., water vapor, and non-saturated air come in contact with each other at a thermally isolated boundary. Heat is transferred from the warmer to the cooler substance. Mass is transferred from the higher to the lower water vapor pressure by evaporation near the water surface, mixing the water vapor into the air. The temperatures and vapor pressures reach equilibrium since heat equalizes the temperatures, and evaporation increases or decreases the vapor pressures in each substance. These phenomena, simultaneous heat and mass transfer, take place until temperatures and vapor pressures are equalized. The cooling efficiency of direct evaporative cooling components thus becomes 100% when the air is saturated at the equilibrium temperature in the adiabatic cooling processes.

Both sensible and latent heat transfer is involved in a direct evaporative cooling process. Sensible heat affects only the temperature while latent heat only affects the moisture level of the mixture. In the case of a mixture of air and water, sensible heat flow raises or lowers the temperatures of both, and latent heat transfers water vapor into the air by evaporation, so that both the temperature and moisture content of the air-water mixture are altered. If no external heat is involved in the processes, the sensible heat of the air is delivered to the water and the amount of sensible heat becomes latent heat by evaporating the water. This net heat conversion from sensible heat to latent heat is adiabatic saturation, and it governs almost all direct evaporative air cooling processes.

The water, however, gains some external sensible heat while being re-circulated or mixed with makeup water which is typically at a different temperature than the air. Adiabatic saturation is thus only a close approximation of most direct evaporative cooling cases. The ideal direct evaporative cooling process takes place when the water temperature and the wet bulb temperature of the air are both the same, and no heat addition or loss occurs during the process.

The air temperature in the ideal direct evaporative cooling thus varies along a line of constant enthalpy on the psychrometric chart, while the most typical direct evaporative cooling processes follow the dashed line, where the temperature of the mixture is slightly higher than that experienced in an ideal adiabatic cooling process as shown in Figure 3.1.

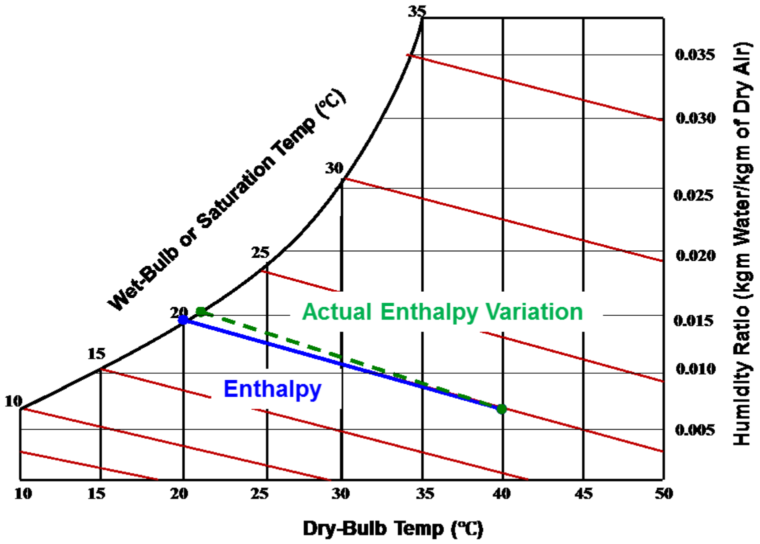


Figure 3.1 Enthalpy variation of the evaporative cooling

Evaporative cooling can be generally divided into two different types: direct and indirect. Direct evaporative cooling is a simple, established, and popular cooling technology. In this type of evaporative cooling, both fluids are in direct contact with each other during the evaporative cooling processes. The water evaporates and humidifies the air, causing a decrease in temperature and an increase in humidity. The wet bulb temperature of the air is the lowest possible temperature of the air leaving the evaporative cooling system. It is thus suitable in hot dry climates due to the large differences between the dry- and wet-bulb temperatures. Applications of this type of cooling system include evaporative coolers, air washers, and humidifiers.

Indirect evaporative cooling is not as extensively used as direct evaporative cooling. It requires an additional heat exchanger to prevent the addition of humidity to the air stream that is being conditioned. An indirect evaporative cooler uses evaporation in a secondary stream (either outside or return air) and then exchanges heat between the primary and secondary air stream to achieve cooling without moisture addition to the primary air stream. In addition, it can cool the air below the wet-bulb temperature as it alters the wet-bulb temperature along a line of constant humidity ratio on the Psychrometric Chart. The applications of indirect evaporative cooling include water ponds, and roof spray cooling systems. It can be an alternative to direct evaporative cooling in hot, humid climates.

3.2 Overview of PDEC System

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; Pearlmutter 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; Pearlmutter 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.

3.2.1 Wind tower

Bahadori (1978) defines wind towers or wind catchers as tall structures employed for natural ventilation and passive cooling of buildings. Wind towers are used as a means of comfort cooling especially in hot, arid regions (Ghammaghami and Mahmoudi, 2005; Givoni, 1994; Santamouris, 2005.) The first known instance of wind towers was found back in the fourth millennium BC (Ghaemmaghami and Mahmoudi, 2005.) The wind tower originated in ancient Egypt and as early as 1300 BC (Wind Towers, 1999) spread eastwards through the Middle East to northern India as well as westwards across northern Africa to southern Spain (Ford, 2002). It is named Malqaf in Egypt, Badinge in Syria, Baud-Geer or badgir in Iran, dessert coolers in India, wind scoops in Pakistan, and wind catcher in Saudi Arabia and the Gulf States (A'zami, 2005; Badran, 2003; Bahadori, 1994; Bom et al., 1999; Ford, 2002; Ghammaghami and Mahmoudi, 2005; Wind Towers, 1999.)

A wind tower is the simplest form of PDEC technology without evaporative devices and typically consists of a shaft in the form of quadrilateral and polygons, a wind catcher at the top of the shaft, a vertical baffle wall in the middle of shaft, and an opening at the bottom as shown in Figure 3.2. Previous studies show that the shape of cross-sectional area is mostly square (four-sided towers), whereas one- or two-sided towers, which with one or two openings at the top, are rectangular, or a few are hexahedral or octagonal in shape, six-sided or eight-sided towers (A'zami, 2005; Ghammaghami and Mahmoudi, 2005.) In addition, the survey conducted by Roaf (1988) shows that wind towers are less than 3 meters tall in over 60% of cases, and only 15% of the total exceeds a height of 5 meters while some towers are higher than 20 meters (Bahadori, 1994; Ghammaghami and Mahmoudi, 2005.)

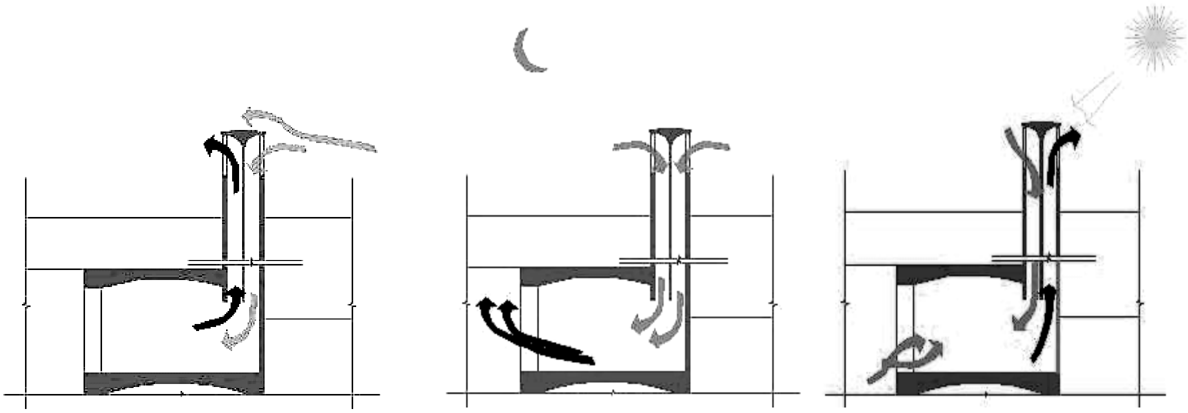
Wind towers can be classified into two types (Mazidi et al., 2006; A'zami, 2005). One is the type utilizing pressure differences without additional air passages at the opposite side. A positive pressure is formed at the side of the wind direction while the other side is at negative pressure as shown in Figure 3.3a. Wind catching and suction of the air from the inside of the space occurs at the same time in this type of wind towers. The other type forms airflows based on density differences due to temperature drops. Airflows in this type of wind tower are different from the first type and depend on temperature differences between the space and the surrounding air as shown in Figure 3.3b. Air moves down from the wind-directional side while the other side is heated by the sun thus pulling inside air up.

The potential advantage of wind towers is that it is a fully passive system with no energy requirements for operation (Bahadori, 1994). It is also comfortable, multi-functional, and economical, maintaining almost constant temperatures of the air (A'zami, 2005; Bahadori, 1994; Mazidi et al., 2006.) On the other hand, shortcomings identified by Bahadori (1978) are as follows: (1) possibility of introduction of pollutants or insects, (2) possibility of airflow loss through the other openings in a tower with more than two openings, (3) insufficient cooling capacity, (4) need of evaporative devices, and (5) dependency on the weather.

Many traditional wind towers introduced evaporative cooling strategies. Wetted materials such as mats or thorns are sometimes placed at the exit of a tower for an additional cooling effect though occupants must supply the water to these materials (Mahmoudi et al., 2005.) Air also moves through foundations and earth coupled tubes in order to achieve larger temperature drops and humidity for comfort cooling than those wind towers on the ground can achieve (Bahadori, 1994; Mazidi et al., 2006.) Ancient Egyptian, Persian, and Middle Eastern wind towers sometimes extended the air passages to foundations or earth coupled pipes to drop the temperature of the air before it was delivered to the spaces as shown in Figure 3.4 (Badran 2003; Bahadori, 1994; Mahmoudi et al., 2005; Yaghoubi et al., 1991.)

Figure 3.2 Examples of wind tower in the Middle East

(Source: Wikipedia, web site http://en.wikipedia.org)



a) Air movements in the first type b) Different air movements in the second type

Figure 3.3 Types of wind towers (Source: A'zami, 2005)

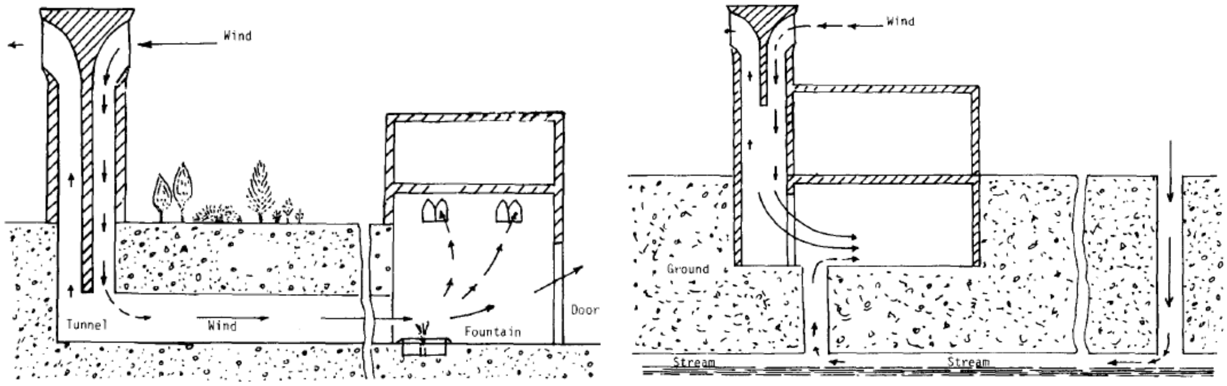


Figure 3.4 Examples of active use of evaporative cooling of ancient wind towers

(Source: Yaghoubi et al., 1991)

Modern applications of wind towers are typically used as a means of heat dissipation using natural ventilation in moderate climates. To date, many studies have reported insufficient cooling capacity (Santamouris, 2005; Yaghoubi et al., 1991) of wind towers without evaporative cooling devices. As a result, they have not been extensively considered as a design solution in the cooling of buildings. Many studies, however, have also proven that they are effective in promoting air circulation in naturally ventilated buildings, improving indoor environmental quality, providing night ventilation (Santamouris, 2005; Yaghoubi et al., 1991), and substantially decreasing the cooling demand. The applicability of these components is thus feasible in moderate areas where natural ventilation is one of major means of cooling such as in the United Kingdom.

3.2.2 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.)

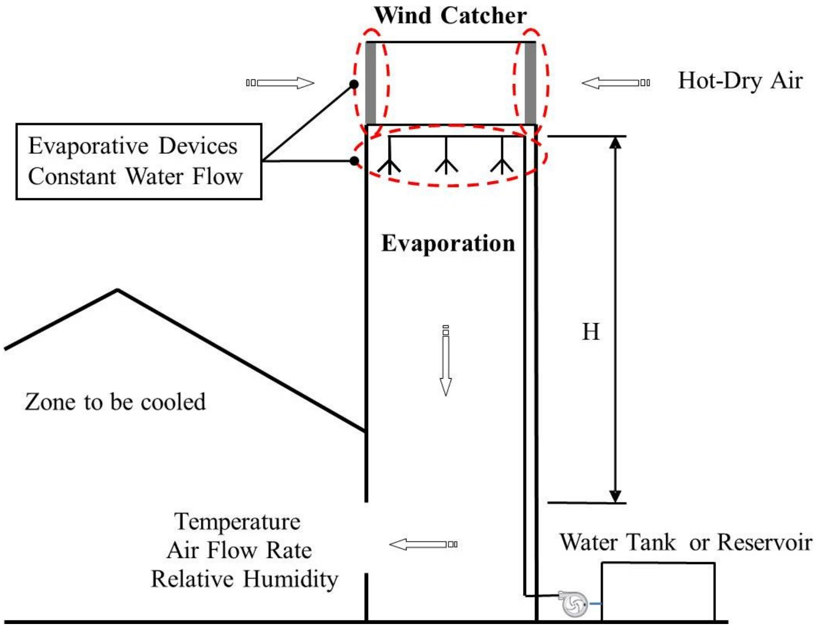


Figure 3.5 Typical configuration of PDEC tower with evaporative devices

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.

3.3 Simultaneous Heat and Mass Transfer

Heat and mass transfer occur simultaneous in many situations such as evaporative cooling, combustion of fuel, and natural convection flow. These applications are characterized by low mass flow rate theory, where the mass fraction of the evaporating fluid's vapor is relatively small. The analysis of the performance of these physical processes should thus include simultaneous heat and mass transfer processes. The major physical phenomenon of the evaporative cooling process in PDEC towers is simultaneous heat and mass transfer. In general, the solutions are fully coupled in that both fluids affect each other, altering thermal properties of the fluids. That is, the governing equations must be solved simultaneously. Situations that involve evaporative cooling processes need to be numerically solved in that the exact solution for the cooling processes of evaporative cooling is not available in the literature due to the complexity the physical phenomenon.

Various solutions involving the evaporation process of a water droplet have been extensively developed. There have been a number of applications that utilize evaporation in many fields. Due to the complexity of the physical processes, major efforts have been made to develop numerical solutions. Computational modeling has also become a trend in solving this process. Analytical solutions are only available for the evaporation of a single water droplet, but these solutions do provide a source of understanding of the physical processes of water evaporation.

3.3.1 Evaporation of a water droplet

The steady-flow surface energy balances in the process of simultaneous heat and mass transfer within the control volume in Figure 3.6 can be written as

$$\dot{m}\Delta h = \dot{Q} \tag{3.1}$$

$$\dot{m}(h_{1,s} - h_{1,u}) = A(q_{cond} - q_{conv} - q_{rad}) \tag{3.2}$$

where $\dot{m}$ [kg/s] is the mass flow rate of water vapor, h [J/kg] is the specific enthalpy, $\dot{Q}$ [W] is the rate of heat transfer, $h_{1,s}$ [J/kg] is the specific enthalpy of species 1 at the surface s , $h_{1,u}$ [J/kg] is the specific enthalpy of species 1 at the surface u, A [m^2] is the area of the surface, q_{cond} [w/m^2] is the conductive heat flux, q_{conv} [w/m^2] is the convective heat flux, and q_{rad} [w/m^2] is the radiant heat flux. Substituting Fourier's law for conduction for q_{cond} [W], and the enthalpy of vaporization for the vapor, h_{fg} [J/kg], in equation 3.2 and rearranging gives:

$$-k\left.\frac{\partial T}{\partial y}\right|_{u} = h_c(T_s - T_e) + g_{m1}(m_{1,s} - m_{1,e})h_{fg} + q_{rad} \tag{3.3}$$

where k [W/mK] is the thermal conductivity, T [K] is the temperature, y [m] is the rectangular coordinate, h_c [W/m^{2}K] is the convective heat transfer coefficient, g_{m1} [kg/m^{2}s] is the mass transfer conductance of species 1, $m_{1,s}$ is the mass fraction of species 1, and $m_{1,e}$ is the mass fraction of free stream air. While the calculations of $m_{1,e}$ and $m_{1,s}$ varies with the situation, in the purely diffusive situation, $m_{1,e}$ it can be expressed as:

$$m_{1,e} = \frac{x_{1.e}}{x_{1.e} + {}^{Mw}\!/_{Ma}(1 - x_{1.e})} \tag{3.4}$$

where $x_{1,e}$ [%] is the vapor quality of the free stream flow, M_a [kg/kmol] is the molecular weight of air, and M_w [kg/kmol] is the molecular weight of water. As for the calculation of the $m_{1,s}$, if the surface temperature is known, it can be obtained from the steam table or from the following equation:

$$m_{1,s} = m_{1,e} + \frac{c_{p,air}}{1.13 h_{fg}}(T_e - T_s) \tag{3.5}$$

where T_s [K] is the temperature of the surface s, P [Pa] is the total pressure, $c_{p,air}$ [J/kgK] is the specific heat of air, and T_e [K] is the temperature of the free stream flow. Otherwise, if the surface temperature is unknown, it can be obtained by iteration using equation 3.5 and the following expression:

$$m_{1.s} = m_{1.s}(T_s, P) \tag{3.6}$$

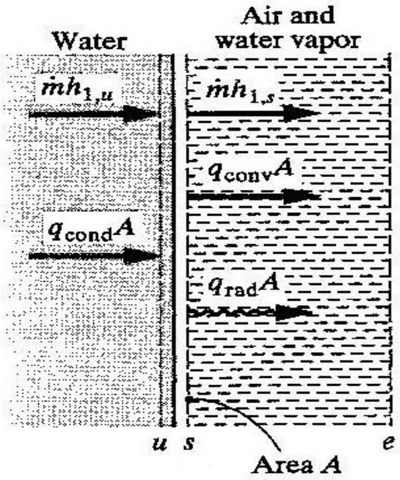


Figure 3.6 Surface energy balance in evaporation of water into air

A number of assumptions are made to the solution of the evaporation process of a single water droplet. The basic assumptions are as follows:

1. The water particles are assumed to be spherical.
2. Radiant heat exchange is negligible.
3. The droplet temperature maintains a constant value in a short transient period.
4. The droplet is entrained into the air stream.

With these assumptions, the evaporation rate of the droplet, $j_{1,s}A$, is expressed as:

$$j_{1,s}A = g_{m1}(m_{1,s} - m_{1,e})A \tag{3.7}$$

where $j_{1,s}$ [kg/m^{2}s] is the diffusion mass flux of species 1, and A [m^2] is the surface area of the droplet. With the assumption of 4, the Reynolds number for the droplets becomes zero in the following equation:

$$\overline{N_{uD}} = 2 + (0.4\,\mathrm{Re}_D^{1/2} + 0.06\mathrm{Re}_D^{2/3})\,\mathrm{Pr}^{0.4} \tag{3.8}$$

The Sherwood number, *Sh*, in a purely diffusive situation, is thus approximated as:

$$Sh = \frac{g_{m1} D}{\rho D_{12}} \approx 2 \tag{3.9}$$

where ρ [kg/s] is the density of the air, *Re* is the Reynolds number, and *Pr* is the Prandtl number. The mass transfer conductance and the evaporation rate of the droplet are characterized by:

$$g_{m1} = \frac{2\rho D_{12}}{D} \tag{3.10}$$

$$j_{1.s} A = \frac{2\rho D_{12} A}{D}(m_{1,s} - m_{1,e}) \tag{3.11}$$

where D_{12} [m^2/s] is the binary diffusion coefficient and D [㎛] is the diameter of the water droplet. Since the mass loss of the droplet indicates the evaporation rate, the mass balance on a droplet is:

$$\frac{d}{dt}(\frac{1}{6}\pi D^3 \rho_l) = -j_{1,s} A \tag{3.12}$$

where ρ_l [kg/s] is the density of the water. Substituting equation 3.11 for $j_{1,s}$, and differentiating:

$$\frac{dD}{dt} = -\frac{4\rho D_{12}(m_{1,s} - m_{1,e})}{D\rho_l} \tag{3.13}$$

Integrating with T_s yields:

$$\int_{D_0}^{0} D dD = -\frac{4\rho D_{12}(m_{1,s} - m_{1,e})}{\rho_l}\int_{0}^{\tau} dt$$

$$\frac{D_0^2}{2} = -\frac{4\rho D_{12}(m_{1,s} - m_{1,e})\tau}{\rho_l}$$

$$\tau = \frac{\rho_l D_0^2}{8\rho D_{12}(m_{1,s} - m_{1,e})} \tag{3.14}$$

where D_0 [㎛] is the initial diameter, and τ [s] is the droplet lifetime.

3.4 Summary

This chapter reviewed basic theoretical backgrounds regarding evaporative cooling and simultaneous evaporative cooling process that is the main physical phenomena occurring in PDEC towers were reviewed. In addition, definitions of these cooling devices and different types of PDEC towers were presented since no specialized terms or definitions are available in the literature. Furthermore, their potential benefits and limitations were reviewed so that the solutions for further improvements can be sought. With this basic knowledge, a computational modeling will be performed in the following chapter so that further understanding of fundamentals of main physical phenomena of the passive down-draft evaporative cooling processes can be made.

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CHAPTER 4: COMPUTATIONAL MODELING

4.1 Model Description

This chapter focuses on the modeling of two-dimensional steady state heat and mass transfer under turbulent flow conditions with constant properties within the effective area of a PDEC tower. The main physical phenomenon, simultaneous heat and mass transfer, was considered in the modeling of the down-draft evaporative cooling process. A general-purpose commercial CFD code (FLUENT) was adapted to solve this situation. The thermodynamic properties used in this computational modeling were obtained from the Engineering Equation Solver (EES.) A pressure-based implicit solver was chosen since it is suited to low-speed incompressible flows. Default material properties for the fluids in FLUENT were used.

The solutions are fully coupled since both the continuous phase, i.e., fluid flows of the air, and the discrete phase, i.e., water droplets, affect each other. According to the FLUENT 6.3 User's Guide, FLUENT solves the differential equations in the following manner:

1. Solve the continuous phase flow field;
2. Introduce the discrete phase by calculating the particle trajectories for each discrete phase injection;
3. Recalculate the continuous phase flow, using the interphase exchange of momentum, heat, and mass determined during the previous particle calculation;
4. Recalculate the discrete phase trajectories in the modified continuous phase flow field;
5. Repeat the previous two steps until a converged solution is achieved in which both the continuous phase flow field and the discrete phase particle trajectories have no variations with each additional calculation.

In addition, the following assumptions, which are typically adapted to most droplet models, are employed to compute the trajectory of a discrete phase droplet:

1. The vaporization process is quasi-steady;

2. The conservation equations for chemical species and enthalpy consist of a balance between convection and diffusion;
3. The droplet is composed of a single chemical species, while the gas in the continuous phase consists of air and vapor from the droplet;
4. Pressures and temperatures are below the critical thermodynamic state of the droplet so that its surface is impermeable to air;
5. The droplet is assumed to be spherical;
6. The spray is assumed to be dilute. Under this assumption, droplet collisions are ignored, and the effect of adjacent droplets on droplet transport rates is neglected;
7. The flow around the droplet is assumed to be quasi-steady i.e., the flow immediately adjusts to the local boundary conditions and droplet size at each instant of time;
8. The radial velocity of the liquid surface due to the evaporation of liquid is neglected;
9. Effects of drag and forced convection are represented by empirical correlations;
10. Gas phase transport is based on mean ambient properties and the effect of turbulent fluctuation is ignored;
11. The liquid surface is assumed to be in thermodynamic equilibrium with negligible temperature jumps due to finite rates of evaporation;
12. The effect of surface tension is neglected when determining phase equilibrium at the liquid surface;
13. The pressure is assumed to be constant and equal to the local mean ambient pressure;
14. Only concentration diffusion is considered, neglecting thermal diffusion;
15. Radiation between the droplets and their surroundings is neglected;
16. The gas phase Lewis number (Le) is not assumed to be unity in the droplet model;
17. The properties of the gas flow field are assumed to be constant at each instant of time;
18. The transport process within the droplet is neglected and its properties are assumed to be constant at each instant of time;
19. The spray is assumed to be monodispersed.

4.2 Governing Equations

The main physical phenomena of down-draft evaporative cooling involve turbulent fluid flow, heat and mass transfer, and species mixing. The differential equations for conservation for mass and momentum, energy, and species must be solved to account for this complex environment. In addition, the transport equations for turbulence modeling should also be solved. Thus, three sets of equations are considered. This set of equations for the continuous phase calculates the fluid flow and species transport, and the set of equations for the dispersed phase calculates the trajectory of the water droplets. Due to a strong interdependence between both phases, the solutions are coupled and must be solved as such. The general equations for the solution are shown in the following subsections.

4.2.1 Continuous phase model

As described in the previous section, FLUENT solves continuous phase flows as it solves the differential equations for conservation for mass and momentum, energy, and species in the following manner. At the beginning of the processes, the model solves continuous phase without inclusion of interchange between two phases. Once the disperse particle trajectories were solved, and the source terms were obtained such as S_m, S_h, and F_i, it solves continuous phase with inclusion of these source terms in the following equations. The equation for the conservation of mass is:

$$\frac{\partial}{\partial x_i}(\rho u_i) = S_m \tag{4.1}$$

where u_i is air velocity component in the continuous phase [m/s] and S_m is the addition of the mass to the continuous phase from the discrete phase [kg/m^{3}s], defined in the following subsection 4.2.3. The momentum transfer from the exchange can be written as:

$$\rho u_i \frac{\partial u_i}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\mu\left(\frac{\partial u_j}{\partial x_j}\right)\delta_{ij}\right]+\rho g_i-\frac{\partial p}{\partial x_i}+F_i \tag{4.2}$$

, and the energy equation with the inclusion of species diffusion and interchange energy source between two phases, defined in the following subsection 4.2.3, i.e., volumetric heat source S_h, calculates the heat transfer using:

$$\rho u_i \frac{\partial e}{\partial x_i} = -p\frac{\partial u_i}{\partial x_i}+\Phi_v+\frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right)+\frac{\partial}{\partial x_i}\left(\sum_{i'=1}^{n} h_{i'}J_i\right)+S_h \tag{4.3}$$

where μ is the molecular viscosity [kg/m.s^2], p is the static pressure [Pa], g_i is gravity [m/s^2], F_i is the momentum source [kg/m^{2}s^2], e is the internal energy [J/kg], Φ_v is the Rayleigh dissipation function [kg/s^{3}m], k is the thermal conductivity [W/mK], T is the air temperature [K], h_i is the enthalpy of species i, J_i is the diffusion flux of species i [kg/m^{2}s], and S_h is the volumetric heat source [kg/s^{3}m]. The conservation equations for species to predict the local mass fraction of each species, i.e., gas phase of water and air, are:

$$\rho u_i \frac{\partial m_i}{\partial x_i} = -p\frac{\partial J_i}{\partial x_i}+S_m \tag{4.4}$$

$$J_i = -\rho D_{i',m}\frac{\partial m_i}{\partial x_i} \tag{4.5}$$

where m_i is the local mass fraction of species i and $D_{i,m}$ is the diffusion coefficient for species i in the mixture.

4.2.2 Discrete phase model

The discrete droplets in the continuous phase are assumed to be spherical. At the beginning of the solutions, the model calculates the trajectory of a discrete phase droplet using the Lagrangian approach by integrating the force balance. Once the continuous phase is recalculated and altered, it solves the discrete phase in the following equation:

$$\frac{du_p}{dt} = F_D(u - u_p) + \frac{g_x(\rho_p - \rho)}{\rho_p} + \frac{\rho}{\rho_p} u_p \frac{\partial u}{\partial x_i} \tag{4.6}$$

$$F_D = \frac{18\mu}{\rho_p d_p^2} \frac{C_D \operatorname{Re}}{24} \tag{4.7}$$

$$\operatorname{Re} \equiv \frac{\rho d_p \left| u_p - u \right|}{\mu} \tag{4.9}$$

$$C_D = a_1 + \frac{a_2}{\operatorname{Re}} + \frac{a_3}{\operatorname{Re}^2} \tag{4.10}$$

where u_p is the velocity of the droplets [m/s], $F_D(u-u_p)$ is the drag force per unit particle mass [m/s^2], the second term in the right-hand side is the gravitational force on the particle, the third term in the right-hand side is an additional force caused by the pressure gradient in the fluid, the term $d\mu_p/dt$ in the left-hand side is the evaporation rate of the particle, g_x is gravity [m/s^2], C_D is the drag coefficient , d_p is the droplet diameter [m], and $a1$, $a2$, and $a3$ are constants given by Morsi and Alexander (Morsi and Alexander, 1972.) The heat balance for computing the heat transfer between the discrete and continuous phases with no consideration of radiant heat transfer is defined as:

$$m_p c_p \frac{dT_p}{dt} = hA_p(T_\infty - T_p) + \frac{dm_p}{dt} h_f \tag{4.11}$$

where c_p is the droplet heat capacity [J/kgK], T_p is the droplet temperature [K], h is the convective heat transfer coefficient [W/m^{2}K], A_p is the droplet surface area [m^2], T_∞ and T_p are the temperatures of continuous phase and droplet [K], respectively, dm_p/dt is the rate of evaporation [kg/s], and h_{fg} is the latent heat [J/kg].

4.2.3 Coupling between the dispersed and continuous phases

In order to solve the two coupled phases, an iterative method is utilized. Once a calculation of a particle trajectory is made, the heat, mass, and momentum gained or lost by the particle stream is calculated, and then these values are incorporated into the continuous phase calculations. The mass exchange, S_m, from the discrete phase to the continuous phase is determined as the mass differences between control volumes using:

$$S_m = \frac{\Delta m_p \dot{m}_{p,0}}{m_{p,0}} \tag{4.12}$$

where Δm_p is the particle mass change in each control volume, m_p is the mass flow rate of the particles, and $m_{p,0}$ is the initial mass flow rate of the particles. This mass exchange is then included into the continuity equation of the continuous phase as well as the species equation as a source of mass. The momentum transfer from the continuous phase to the discrete phase can be written as the change in momentum of a particle between control volumes using:

$$F_i = \sum \left(\frac{18\mu}{\rho_p D_p^2} \frac{C_D \mathrm{Re}}{24} (u_p - u) + \frac{g_x(\rho_p - \rho)}{\rho_p} + \frac{\rho}{\rho_p} u_p \frac{\partial u}{\partial x_i} \right) \dot{m}_p \Delta t \tag{4.13}$$

The rate of vaporization is governed by the gradient of the vapor concentration between the droplet surface and the gas phase:

$$N_i = K_c (C_{i,s} - C_{i,\infty}) \tag{4.14}$$

$$K_c = \frac{Sh D_{i,m}}{d_p} = \frac{(2 + 0.6 \mathrm{Re}^{1/2} Sc^{1/3}) D_{i,m}}{d_p} \tag{4.15}$$

$$C_{i,s} = \frac{P_{sat}(T_p)}{R(T_p)} \tag{4.16}$$

$$C_{i,\infty} = X_i \frac{p}{RT_\infty} \tag{4.17}$$

where N_i is the molar flux of vapor [kgmol/m^{2}s], K_c is the mass transfer coefficient [m/s], $C_{i,s}$ is the vapor concentration at the droplet surface [kgmol/m^3], $C_{i,\infty}$ is the vapor concentration in the continuous phase [kgmol/m^3], p_{sat} is the saturated vapor pressure [Pa], R is the universal gas constant [J/kgK], X_i is the local bulk mole fraction of species i, Sh is the Sherwood number, defined as the ratio of convective to diffusive mass transport, and Sc is the Schmidt number, defined as the ratio of momentum diffusivity and mass diffusivity. The mass change of the droplet is determined by the following equation:

$$m_p(t+\Delta t) = m_p(t) - N_i A_p M_{w,i} \Delta t \tag{4.18}$$

where $M_{w,i}$ is molecular weight of species i [kg/kgmol]. The volumetric source term, S_h, can be given by the following expression:

$$S_h = \left[\frac{\overline{m}_p}{m_{po}} C_p \Delta T_p + \frac{\Delta m_p}{m_{p,o}} \left(-h_{fg} + \int_{T_{ref}}^{T_p} C_{p,i} dT \right) \right] \dot{m}_{p,o} \tag{4.19}$$

where $\overline{m}_p$ is the average mass of droplet in a control volume [kg].

4.3 Physical Models

A coupled pressure-velocity condition to solve equations for fluid flow, species transportation, and energy was imposed on the solution domain. A second order discretization scheme for pressure and a second order upwind discretization scheme for momentum, turbulent kinetic energy, turbulent dissipation rate, species, and energy were employed. To increase the stability of the solutions, the under-relaxation factors were calibrated. The best values for these parameters were determined to be: 0.3 for turbulent kinetic energy, 0.7 for turbulent dissipation rate, and 0.5 for turbulent viscosity, respectively. The other values were set to the defaults in FLUENT.

4.3.1 Computational domain

The computational domain for the physical modeling of down-draft evaporative cooling includes an effective area over the vertical tower from the sprays at the upper end to the outlets at the lower portion of the tower as illustrated by the dashed box in Figure 4.1. This is where the main phenomenon, simultaneous heat and mass transfer, takes place. In fact, numerous cases need to be considered to appropriately model the fluid flow through the wind catchers and outlets at the bottom of the tower. It, however, is difficult to include hundreds of possibilities for modeling various types of wind catchers as well as bottom outlets. While turbulent flow is strongly dependent on the initial conditions, all initial conditions such as air conditions and the area of wind catchers are known for this system. Thus, it is reasonable to simplify the mass flow rate of air across the wind catcher area by assuming that it is uniformly distributed over the surface area over which water droplets are injected by the system. This simplification, however, does not properly model turbulent flow at the inlet as well as wall-bounded flows. To remedy this gap and minimize computational demands, the outdoor air is assumed to be diagonally distributed over the inlet surface with a 45-degree angle.

Other assumptions that have been employed to simplify the computational domain are as follows:

1. The air entering through the wind catcher is distributed evenly over the inlet surface area of the tower without loss;
2. Both fluids are uniformly distributed over the surface area and completely mixed with each other throughout the domain;
3. The temperature of inside wall reaches an equilibrium and is maintained at a constant and uniform temperature throughout all the walls;
4. The walls are well insulated, so that heat flux through the walls is negligible;

5. Changes in kinetic and potential energy are neglected;
6. Radiation heat transfer, viscous heat dissipation and other secondary effects are negligible;
7. No heat generation within the computational domain takes place;
8. The pressure in the domain maintains positive pressure.

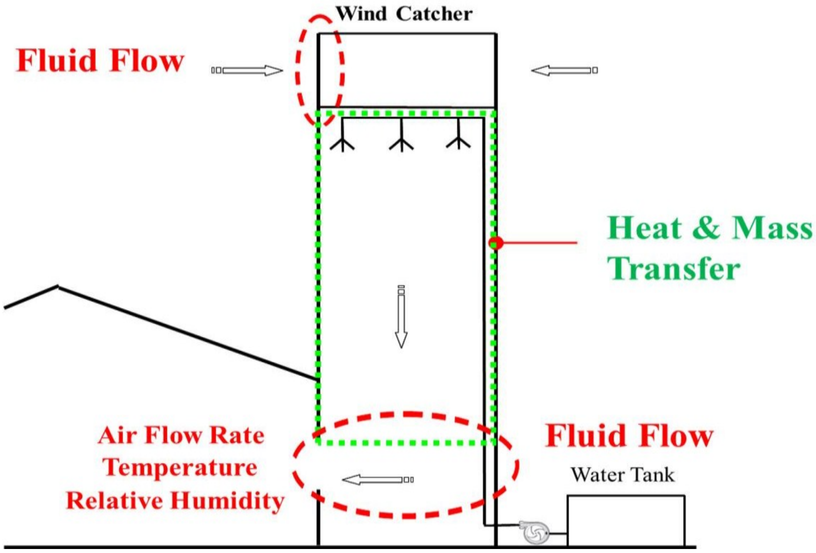

Figure 4.1 Schematic of main phenomena in a PDEC tower

4.3.2. Convergence

A number of criteria can be considered to judge the convergence of the solutions. The very first step is to monitor scaled residuals. The convergence criterion for continuity was 10^{-2}. This was chosen because the solutions are very stable after approximately 150 iterations, and a stricter criterion for continuity required too much computational effort. The criteria for k and ε were 10^{-3} and that for the velocity components and species were 10^{-5}. The criterion for energy was set to be 10^{-6}.

In addition, the stability of the solutions was considered. A solution can be considered stable when the truncation errors are stable and consistent. The truncation errors should not grow with integration. Furthermore, the $y+$ values were observed to determine the proper treatment of the wall-bounded flows. They are defined as:

$$y+ = \frac{\rho u_\tau y_p}{\mu} \tag{4.19}$$

where ρ is density of the fluid [kg/m^3], u_τ is the friction velocity [m/s], y_p is distance from wall [m], and μ is dynamic viscosity [kg/m·s]. This y+ value should not be between 5 and 30 in a buffer layer, but in between 30 and 300, or below 5 for a low *Re* flows. It is desirable to be close to the lower bound of 30. The value of mass imbalance was also monitored, and this value was compared to the mass flow rate of the discrete phase droplet to insure that continuity was satisfied.

Grid independency was investigated to verify that variations in the size of grid generated did not influence the results. All criteria described above were considered to judge the independence of the mesh. As an example, a PDEC tower in the literature was modeled to test grid independence and to validate the results against the experimental data obtained. The effective area of the computational domain for the tower in this study was 3.9m × 7.15m. To properly model wall-bounded flows and turbulence at the inlet and outlet, a bi-exponent mesh type was adopted, varying different interval size as well as the grading ratio. As for the turbulence modeling, the standard *k-ε* model was employed for the initial iterations. Almost no variations in the results of temperature and relative humidity at the outlet were observed when the horizontal interval size was 4cm and the vertical distance was 3cm with a gradient ratio of 0.6. The total number of cells was 23324. The average $y+$ along the wall of 40 and mass imbalance of below 0.2% were observed.

4.3.3 Discrete phase modeling

Different models and parameters, which are required to track the discrete phase, were tested. Two-way coupling was necessary as a strong interdependency between species appeared. The discrete phase was set to interact with the continuous phase, updating the discrete phase sources every 10 continuous phase iteration to increase the stability of the solution. Unsteady water particle treatment was also considered. With variation of particle time step ranging from 1.0E-04s to 1.0s, temperature and relative humidity have been monitored to find proper time step at the lowest cost. As a result, a time step of 0.1s was used since it reduces the computational expense while still providing the same level of accuracy. The trajectory of the particle is thus calculated each 10th particle time step. The integration time steps for tracking particles was set to be controlled by the length scale determined as the ratio of the inlet velocity of the air and the turbulent length scale. Two-Way turbulent coupling was chosen so that the variation of turbulent quantities due to the interaction between the two phases could be considered. Default numerical schemes to calculate equations for particle heat and mass transfer and particle tracking were chosen.

The surface injection type was chosen for the discrete phase droplet injection so that the mass of water can be uniformly distributed over the inlet surface area. The diameter of the droplet was set to be uniformly distributed with no consideration of particle breakdown. The temperature of the particles was assumed to be equal to the wet-bulb temperature of the outdoor air. The discrete phase droplets were set to be continuously injected during calculations at a constant mass flow rate, and the inlet surface area scaled the mass flow rate. A stochastic tracking approach was considered to model particle turbulent dispersion with the option of Time Scale Constant of 0.15.

4.3.4 Turbulence modeling

It is generally known that the standard k-ε model is overly diffusive and inaccurate for treating near wall situations. Two viscous models in FLUENT were considered as they are appropriate to model turbulence and wall-bounded flows with reasonable accuracy and speed. Two different viscous flow models such as the k-ε and k-ω models were also available. The k-ε model has three different models including the Standard, the RNG, and the Realizable models, and the k-ω model has two different models including the Standard and the SST models. All five of these viscous models were considered. While no significant variations in the results appeared, the RNG k-ε model with the options of enhanced wall treatment (EWT) showed the best agreement with the experimental data though it required approximately 1.5 times more computational effort in comparison to the standard *k*-*ε* model.

Turbulence modeling requires various parameters, and these parameters are different depending on the turbulent model and modeling method used. The RNG *k*-*ε* model with the Intensity and Length Scale method was chosen to adequately model turbulence and wall-bounded flow in the computational domain. The turbulence quantities used as input values were determined as shown in the following equations.

The mass flow rate of the air [kg/s], $\dot{m}$, through the wind catcher can be obtained from the continuity equation:

$$\dot{m} = \rho A_{wc} V \tag{4.22}$$

where ρ is the density of air [kg/m^3], A_{wc} is the area of wind catcher [m^2], and V is the velocity of air [m/s]. The inlet velocity [m/s] for the computational domain, V_i, is thus expressed as:

$$V_i = \frac{\dot{m}}{\rho A_t} \tag{4.22}$$

where A_t is the cross-sectional area of the PDEC tower [m^2]. The hydraulic diameter [m], D_h, to determine the Reynolds number, is:

$$D_h = \frac{4A_t}{P} \tag{4.22}$$

where P is the perimeter of the tower [m]. The Reynolds number, Re, is given by:

$$\mathrm{Re} = \frac{UD_h}{\nu} \tag{4.23}$$

where U is the average air velocity [m/s] and ν is the kinematic viscosity [m^2/s]. The turbulence intensity, I, is thus:

$$I = 0.16\mathrm{Re}^{-1/8} \tag{4.24}$$

The turbulent kinetic energy, k, is given by:

$$k = \frac{2(UI)^2}{3} \tag{4.25}$$

As for wall-bounded flows, the turbulence length scale, l, can be calculated as:

$$l = 0.4\delta_{99} \tag{4.26}$$

where the boundary-layer thickness [m] is:

$$\delta_{99} = 5.0\sqrt{\frac{\nu x}{U_\infty}} \tag{4.27}$$

The dissipation rate is therefore:

$$\varepsilon = C_\mu^{3/4}\frac{k^{3/2}}{l} \tag{4.28}$$

where C_μ is an empirical constant.

4.4 Boundary Conditions

Three sets of boundary conditions for the inlet, the outlet, and the wall conditions were input based on the FLUENT documentation (FLUENT 6.3 User's Guide.) The wet-bulb temperature and humidity ratio were obtained from the Engineering Equation Solver (Klein, 2006) as described in the previous section. A velocity-inlet type was chosen for the inlet. The velocity of the air calculated at the inlet surface was input as the velocity magnitude. Each X and Y component of flow direction was set to 1 so that the direction of the incoming air was maintained at a 45-degree angle with respect to the outlet. The Intensity and Length Scale methods for modeling turbulence were chosen to properly model turbulence, and the calculated values of turbulent intensity and turbulent length scale were input into FLUENT. An accurate relative humidity at the inlet was obtained when the species mass fractions were set to be 98% of the humidity ratio. The discrete phase droplets were set to be trapped at the inlet surface so that they were entrained into the continuous phase field.

Stationary, non-slip wall properties were considered. The inside surface temperature of the walls was set to be 3°C higher than the wet-bulb temperature of the outdoor air. While the temperature and relative humidity with surface temperature variations has almost no change, a 3°C difference between the wet-bulb temperature and the wall temperature were imposed. Zero diffusive flux of the species boundary condition was chosen. The discrete phase model conditions were set to be reflected from the wall surfaces after any collisions, and the discrete phase reflection polynomial coefficients for both the normal and tangent components were selected. In addition, the outflow type for the outlet boundary condition was considered, and the mass flow of both phases over the domain was set to be exhausted without loss through the outlet opening.

4.5 Validation

A PDEC experimental test facility[1] was modeled and the results of the computational model were validated against the experimental data provided by Prof. Ford at University of Nottingham, UK. The dimensions of the PDEC tower were 4.1m × 4.4m × 10.7m, and the air flow was in one direction toward a room that was being served by the tower. The 1.7m × 3.7m wind catchers were placed on the east and west sides of the tower. The size of the droplets injected into the air stream was approximated 30 ㎛. Data was obtained every minute. The data sets taken by various data acquisition systems included the outdoor air conditions such as temperature and relative humidity, wind direction and velocity and temperatures at five different points at the exit of the tower. The temperatures at the exit of the tower were measured at three points at the level of roof of the room, a point at the center of the outlet, and a point near the floor level. Since the effective tower height was defined from the top of spray to the top of the PDEC outlet, the temperatures taken at the middle point of the outlet and the floor level temperature were averaged. The experimental data shown in Table 4.1 were collected on three different days in August, 1997.

Table 4.1 shows the differences between the measured and predicted temperature and relative humidity at the exit of the tower. It includes the outdoor air temperature, T_o, the outdoor relative humidity RH_o, and the outdoor wind speed, V_o. The average values of these variables over 10 minute time periods were used to minimize any uncertainties that could be involved due to the experimental set-up. In the full data set, the outdoor air temperatures ranged from 29.7°C to 37.9°C, and the relative humidity ranged from 27.7% to 76.4%. However, outdoor relative humidity in most of hours during the period was very high even afternoon hours, and wind direction in some of those hours significantly varied. In addition, the most desirable range for PDEC operation is a dry climate. Thus, a few relatively dry conditions were chosen as shown in Table 4.1.

Very good agreement between the measured outlet temperature and humidity levels and those predicted by the computational model described in this chapter is observed as shown in Table 4.1. The maximum difference in temperature was 0.7°C at the outdoor temperature of

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[1] The data set were measured in the experimental PDEC tower at the Conphoebus Institute, Catania, Sicily, and this work was partly funded by the European Commission.

36.9°C and relative humidity of 29% while the maximum difference in relative humidity was 3.3% at outdoor air conditions of 32.5°C and 50.7%RH. The root mean square (RMS) value calculated were 0.48°C for temperature and 2.3% for relative humidity.

Table 4.1 Comparison between measured and predicted air conditions

T_o (°C)	RH_o (%)	V_o (m/s)	T_M (°C)	T_P (°C)	Diff.	RH_M (%)	RH_P (%)	Diff.
31.0	55.7	3.3	26.0	26.35	-0.35	79.4	82.3	-2.9
32.5	50.7	3.2	26.56	27.25	-0.69	76.2	79.5	-3.3
33.0	45.4	3.2	26.9	26.6	0.3	77.4	79	-1.6
36.9	29.0	3.2	25.9	26.6	-0.7	72.7	71.2	1.5
37.4	27.7	4.0	28.78	29.05	-0.27	59.9	57.2	2.7
37.9	28.0	3.6	28.26	28.64	-0.38	62.5	61.9	0.6

* O: outdoor, M: measured, P: predicted

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CHAPTER 5: EFFECT OF VARIABLES ON PDEC COOLING PERFORMANCE

In the previous chapter, a computational model was developed to study the fundamentals of the passive down-draft evaporative cooling (PDEC) process. Previous studies have investigated what parameters affect the cooling performance of PDEC systems. These studies, however, did not include the influence of the droplet size, which is one of the most important variables and has a strong impact on the cooling performance of PDEC towers. It is also necessary to investigate which parameters, including ones defined in the previous studies, can potentially affect the performance of the PDEC system and how significant the impact of each individual parameter is. In fact, this characterization of the impact of different parameters on the PDEC system is very important because many of these parameters play a key role in determining the cooling capacity of PDEC tower, and a better understanding of the role of these parameters would led to substantially improved performance of PDEC systems. In addition, this may also lead to an extension of the applicability of these particular systems to other situations and climates. This chapter will thus present a computational analysis of the fundamental physics of PDEC systems and the significance of the different variables that impact the performance of these systems.

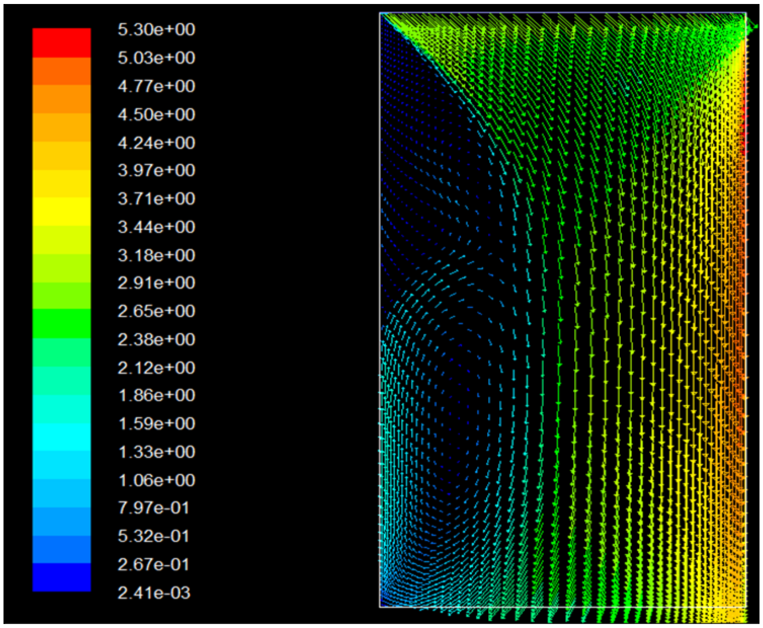
5.1 Air Distribution Characteristics

5.1.1 Velocity profile

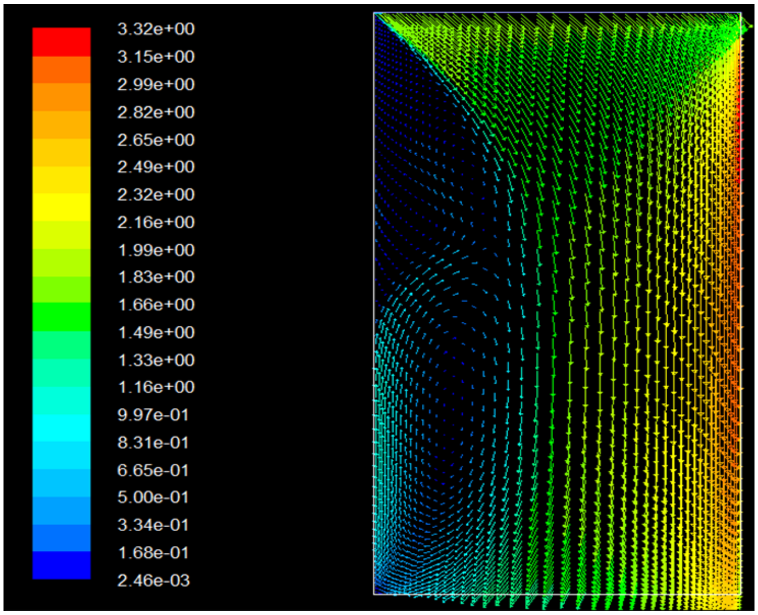
A computational analysis on the characteristics of air distribution within the effective tower area was performed. It is important to investigate how the air flows through the tower and is influenced by various effects such as turbulence at the inlet and wall-bounded flows along the walls. In fact, some studies have attempted to model the physical processes occurring within the tower. These studies, however, assumed that fluid flows straight from the top to the bottom of the tower in a manner that is consistent with a fully-developed flow. As a result, the air flow profiles in the tower have never been properly studied. A computational analysis was thus performed in order to appropriately handle the unique flow features in the down-draft towers such as turbulence at the inlet and wall-bounded flows. Note that many variables used in this computational analysis were employed form the experimental conditions such as tower height, droplet size, and water flow rate, utilized to validate the computational model. The sizes for the wind catcher and cross-section of the towers were chosen to be 4m×2m and 4m×4m, respectively for a bigger tower, and 2m×1m and 2m×2m for a smaller tower. A tower height of 7.15m was assumed. The temperature and relative humidity of the air were set to be 35°C and 20%, respectively. A water mass flow rate of 50l/h and droplet size of 30 ㎛ were assumed for this portion of the study.

Figure 5.1 shows the characteristics of the air distribution and its velocity profiles within the effective tower area. A high speed air stream was formed along the wall opposite to the wind catcher-mounted wall where the air was induced. This air stream in conjunction with induced fluid flows caused the air to move down from the top. The wall-bounded flows and the high speed stream near the wall then came to be slightly diffusive toward the opposite side once the momentum of the incoming downward air stream was being decreased at the bottom. Accordingly, an air stream toward the outdoor air-induced side was formed, and it flew upward along the wall, which is called backflow. The down-draft fluid flow induced such backflow in the middle of the tower, causing a continuous circulation of backflow along the wind catcher-mounted wall. It was thus expected that this backflow may delay the cooling processes in a humid air condition since the evaporative cooling processes took longer, and some water droplets would be induced into the backflow stream. This particular case was observed in some humid cases, and a discussion will be provided in the following sections.

The overall characteristics of air movement in the PDEC towers were very similar as the outdoor wind speeds and the cross-sections of the PDEC tower was changed as shown in Figure 5.1 and 5.2. The main differences in the air distribution at the three different outdoor wind speeds were the magnitude of the velocities and the diffusivity of the backflow that was formed along the outdoor air-induced side wall. The stream of backflow was re-entrained into the down-draft air stream in the middle of the computational domain since the high-velocity incoming air stream dominated the fluid flow pattern in the tower due to the high momentum of these streams in comparison to the low-speed backflow. The backflow was thus continuously circulated between the incoming, downward moving air stream and the upward moving backflow. In addition, the backflow that was entrained into the incoming air stream was a bit diffusive as the wind speed decreased. These characteristics of the air distribution were also seen in the other narrower cross-section tower as shown in Figure 5.2, forming a vertically longer backflow section than in the wider cross-section tower.

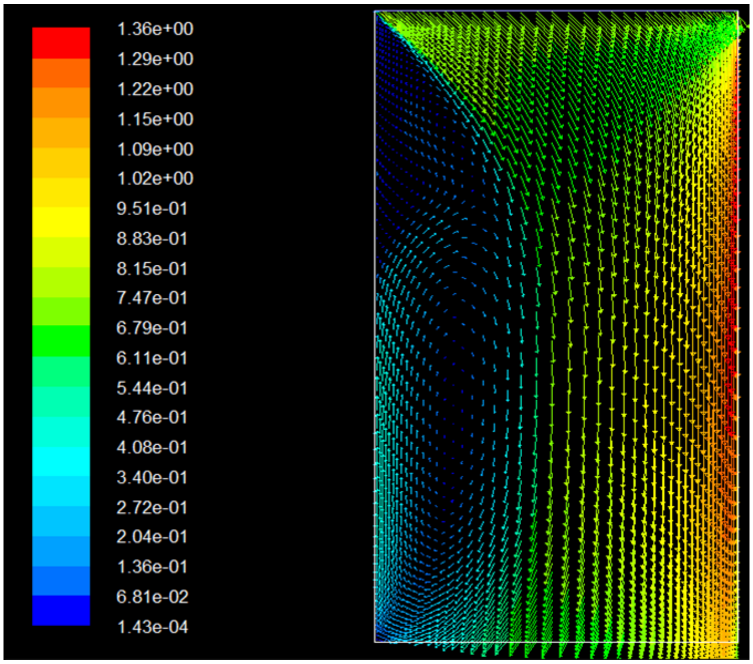


a) Outdoor wind speed of 5.5m/s



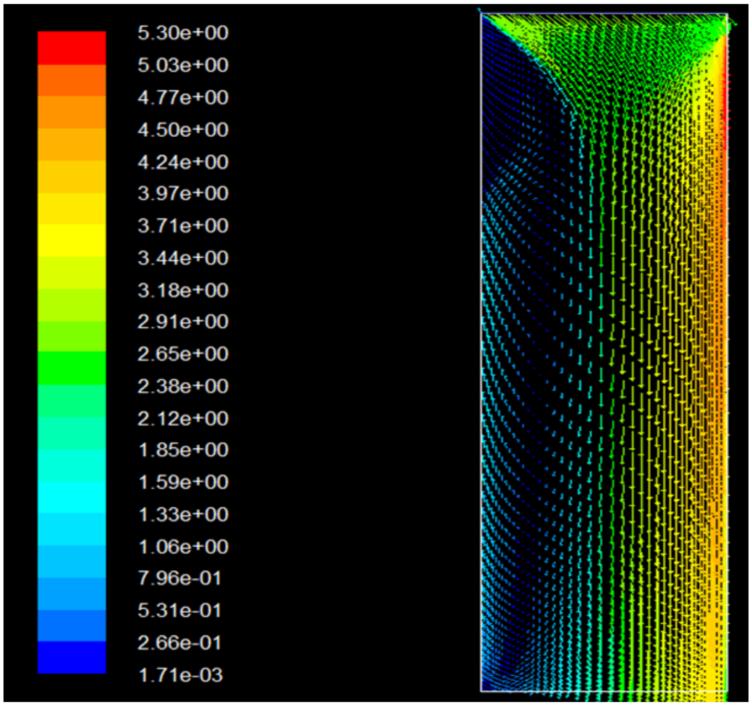
b) Outdoor wind speed of 3.5m/s

Figure 5.1 Air flow profile in a wider cross-section along the variations of wind speed



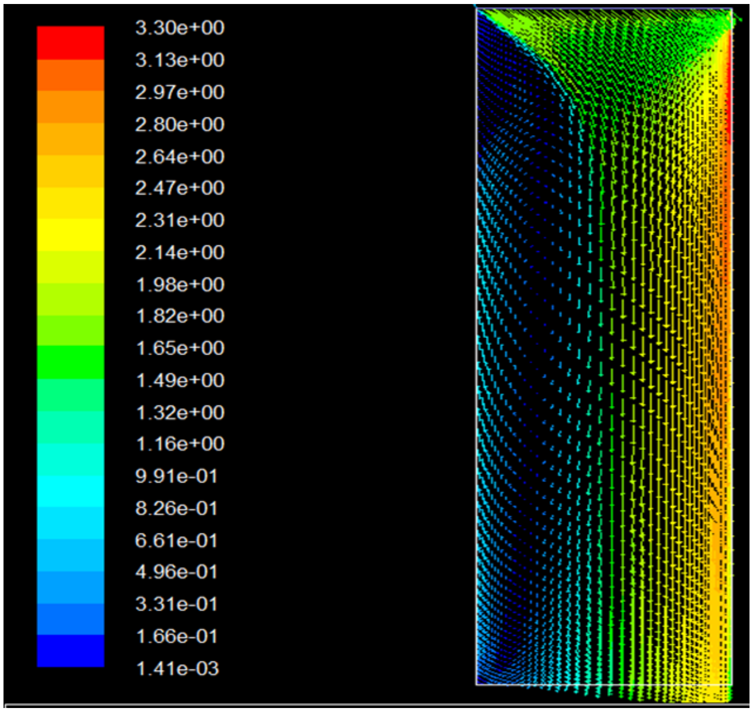
c) Outdoor wind speed of 1.5m/s

Figure 5.1 Air flow profile in a wider cross-section (con't)

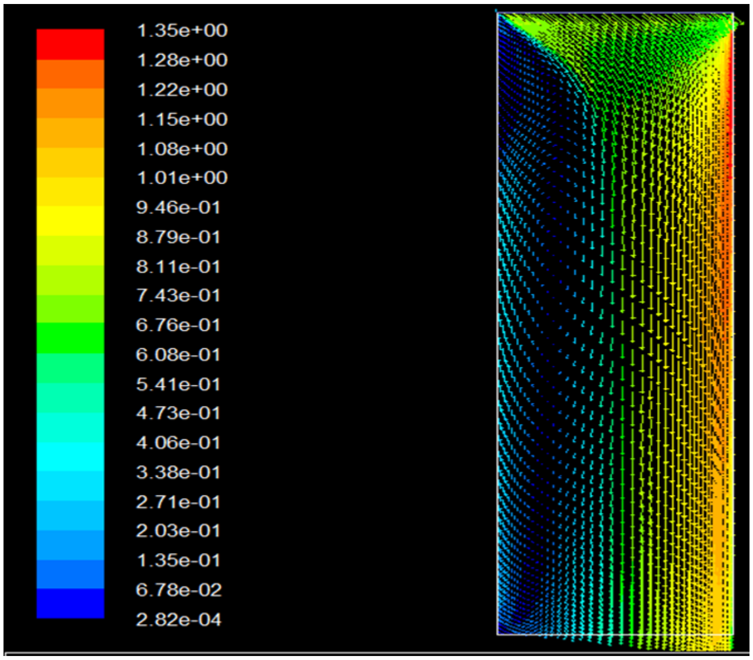


a) Outdoor wind speed of 5.5m/s

Figure 5.2 Air flow profile in a narrower cross-section along the variations of wind speed



b) Outdoor wind speed of 3.5m/s



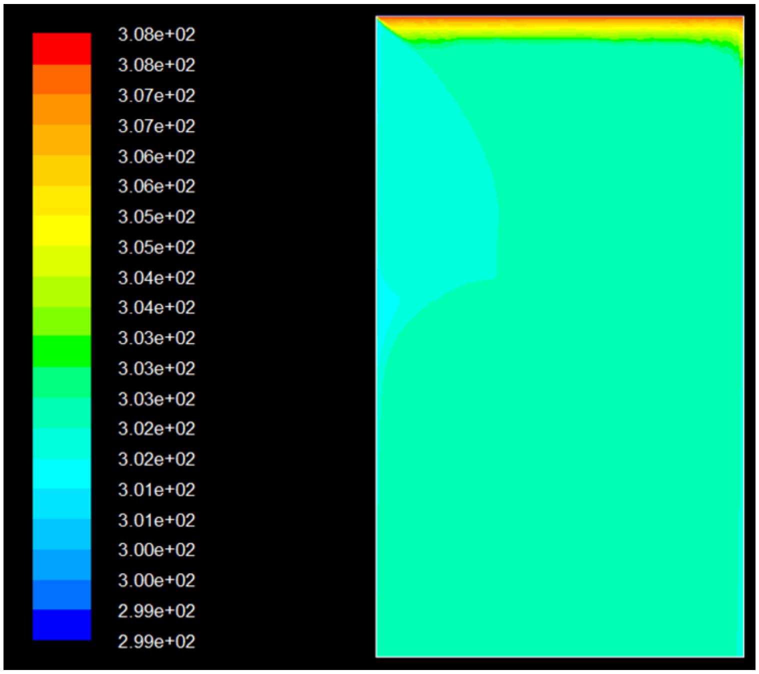
c) Outdoor wind speed of 1.5m/s

Figure 5.2 Air flow profile in a narrower cross-section (con't)

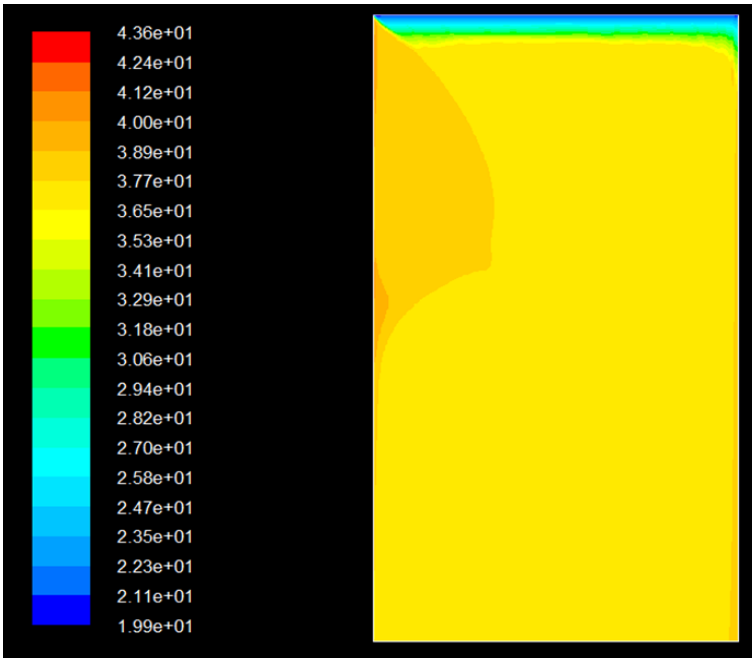
5.1.2 Temperature and relative humidity

The conditions of the air and water including temperature, relative humidity, and water droplet residence time were compared to verify how the down-draft evaporative cooling processes was impacted by different situations. Two different relative humidity conditions were considered: 20% to represent dry conditions and 40% to represent humid conditions. As the humidity conditions were varied, the tower configuration including the sizes of the wind catcher, the tower cross-sectional area, and the tower height were kept constant at 2.64m×2.64m, 4m×4m, and 7.15m, respectively. An outdoor temperature of 35℃ and wind speeds of 4m/s for the high speed case and 2m/s for the low speed case were selected. The water mass flow rate and droplet size were chosen to be 50l/h and 30 ㎛, respectively. Detailed investigations on the main physical processes will be provided in the following sections since they significantly vary with different situations.

Most of the temperature drop within the PDEC system occurred at the very top of the tower. Direct temperature drop of the air appeared as soon as water droplets were entrained into the air, and its temperature, once lowered by the evaporative cooling process, was maintained at an almost constant value with no considerable changes throughout the rest of the tower. Temperature drops achieved under dry humidity conditions were 6.0℃ at a wind speed of 4m/s and 11.84℃ at wind speed of 2m/s as shown in Figure 5.3 a) and 5.4 a), respectively. Similarly, the relative humidity reached its maximum level very near the top of the tower, and the distribution of relative humidity at the lower wind speed 2m/s was more constant throughout the tower than the higher velocity condition of 4m/s, as shown in Figure 5.3 b) and 5.4 b). Higher relative humidity zones were formed along the opposite sidewall from the wind induced side since the water injected was mostly entrained into the high-velocity air stream. This phenomenon was also seen on the backflow-formed side while differences in relative humidity between these zones and the main down-draft flow were less than approximately 3%. In addition, it appeared that the evaporative cooling process, under dry conditions where the relative humidity was 20%, was completed within a very short time: within 0.3 second at a wind speed of 4m/s and within 0.4 second at a wind speed of 2m/s as illustrated in Figure 5.3 c) and 5.4 c).

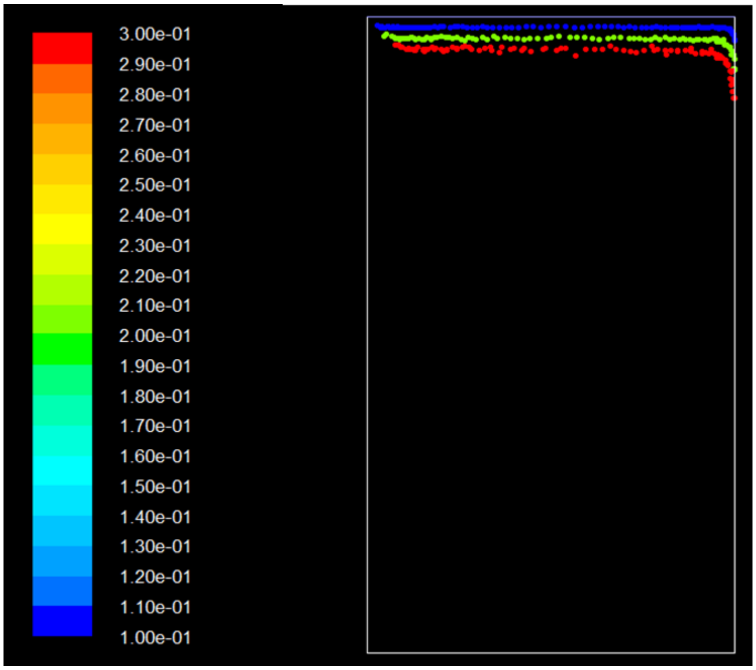


a) Temperature [°C]



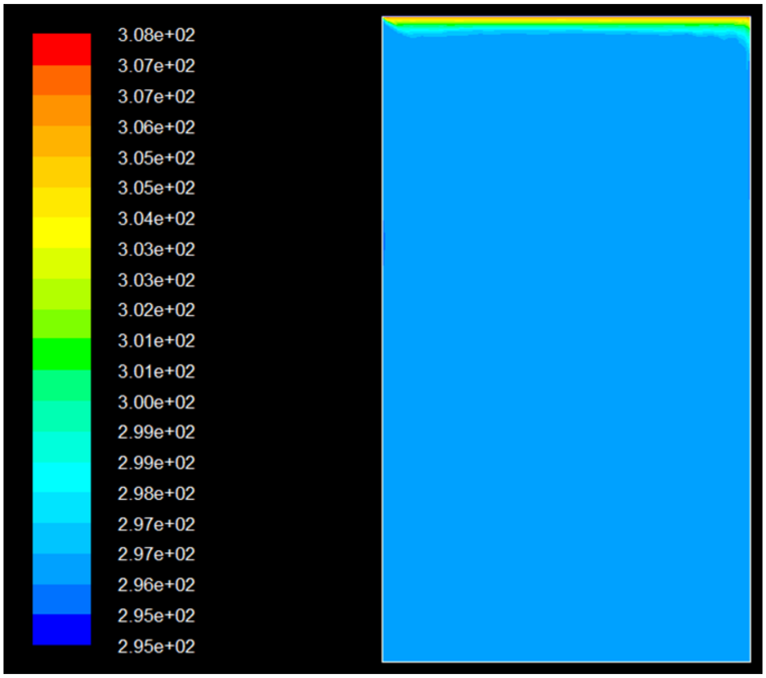
b) Relative humidity [%]

Figure 5.3 Distributions of temperature, RH, and droplet remaining time at the high speed, dry condition



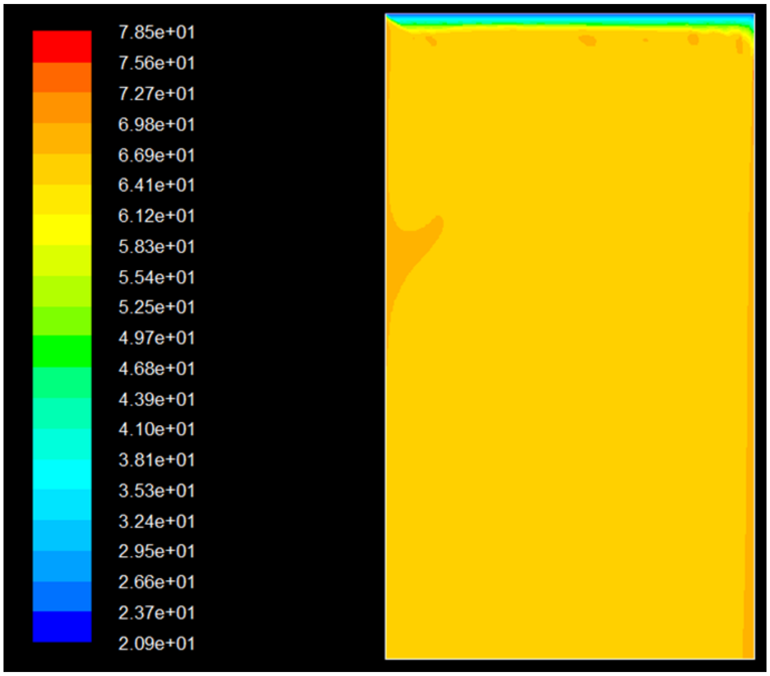
c) Droplets residence time [s]

Figure 5.3 Distributions of temperature, RH, and droplet remaining (con't)

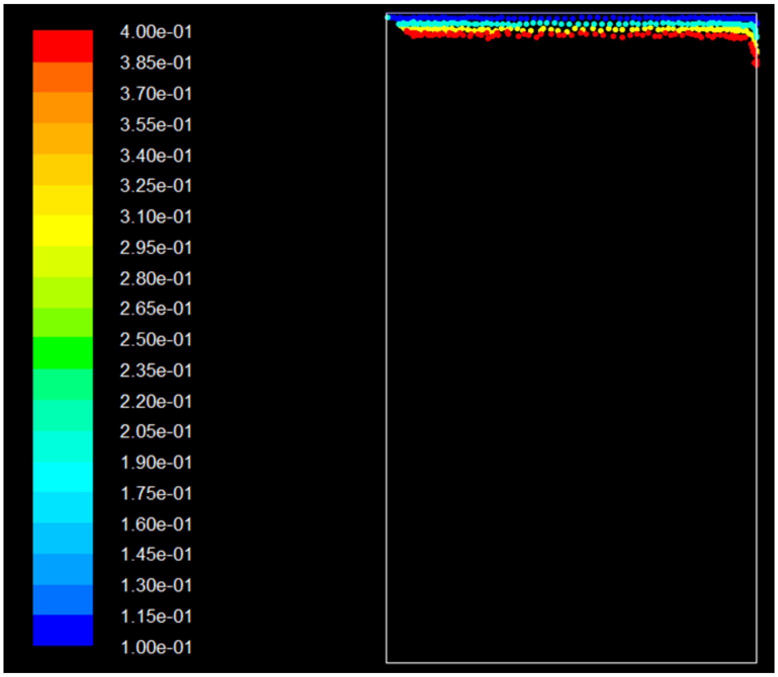


a) Temperature [°C]

Figure 5.4 Distributions of temperature, RH, and droplet remaining time at the low speed, dry condition



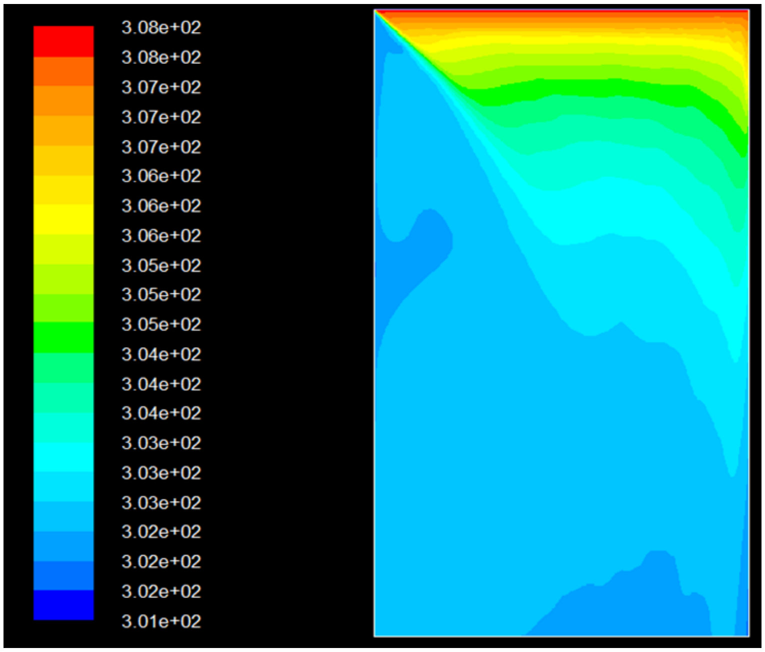
b) Relative humidity [%]



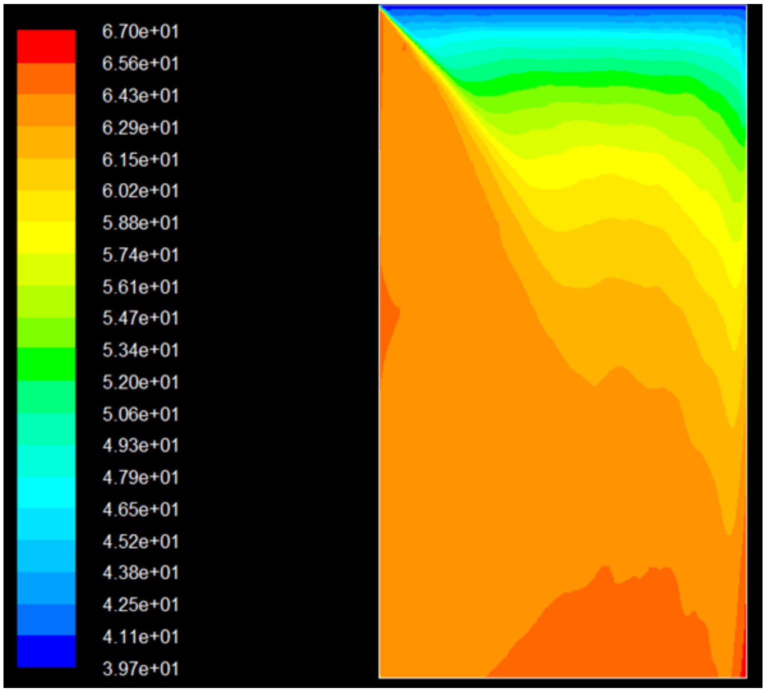
c) Droplet residence time [s]

Figure 5.4 Distributions of temperature, RH, and droplet remaining time (con’t)

An increased level of humidity in the outside air delayed the evaporative cooling process as shown in Figure 5.5 and 5.6. In the humid cases, gradual temperature drops occurred at the very top and continued over the tower area since the increased humidity in the air (relative humidity of 40%) hindered the physical cooling process throughout the tower. Average temperature drops at the outlet in the humid case were predicted to be 5.77°C at the high wind speed and 11.24°C at the low wind speed. The average temperature drops under dry conditions (relative humidity of 20%) were 6°C at the high wind speed (4m/s) and 11.84°C at the low wind speed (2m/s). The similarity of the temperature drops achieved under both the dry and humid conditions were due to the low water flow rate of 50l/h in the dry air condition. The theoretical maximum achievable temperature drop in a dry condition would have been 16.13°C, which is the difference between the dry- and wet-bulb temperatures of the air. Thus the temperature drops could be up to 16.13°C when the water flow rate in the dry air condition increased. On the other hand, a portion of air in the down-draft flow at the bottom and in the backflow section of the tower was saturated in the low wind speed case. Likewise, the average relative humidity at the outlet was predicted to be 61.8% for the high wind speed case and 92% for the low wind speed case. A continuous gradient in relative humidity appeared at the high wind speed while the backflow zone and the central area at the bottom at the low wind speed reached maximum relative humidity achievable, i.e. saturated at 100%. In addition, the maximum particle residence time, defined as the time that the particle has spent inside a domain since its entry (Ghirelli, 2004), over the area was observed to be 4.2 seconds at the high wind speed and 14.6 seconds at the low wind speed. Note that a noticeable portion shown in black in Figure 5.6 a) and b) indicated that the air in this portion was saturated. The temperature and relative humidity in this portion was the wet-bulb temperature and 100%RH, respectively.

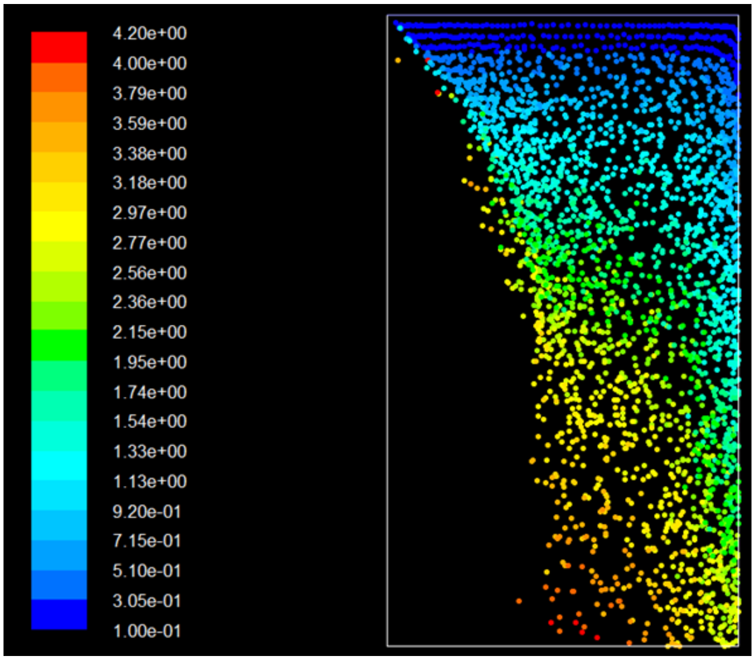


a) Temperature gradient [°C]



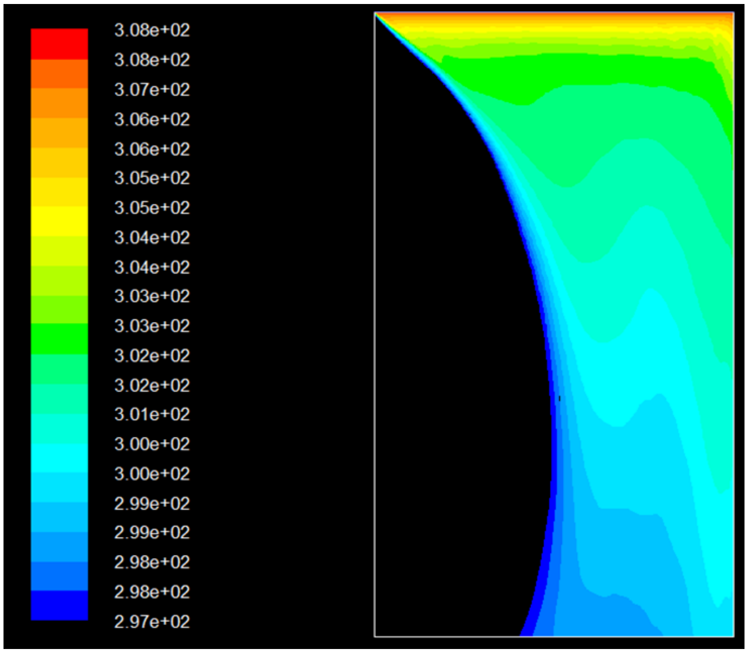
b) Relative humidity gradient [%]

Figure 5.5 Distributions of temperature, RH, and droplet remaining time at the high speed, humid condition



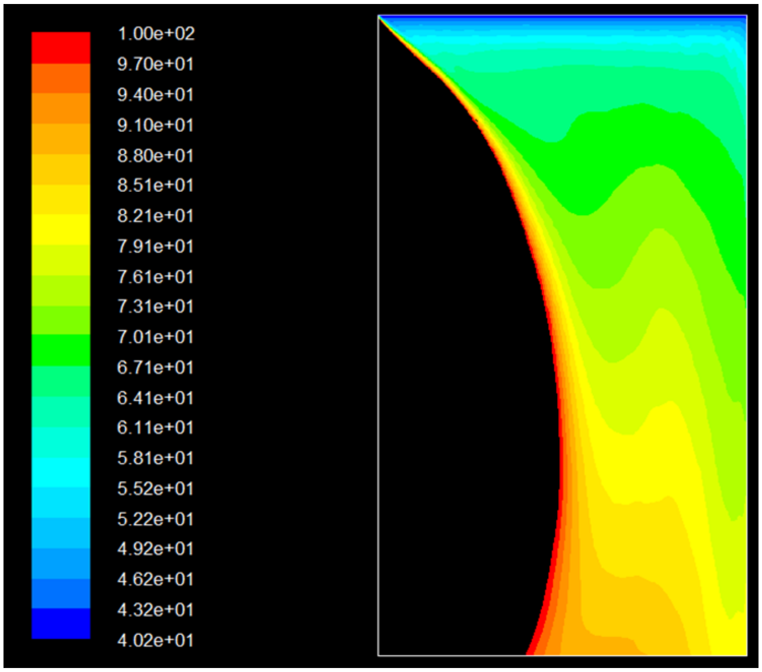
c) Droplet residence time [s]

Figure 5.5 Distributions of temperature, RH, and droplet remaining time at the high speed, humid condition (con't)

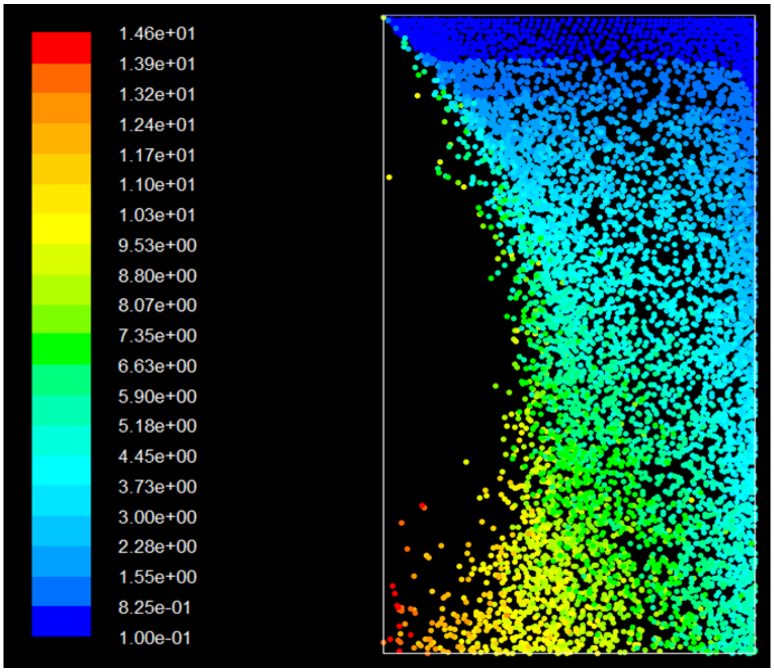


a) Temperature [℃]

Figure 5.6 Distributions of temperature, RH, and droplet remaining time at the low speed, humid condition



b) Relative humidity [%]



c) Particle residence time [s]

Figure 5.6 Distributions of temperature, RH, and droplet remaining time at the low speed, humid condition (con't)

5.2 Physical Tower Dimension

5.2.1 Air mass flow rate with tower configuration

The influence of the physical dimensions of PDEC towers on their performance was also investigated. Some efforts have been made to studying what types of wind catchers were effective in increasing the air mass flow rate to a PDEC tower so that it delivered a larger amount of air cooled by evaporation. In addition, some studies have dealt with the influence of wind speed, which determines the air mass flow rate, and the tower height under particular conditions. No study, however, has properly treated the impact of air mass flow rate corresponding to the physical size of the wind catcher and the cross-sectional area of PDEC towers. In fact, the air conditions at the exit of the tower vary with the physical configuration of the tower. The computational model predicted air conditions leaving the tower in eight different combinations of wind catcher and cross-sectional area of the tower with the variations in wind speed from 1 m/s to 6 m/s. The other conditions imposed were an outdoor temperature of 35℃, a relative humidity of 20%, a wet bulb temperature of 18.87℃, a tower height of 7.15m, a droplet size of 30 ㎛, and a water flow rate of 50l/h. Table 5.1 lists the different combinations of dimensions of the wind catcher and the tower, and the resulting air conditions at the outlet of each combination at different wind speeds are listed in Table 5.2 below.

It was clear from the output data presented in Table 5.2 that the PDEC towers receiving lower air velocities at their inlet accomplished greater temperature drops than higher air velocities. It can also be seen that the mass flow rates are the same when the product of the area of the wind catcher and the wind velocity yield the same result. For instance, the mass flow rate of dimension 3 at wind speed of 6m/s was 55.01kg/s. The mass flow rate was also 55.01kg/s for dimension 2 at a wind speed of 4m/s as well as for dimension 1 at a wind speed of 3m/s. The exit temperatures and relative humidity for these cases were almost all the same at 31.46℃ and 29%, respectively. This is because the same turbulent parameters such as turbulent intensity and length scale were determined due to the same Reynolds number within a particular tower cross-section. Negligible differences were noted among these three different dimensions such as 0.03℃ in temperature, 0.01% in relative humidity, and 0.01m/s in outlet velocity and were considered to be a result of computational uncertainties.

Air mass flow rate should be considered as a critical parameter. The performance of PDEC towers varied significantly with air mass flow rate. Temperature drops achieved was greater as the ambient wind speed decreased. Similarly, it was seen that a smaller wind catcher thus a lower air mass flow rate produced greater temperature drops and relative humidity increases within the same cross-sectional area of the tower. Differences in temperature and relative humidity in tower configurations 1 through 4, which have four different sizes of wind catcher at a particular tower cross-sectional area of 4m×4m, increased as ambient air speed decreased.

The ratio of the wind catcher area to the tower cross-sectional area was seen to be an important factor in the cooling performance of the PDEC tower. The air leaving the tower was saturated in a number of cases. Saturation was observed in the cases where the air mass flow rate was below approximately 10kg/s and the inlet velocity at the top of the PDEC tower was generally below 1m/s. However, it appeared that lower values of the wind catcher to tower cross-sectional area ratio caused saturation at high wind speeds.

For example, the area ratio between the wind catcher and the tower cross-sectional area was 0.25 in configurations 4 and 8. The air in the configuration 8 was saturated at an ambient wind speed of 5m/s with a corresponding inlet air velocity at the very top of PDEC tower of 1.25m/s. Saturation at a relatively high wind speed 2m/s and thus an inlet air velocity of 0.5m/s was seen in configuration 4. To avoid saturation of air, it was necessary that, in general, the ratio between wind catcher area and tower cross-sectional area maintained a certain value such as 0.5 and that the tower inlet velocity was between 1.25m/s and 0.75m/s for wider towers and between 1.5m/s and 1m/s for narrower towers.

Table 5.1 Combinations of sizes of wind catcher and tower

Configuration	1	2	3	4	5	6	7	8
Wind catcher size (m)	4×4	4×3	4×2	4×1	3×3	3×1.5	2×1	2×0.5
PDEC tower size (m)	4×4	4×4	4×4	4×4	3×3	3×3	2×2	2×2

Table 5.2 Air conditions at the exit under various combinations of wind catcher and tower

Configuration	V_i (m/s)	V_o (m/s)	$\dot{m}$ (kg/s)	T_e (°C)	RH_e (%)	V_e (m/s)
1	6	6	110.02	33.22	24.05	4.77
2	4.5	6	82.51	32.63	25.63	3.57
3	3	6	55.01	31.46	29.0	2.36
4	1.5	6	27.50	27.99	39.4	1.16
5	6	6	61.88	32.63	25.63	4.58
6	3	6	30.94	30.3	32.64	2.27
7	3	6	13.75	27.99	41.33	2.11
8	1.5	6	6.88	21.25	76.55	1.03
1	5	5	91.68	32.87	25.0	3.96
2	3.75	5	68.76	32.16	26.95	2.96
3	2.5	5	45.84	30.76	31.2	1.97
4	1.25	5	22.92	26.65	47.4	0.97
5	5	5	51.57	32.16	26.96	3.8
6	2.5	5	25.79	29.38	36.05	1.89
7	2.5	5	11.46	26.62	47.54	1.75
8	1.25	5	5.73	18.87	Saturated	0.97
1	4	4	73.34	32.34	26.4	3.16
2	3	4	55.01	31.46	29.03	2.35
3	2	4	36.67	29.75	34.8	1.55
4	1	4	18.34	24.65	57.6	0.76
5	4	4	41.26	31.46	29.04	3.04
6	2	4	20.63	28.0	41.4	1.55
7	2	4	9.17	24.6	57.75	1.39
8	1	4	4.58	18.87	Saturated	0.68
1	3	3	55.01	31.45	29.0	2.37
2	2.25	3	41.26	30.3	32.7	1.77
3	1.5	3	27.50	28.0	41.3	1.16
4	0.75	3	13.75	21.35	79.14	0.57
5	3	3	30.94	30.3	32.77	2.27
6	1.5	3	15.47	25.74	50.28	1.11
7	1.5	3	6.88	21.25	79.84	1.03
8	0.75	3	3.44	18.87	Saturated	0.5

Table 5.2 Air conditions at the exit under various combinations of wind catcher and tower (con't)

1	2	2	36.67	29.73	34.78	1.55
2	1.5	2	27.50	28.0	41.3	1.17
3	1	2	18.34	24.65	57.75	0.76
4	0.5	2	9.17	18.87	Saturated	0.38
5	2	2	20.63	28.0	41.42	1.49
6	1	2	10.31	21.3	79.4	0.73
7	1	2	4.58	18.87	Saturated	0.67
8	0.5	2	2.29	18.87	Saturated	0.32
1	1	1	18.34	24.64	57.73	0.77
2	0.75	1	13.75	21.35	79	0.57
3	0.5	1	9.17	18.87	Saturated	0.38
4	0.25	1	4.58	18.87	Saturated	0.18
5	1	1	10.31	21.3	79.47	0.73
6	0.5	1	5.16	18.87	Saturated	0.35
7	0.5	1	2.29	18.87	Saturated	0.32
8	0.25	1	1.15	18.87	Saturated	0.18

* i: tower inlet; o: outdoor; and e: tower exit

5.2.2 Tower height

The height of PDEC tower is known to be an important factor affecting the cooling performance of a PDEC system. While some studies presented that this parameter did not have a linear relationship with the cooling capacity (Kang and Strand, 2009; Pearlmutter et al., 1996), previous studies did not provide enough guidance to assist in the proper design of the tower height to achieve the best cooling output. It is thus necessary to investigate how this parameter plays a role in the performance of the system. Different input conditions such as hot-humid and hot-dry climates, various tower cross-sectional areas, and a range of wind speeds were employed. Conditions imposed in this case study are given in Table 5.3 below. Tower heights were varied between 3m to 14m with an interval of 1m. Table 5.4 shows the air conditions predicted at the exit of the tower in four different situations.

As can be seen in Table 5.4, the variations in temperature, relative humidity, and air velocity were greater in the lower tower height ranges than in the higher ranges. The biggest differences in these air conditions were mostly seen between a tower height 3m and 5m because the evaporative cooling process was not fully completed in relatively low tower heights. Another trend that was observed was that these relatively larger differences in the lower height regions decreased after a certain height and this was observed to be approximately 6m in the smaller cross-sectional towers and 8m in the bigger towers. In addition, these differences in the exiting air conditions were a bit greater in the case 4, the lowest wind speed case. The tower height that appeared to allow complete interaction between the water and air was thus approximately 2 times greater than in the smaller towers and 1.5 times greater in the bigger towers than one side of the tower cross-section in order to accomplish the greatest temperature drops.

Cooling processes took place longer in smaller towers while air flows gradually decreased. Temperature drop and relative humidity growth continued in the smaller towers, case 1 and 2, as tower height increased through 14m as shown in Table 5.4. In contrast, no significant variations were observed beyond a height of 5m for the wider tower cases 3 and 4. It was likely that air flows in the narrower tower have higher turbulent intensity, which means less diffusive than those in wider tower. Water droplets were thus entrained to the bottom area of the tower and remained for a longer time while those in the wider tower evaporated at the very top portion of the surface area in a very short time. Differences in the exit temperature between the lowest and highest tower heights in case 1 and 2 were 5.34°C and 5.77°C, and differences in the exit relative humidity were 25.37% and 29.36%, respectively. Much smaller variations were seen in the exit temperature and relative humidity in cases 3 and 4 where the differences were 0.55°C and 2.04°C and 1.81% and 11.93%, respectively. On the other hand, much smaller differences in the air velocity were seen in all of the case where the predicted values were 0.23m/s, 0.29m/s, 0.29m/s, and 0.15m/s, respectively. While not definitive, it is likely that these trends will hold for most other situations even though the physical cooling process may vary with the water flow rate and the particle size.

Cooling capacity of PDEC towers substantially varied with case. While they should be designed according to building loads and local weather conditions, a simple comparison in the cooling capacity would be good as for an informational purpose. Assuming indoor setpoint temperature of 25°C, both case 1 and 4 at the lowest temperatures were predicted to produce approximately -61.8kW and -127kW, respectively, causing heating loads. In contrast, both case 3 and 5 at the lowest temperature were approximated to produce 40.4kW and 29.7kW, respectively.

Table 5.3 Conditions of variables for the analysis of tower height

Case	A_{wc} (m)	A_t (m)	T_{db} (°C)	RH_o (%)	V_i (m/s)	V_o (m/s)	$\dot{m}$ (kg/s)	WF(l/h)	D (μm)
1	2.5 × 1.25	2.5 × 2.5	41.5	30	1.4	2.8	9.82	50	60
2	2.5 × 1.50	2.5 × 2.5	32.5	20	1.8	3.0	13.0	60	80
3	2.64 × 2.64	4.0 × 4.0	35.0	20	1.75	4.0	32.0	50	30
4	2.64 × 2.64	4.0 × 4.0	35.0	20	0.87	2.0	16.0	50	30

* t: tower; wc: wind catcher; db: dry bulb; i: tower inlet; o:outdoor air

Table 5.4 Air conditions at the tower outlets with variation of tower height in different situations

H (m)	Case 1			Case 2		
	T_e (°C)	RH_e (%)	V_e (m/s)	T_e (°C)	RH_e (%)	V_e (m/s)
3	36.6	44.87	1.17	27.68	34.86	1.49
4	35.63	48.85	1.11	26.51	39.61	1.43
5	34.43	54.27	1.07	25.64	43.5	1.38
6	34.33	53.92	1.04	24.88	47.19	1.35
7	34.03	55.37	1.02	24.08	51.38	1.31
8	33.47	57.45	1.0	23.61	53.38	1.28
9	33.3	56.66	0.97	23.2	56.27	1.26
10	32.79	61.27	0.96	22.82	58.3	1.24
11	32.22	64.35	0.95	22.52	60.22	1.22
12	31.61	68.89	0.94	22.16	62.54	1.21
13	31.39	69.76	0.94	22.14	62.73	1.21
14	31.26	70.24	0.94	21.91	64.22	1.20
	Case 3			Case 4		
3	29.5	35.62	1.52	25.27	54.53	0.75
4	29.09	37.18	1.49	24.63	58.01	0.74
5	29.07	37.2	1.45	23.3	65.73	0.71
6	29.03	37.34	1.4	23.22	66.2	0.69
7	28.99	37.37	1.37	23.17	66.56	0.67
8	28.98	37.47	1.35	23.15	66.5	0.65
9	28.97	37.38	1.32	23.15	66.51	0.64
10	28.96	37.29	1.31	23.15	66.53	0.64
11	28.96	37.53	1.26	23.15	66.25	0.63
12	28.95	37.46	1.25	23.16	65.97	0.62
13	28.95	37.48	1.25	23.17	66.29	0.60
14	28.95	37.43	1.23	23.16	66.46	0.60

5.2.3 Shape of tower cross-section

Various shapes of PDEC tower cross-sections can be considered. While the majority is square in cross-section, some towers are rectangular, hexahedral, or octagonal in shape (A'sami, 2005; Ghaemmaghami and Mahmoudi, 2005.) It is thus interesting to compare any differences due to the shape of the tower cross-sectional area. While a more accurate prediction of the overall air distribution would be obtained with a 3-D model, the prediction of air conditions, however, at the end of the tower with the 2-D model is likely to be accurate since it properly models the turbulence at the inlet and the wall-bounded flows over the computational domain.

To properly model rectangular-shaped towers, the turbulent parameters such as turbulent intensity, turbulent kinetic energy, and turbulent dissipation rate were calculated using equations presented in the Section 4.3.3 in Chapter 4. Since the aspect ratios of almost all the rectangular-shaped towers in the literature were either 4:3 or 3:2, the aspect ratio of approximately 3:2 was considered for this case study. The weather conditions imposed were an ambient air temperature of 35°C, a relative humidity of 20%, and a wind speed of 4m/s. A tower height of 7.15m was considered, and the configurations of the wind catcher and the tower cross-section are listed in Table 5.5. The wind catcher was assumed to be placed on the surface along depth of the rectangular tower, so that air flowed along the width of it. The rectangular 1 configuration had a longer width than depth and the widths for the smaller and bigger towers were 2.5m and 5.0m, respectively. For the rectangular 2 configurations, the widths were shorter than the depths. The width of the tower is defined to be parallel to the wind direction, which is perpendicular to the wind catcher surface. The droplet size was assumed to be 30 μm, and a water flow rate of 50l/h was used.

Table 5.6 illustrated the results predicted in the four different tower configurations. The temperatures predicted at the exit of the towers were dependent on the tower width, and a wider tower produced a greater temperature drop. For example, the 5m wide rectangular tower (rectangular 1) resulted in a greater outlet temperature than the 4m square tower which in turn had a greater outlet temperature than the 3.2m wide rectangular tower (rectangular 2.) Similarly, the air velocities at the exit of the wider towers were greater than the square ones, and those of narrower ones showed a bit lower values. In addition, the bigger differences between the square and rectangular towers were observed in the lower mass cases, where the tower inlet velocity, V_i, was 1m/s.

It was likely that the air conditions at the exit of rectangular towers were determined along the length of the widths since fluid flows were characterized within the projected area on the surface. While turbulent quantities differed from those of square towers, the characteristics of the fluid flows, wall-bounded flows, and backflows were formed as similar to square towers whose length of a side was equal to the width of rectangular tower. It can be said that rectangular towers could be considered as a square tower with the same length as the side of rectangular one in the same direction of incoming air flows.

Table 5.5 Configurations of PDEC tower for the analysis of tower cross-section shape

	Square		Rectangular 1		Rectangular 2		V_i (m/s)	V_o (m/s)	$\dot{m}$ (kg/s)
	A_t (m)	A_{wc} (m)	A_t (m)*	A_{wc} (m)	A_t (m)*	A_{wc} (m)			
A	4 × 4	4 × 2	5 × 3.2	4 × 2	3.2 × 5	4 × 2	2	4	36.67
B	4 × 4	4 × 1	5 × 3.2	4 × 1	3.2 × 5	4 × 1	1	4	18.34
C	2 × 2	2 × 1	2.5 × 1.6	2 × 1	1.6 × 2.5	2 × 1	2	4	9.17
D	2 × 2	2 × 0.5	2.5 × 1.6	2 × 0.5	1.6 × 2.5	2 × 0.5	1	4	4.58

* Note that dimensions are listed as width by depth.

Table 5.6 Air conditions predicted in different tower configurations and shapes

	Square			Rectangular 1			Rectangular 2		
	T_e (°C)	RH_e (%)	V_e (m/s)	T_e (°C)	RH_e (%)	V_e (m/s)	T_e (°C)	RH_e (%)	V_e (m/s)
A	29.75	34.8	1.55	30.76	31.23	1.62	28.42	37.71	1.51
B	24.65	57.6	0.76	26.67	47.23	0.8	22.13	72.14	0.74
C	24.6	57.75	1.39	26.63	45.21	1.45	22.06	69.56	1.34
D	18.87	Sat.	0.68	18.87	Sat.	0.71	18.87	Sat.	0.64

* sat.: saturated

5.3 Droplet Size

Water droplets size is a very important factor that significantly changes the cooling performance of PDEC towers. It is generally known that finer particle size achieved better cooling performance. While many studies recognized the significance of this parameter (Cook et al., 2000; Pearlmutter et al., 1996; Santamouris, 2005), almost no attempts have been made to investigate the impact of the size of water droplets injected on the cooling performance of the PDEC towers. It is thus important to verify how significant the impact is so that the performance of these systems can be improved. To study the impact of water droplet size on system performance, the following input conditions were used to create a variety of cases: an outdoor air temperatures of 30°**C** and 35°**C**, a relative humidity of 20% and 40%, a tower height of 7.15m, a wind catcher size of 4m×2m, and a tower cross-section of 4m×4m.

Significant differences appeared in temperature and relative humidity as the droplet size changed as shown in Tables 5.7 and 5.8. At a relative humidity of 20%, the temperature differences for the exit air between the smallest and largest droplet size were 8.49°**C** at an outdoor air temperature of 35°**C** and 8.14°**C** at an outdoor air temperature of 30°**C**. At a relative humidity of 40%, the exit temperatures varied 8.17°**C** and 8.87°**C** as the droplet size varied from smallest to largest at outdoor temperatures of 30°**C** and 35°**C**, respectively. Differences in the relative humidity at the exit ranged from 30.85% under dry outdoor conditions at the ambient temperature of 35°**C** to 53.83% under humid outdoor conditions at the temperature of 30°**C**. These differences were expected to increase with changes in the other parameters such as water flow rate and wind speed since saturation of the air was seen only at the ranges in droplet size between 30 ㎛ and 70 ㎛ in the humid case at an outdoor air temperature of 30°**C**.

The effect of momentum transfer of bigger water droplets to the air stream was negligible. Almost no variation was observed in air velocity at the exit which ranged from 0.76m/s to 0.79m/s. Some studies (Bowman et al., 1998; Pearlmutter et al., 2008) suggested that bigger droplets may help create air flows toward the bottom as they transfer momentum to the air stream. It, however, appeared that the air velocities at the outlet were fairly constant, showing only 0.01m/s differences between the smaller and larger droplet ranges. It could perhaps be helpful for the system to provide more air volumetric flows to a space when larger droplets were injected with a large water flow rate. The sizes of droplets, however, did not have a considerable effect on the air flow rates within a range of general use of PDEC systems represented in these case studies.

It can be seen from the data that smaller droplets generally produced larger temperature drops and increased relative humidity. One tendency in the data was that the performance of the system began to drop off (an increase in the exit temperature was noted) when the droplet size was increased beyond approximately 100 ㎛. In addition, it was noted that finer droplets below approximately 30 ㎛ were inefficient since the cooling process was completed at the very top of the tower and no further interaction took place over the remaining height of the tower. As a result, it is recommended that the droplet size be between 30 ㎛ and 100 ㎛ in order to minimize the use of water while achieving the best performance.

Table 5.7 Air conditions along the variation of water droplet sizes at ambient air temperature of 35°C

D (㎛)	RH$_o$ 20%			RH$_o$ 40%		
	T$_e$ (℃)	RH$_e$ (%)	V$_e$ (m/s)	T$_e$ (℃)	RH$_e$ (%)	V$_e$ (m/s)
10	25.1	55.18	0.77	27.28	76.27	0.76
20	24.72	57.3	0.77	26.45	83.98	0.78
30	24.65	57.75	0.76	26.13	86.86	0.77
50	24.63	57.78	0.77	26.15	86.43	0.77
70	24.6	58	0.77	27.06	79.94	0.78
80	24.61	57.88	0.77	27.48	76.88	0.78
90	24.59	58	0.77	28.2	72	0.78
100	24.61	57.95	0.77	28.7	69.4	0.78
110	24.67	57.68	0.77	29.18	66.56	0.78
125	24.95	56.18	0.77	29.84	62.85	0.78
150	25.67	52.45	0.77	31.02	56.83	0.78
175	26.77	46.97	0.77	32.17	50.77	0.78
200	27.86	42.33	0.78	32.6	49	0.78
225	28.68	39.08	0.78	32.94	47.6	0.78
250	29.49	35.8	0.78	33.24	46.4	0.78
275	30.16	33.36	0.78	33.43	45.79	0.78
300	30.75	31.26	0.78	33.64	44.78	0.78
325	31.21	29.84	0.78	33.79	44.24	0.79
350	31.65	28.41	0.78	33.89	43.8	0.79
375	31.99	27.44	0.78	34.02	43.37	0.78
400	32.25	26.6	0.78	34.1	43.1	0.78
450	32.75	25.2	0.79	34.22	42.66	0.78
500	33.08	24.33	0.78	34.3	42.3	0.78

Table 5.8 Air conditions along the variation of water droplet sizes at ambient air temperature of 30°C

D (㎛)	RH$_o$ 20%			RH$_o$ 40%		
	T$_e$ (℃)	RH$_e$ (%)	V$_e$ (m/s)	T$_e$ (℃)	RH$_e$ (%)	V$_e$ (m/s)
10	20.37	61.38	0.77	20.24	98.14	0.77
20	19.91	64.53	0.77	20.07	Saturated	0.77
30	19.82	65.18	0.77	20.07	Saturated	0.77
50	19.79	65.38	0.77	20.07	Saturated	0.77
70	19.81	65	0.77	20.07	Saturated	0.77
80	19.79	65.4	0.77	20.08	99.59	0.77
90	19.76	65.57	0.77	20.32	97.47	0.77
100	19.8	65.37	0.77	20.7	94.28	0.77
110	19.78	65.26	0.77	21.28	89.36	0.78
125	19.78	65.64	0.77	22.02	83.64	0.78
150	20.15	63.03	0.77	23.2	74.98	0.78
175	21.1	57.5	0.78	24.2	68.62	0.78
200	22.04	51.68	0.77	25	63.72	0.78
225	23.03	46.27	0.78	25.8	59.05	0.78
250	23.74	42.88	0.77	26.3	56.39	0.78
275	24.53	39.19	0.78	26.8	53.7	0.78
300	25.2	36.22	0.77	27.27	51.43	0.78
325	25.66	34.23	0.78	27.58	49.9	0.78
350	26.21	31.79	0.77	27.85	48.62	0.78
375	26.6	30.64	0.78	28.09	47.48	0.78
400	26.97	29.16	0.78	28.3	46.53	0.78
450	27.49	27.39	0.78	28.59	45.28	0.79
500	27.9	26	0.77	28.82	44.31	0.78

5.4 Water Flow Rate

The water flow rate injected into a PDEC tower is a key variable, and it has been utilized to control the performance of the system. It is also important in that it determines the level of humidity of the air to be delivered to a space. A tendency for PDEC systems to use a large amount of water has been mentioned in the literature in order to achieve the best cooling performance. To date, there have not been enough studies on the efficient use of water, and many studies have mentioned that a large amount of water usage is a potential disadvantage of this particular system. It is thus necessary to present how this parameter works, so that a method for the effective use of water to accomplish the best performance can be demonstrated.

A significant variation in the exit air conditions as the water flow rates were changed appeared in the results. Table 5.9 shows the conditions for the three different cases, and the results of predictions in these three cases are shown in Table 5.10. In case 1 with an outdoor wind speed of 4m/s, the average variation of exit temperatures as the water flow rate increased was nearly constant at approximately 0.58°C per 5l/h increase in water flow rate. It increased at approximately double that rate in case 2 where the ambient wind speed was 2m/s, while the case 3 with the highest wind speed of 6m/s and a smaller wind catcher attached to a large tower showed an approximately 0.89°C per 5l/h increase in water flow rate. The relative humidity with each 5l/h increase in water flow rate showed a rise of 3.16% at the first interval of water flow rate between 5l/h and 10l/h and gradually increased up to 3.55% at the very last interval between 95l/h and 100l/h. These increases in case 2 were 3.18% through 9.66%. The lowest and greatest increases in case 3, where the inlet air velocity was similar to the case 1, were 2.29% and 7.88%. On the other hand, the air velocity at the exit showed very little reduction with the rise in water flow rate.

Table 5.9 Conditions of variables for the analysis of water flow rate

Case	A_{wc} (m)	A_t (m)	T_{db} (°C)	RH_o (%)	V_i (m/s)	V_o (m/s)	$\dot{m}$ (kg/s)	D (μm)	H (m)
1	2.64 × 2.64	4.0 × 4.0	35.0	20	1.75	4.0	32.0	30	7.15
2	2.64 × 2.64	4.0 × 4.0	35.0	20	0.87	2.0	16.0	30	7.15
3	4.0 × 1.0	4.0 × 4.0	35.0	20	1.5	6.0	27.5	30	7.15

Table 5.10 Air conditions at the tower exit in three different situations

WF (l/h)	Case 1			Case 2			Case 3		
	T_e (°C)	RH_e (%)	V_e (m/s)	T_e (°C)	RH_e (%)	V_e (m/s)	T_e (°C)	RH_e (%)	V_e (m/s)
5	34.27	21.23	1.38	33.59	22.83	0.68	33.91	22.14	1.5
10	34.74	22.72	1.38	32.42	26.01	0.68	33.0	24.43	1.5
15	33.1	24.25	1.38	31.25	29.47	0.68	32.08	26.99	1.5
20	32.52	25.88	1.38	30.08	33.18	0.68	31.17	29.75	1.5
25	31.92	27.53	1.37	28.94	37.48	0.68	30.26	32.85	1.5
30	31.33	29.19	1.37	27.77	41.55	0.68	29.35	36.0	1.5
35	30.74	31.12	1.36	26.62	47.44	0.68	28.44	39.47	1.5
40	30.15	33.21	1.37	25.46	53.27	0.68	27.54	43.04	1.5
45	29.57	35.24	1.37	24.31	59.25	0.67	26.64	47.47	1.5
50	29.0	37.49	1.37	23.16	66.57	0.67	25.72	51.79	1.5
55	28.41	39.76	1.37	22.03	74.22	0.67	24.84	56.63	1.5
60	27.83	42.18	1.37	20.87	82.81	0.67	23.94	61.61	1.5
65	27.24	44.71	1.36	19.72	92.27	0.67	23.04	67.31	1.5
70	26.66	47.38	1.36	18.6	Saturated	0.66	22.14	73.3	1.5

Water flow rate is a key parameter for determining the PDEC system performance in a hot-dry climate. Various conditions such as different tower size and conditions of the air as well as water were employed to investigate the impact of water flow rate on the overall performance of the system. The conditions imposed are shown in Table 5.11, and the air conditions predicted are shown in Table 5.12. In hot dry conditions, case 2 and 3, larger temperature drops through the PDEC system were noted in comparison with the moderate weather conditions in the other cases. Average temperature drops of 1.06°C and 2.76°C were observed in cases 2 and 3, respectively, as the water flow rate increased by 10l/h while the average temperature drops were 0.69°C and 1.69°C for cases 1 and 4, respectively. The increase in water flow rate in hot-dry climate was thus more effective than for the moderate air conditions at the relative humidity of 30% under different tower and water conditions. In addition, the variations of the exit air velocity were a bit larger for the smaller tower configurations in cases 3 and 4 than the bigger ones due to larger air resistance and thus smaller diffusivity in the smaller towers. These reductions in the air velocity, which reached a maximum of 0.05m/s in case 3, will likely have no significant impact on the capacity of the system. Due to the large impact that the water flow rate has on the exit temperature without any significant change to the exit velocity, the water flow rate can thus be considered a key parameter in the performance of PDEC systems.

Table 5.11 Combinations of various conditions for the analysis of water flow rate

Case	A_{wc} (m)	A_t (m)	T_{db} (°C)	T_{wb} (°C)	RH_o (%)	V_i (m/s)	V_o (m/s)	$\dot{m}$ (kg/s)	D (μm)	H (m)
1	3.0 × 2.0	3.0 × 3.0	33.0	20.1	30	1.4	2.8	9.82	75	7.5
2	3.0 × 1.5	3.0 × 3.0	38.0	19.19	20	1.8	3.0	13.0	90	8.0
3	1.5 × 1.5	1.5 × 1.5	42.0	21.89	16	2.0	2.0	5.04	20	5.0
4	1.5 × 1.5	1.5 × 1.5	32.0	32.0	30	2.5	2.5	6.51	70	5.0

Table 5.12 Air conditions predicted in four different combinations

WF (l/h)	Case 1			Case 2		
	T_e (°C)	RH_e (%)	V_e (m/s)	T_e (°C)	RH_e (%)	V_e (m/s)
10	32.17	32.13	2.51	36.72	17.02	1.86
20	31.42	34.6	2.51	35.61	19.34	1.86
30	30.66	37.3	2.51	34.5	21.97	1.87
40	29.91	40.01	2.51	33.41	24.79	1.87
50	29.18	43.05	2.5	32.38	27.64	1.86
60	28.49	45.98	2.51	31.26	31.08	1.85
70	27.82	49.01	2.49	30.2	34.64	1.85
80	27.21	51.9	2.52	29.21	38.06	1.85
90	26.47	55.72	2.52	28.26	42.25	1.84
100	25.93	58.61	2.5	27.15	47.26	1.85
	Case 3			Case 4		
10	38.99	21.16	1.43	29.82	36.84	1.79
20	36.19	27.68	1.41	27.89	44.57	1.78
30	33.42	35.98	1.41	25.96	53.9	1.78
40	30.65	46.13	1.4	24.24	63.54	1.78
50	27.91	59.1	1.39	22.6	74.39	1.77
60	25.17	74.71	1.38	21.1	85.7	1.77
70	22.42	95.43	1.38	19.66	92.69	1.75
80	Saturated			Saturated		

Careful design of PDEC systems and control of the water flow rate is necessary for the effective use of water. This means that the water flow rate must be controlled to maximum the output of the system while not wasting water. Water would be wasted in a situation where more water was introduced into the system than was required to achieve saturated conditions at the exit. The water flow rates that led to the saturation of the exiting air in various situations are given in Table 5.13. Various tower configurations and air conditions in a range of droplet sizes between 30 and 90 were applied to investigate what water flow rate caused the air to be saturated in these various situations. The air at the exit was either saturated or about to be saturated at the water flow rate of 50l/h in case 1 and 6 and 70l/h in case 4, where the tower inlet velocities were set to be below 1m/s and hot-dry conditions with the smaller ratio of wind catcher area to tower area were imposed. On the other hand, medium sized towers with a high wind speed condition, namely cases 2, 3, and 5, required a high water flow rate such as 175l/h, 120l/h, and 200l/h, respectively, to achieve saturated conditions at the exit due to the high wind speed is these cases. In addition, the air through smaller towers at moderate wind speed such as 1.5m/s and 2.5m/s were saturated at the condition of the water flow rate of 75l/h in case 7 and 55l/h in case 8. The design of water flow rate, therefore, must consider other parameters such as tower configuration in conjunction with air mass flow rate at a specific range of droplet sizes to avoid saturation and thus minimize inefficient water use.

Table 5.13 Demand for water flow rate in various situations

Case	A_t (m)	A_{wc} (m)	H (m)	T_{db} (°C)	RH_o (%)	V_i (m/s)	V_o (m/s)	$\dot{m}$ (kg/s)	WF (l/h)	D (μm)	T_e (°C)	RH_e (%)
1	4.0 × 4.0	4.0 × 1.0	7.15	35	20	0.63	2.5	11.46	50	30	18.9	99.73
2	3.0 × 3.0	3.0 × 1.5	6.5	30.4	14	3.0	6.0	31.21	175	60	14.5	Sat
3	3.0 × 3.0	3.0 × 1.0	6.5	30.4	14	2.0	6.0	20.81	120	80	14.5	Sat
4	3.6 × 3.6	3.6 × 1.0	8.0	36.6	18	0.92	3.3	13.54	70	90	19.1	Sat
5	3.0 × 3.0	3.0 × 1.5	8.0	38	15	2.5	5.0	25.54	200	90	19.23	99.03
6	2.5 × 1.6	2.0 × 0.5	7.15	35	20	1.0	4.0	4.58	50	30	18.87	Sat
7	1.5 × 1.5	1.5 × 1.5	4.0	37	27	2.5	2.5	6.40	75	50	22.14	Sat
8	1.5 × 1.5	1.5 × 1.5	6.0	38.6	12	1.5	1.5	3.82	55	80	18.61	99.65

5.5 Summary

A number of case studies have been performed to understand the physical phenomena that occur in the effective area of PDEC towers as well as the impact of various parameters on the cooling performance of these devices. While some parameters such as wind speed, tower height, water flow rate, and droplet size significantly alter the exit air conditions of the system, thus indicating a strong impact on the performance of PDEC towers, the ratio of wind catcher area to tower cross-sectional area was an important factor that should be included in PDEC tower modeling. In addition, the effective tower height that could complete evaporative cooling performance within the tower area would be approximately 2 times greater than the length of the tower cross-sectional area. Furthermore, droplet sizes between 30 and 100 would be the one that could be used in most of PDEC design conditions. Likewise, water flow rate is a very strong impact to the performance of PDEC towers, and must be properly designed with consideration of other parameters to overcome one of the disadvantages of these systems, i.e., large quantity of water use.

In summary, the cooling performance of PDEC systems are determined not by a single strong factor, but by various factors such as tower configurations, water flow rates, and droplet sizes. A vigilant design process is therefore required for a successful integration of this particular system in the cooling of buildings. Based on these findings, a regression analysis to find appropriate relation between the performance of PDEC towers and all critical parameters defined in this chapter will be performed in the following chapter. As a result, mathematical models that accounts for PDEC air conditions will be developed.

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CHAPTER 6: REGRESSION ANALYSIS FOR MATHEMATICAL MODELS

6.1 Overview

Regression analysis, in general, is widely used to explain the relationship between dependent variables and independent variables, creating mathematical forms of equations. These mathematical models are then used to determine the applicability as well as the performance of various types of environmental control systems in buildings during the decision-making process. In addition, these mathematical models are critical when a detail analysis is needed on impacts of a technology or system to energy performance, indoor environment, cost-effectiveness, and environmental factors such as pollution production. They are often implemented in energy simulation software so that overall performance of those systems and their impact on the built environment in many situations can be accurately modeled within a reasonable computational cost while some other methodologies such as CFD analysis cannot achieve due to time constraints. To date, there have been a number of mathematical models that have the ability to predict the performance of PDEC towers. However, they are mostly limited to models that are based on the efficiency of the wet-bulb depression. In reality, the cooling output of PDEC towers can vary substantially with a number of parameters such as the weather conditions, physical tower size and dimensions, and the water conditions, as shown in the previous chapter. A new mathematical model that includes relationships between such parameters and the performance of PDEC towers is thus critical to accurately model the impact of these parameters on the output of these systems.

The mathematical model should also include the impact of a PDEC tower on the interior environment as well. PDEC towers alter the indoor environment depending on their capacity, affecting both the humidity level and the overall ventilation strategy. They thus improve the indoor environmental quality in a space by raising the thermal comfort of the occupants and positively impacting indoor air quality via increased outdoor air quantities. To date, almost all mathematical models in the literature are only capable of predicting the exit temperature of the air, assuming a certain value of the efficiency of the wet-bulb depression. As a result, the actual impact of PDEC systems on the built environment cannot be properly or fully evaluated. The one exception is Givoni’s mathematical model that includes the influence of water flow rate and predicts the temperature and humidity level of the exit air based on an adiabatic cooling process, which satisfies the law of conservation of energy. This model, however, is limited to a very narrow range of weather conditions and small-sized towers with no consideration of the effect of the tower configuration and the droplet sizes. Thus, in order to accurately model PDEC towers and considering the strong dependence of the performance of PDEC towers on all of these variables, a model should include the influence of these main factors for the accurate predictions of the cooling performance of PDEC towers. A mathematical model is critical so that correlations between main parameters and air conditions at the exit of PDEC towers can be adequately described and is also necessary to properly evaluate the potential impact of PDEC towers on building performance.

6.2 Methods and Sampling

Figure 6.1 shows the overall approach of the regression analysis. Since one of main goals of this study is to extend the applicability PDEC systems, wide range of weather conditions were considered as shown in Figure 6.2. In addition, five main parameters, which were defined as a critical factor significantly affecting the performance of PDEC towers, were included, and intervals for each parameter were determined based on the computational analysis. In the preliminary sampling process, CFD simulations were run for every single sample, which means that the total number of CFD runs was the same as the number of samples. A correlation analysis was then followed to determine independent variables, which will be included in the mathematical models. Once these processes were completed, efforts were made to find appropriate relation between individual variables and dependent variables, which can explain the relation the best. Intervals and numbers of samples were then added as needed in the calibration process depending on differences between individual sample and predictions of the regression model. These processes were then repeated until the calibration process has no impact to the regression model, which will be considered as the final mathematical models.

Two dependent variables, temperature and air velocity, were considered while remainder of the main parameters defined in this study were included as independent variables. The sensible cooling capacity of any PDEC system can be determined when the mass flow rate of air and temperature difference between the air exiting the PDEC tower and the space being conditioned are known. The humidity level of the air should also be known since it affects the thermal environment of the space. These air conditions such as temperature, relative humidity, and velocity must be known in order to determine the cooling output of the systems. The relative humidity, however, can be found from the air temperature since the evaporative cooling process in PDEC towers is generally considered an adiabatic process. Multiple regression analyses for temperature and velocity were thus necessary, so that two different regression equations for predicting these two dependent variables were obtained.

Wide ranges of samples in ambient air conditions, tower configurations, and water conditions were collected using CFD simulations. While PDEC systems have a strong dependency on the outdoor weather conditions and seem to be best suited for hot-arid climates, other climate regions were included in this study in order to extend the applicability of this particular type of systems to more buildings. Six different climates were thus considered as illustrated in Table 6.1 below, and the influence of the five main parameters under all of these climatic conditions were included as shown in Figure 6.2.

The ranges of the five main variables were:

- Droplet size was varied from 20 ㎛ to 500 ㎛, with intervals of 20 ㎛ from the minimum size through 200 ㎛ and intervals of 50 ㎛ between 200 ㎛ and 500 ㎛
- Water flow rate was varied from 5l/h to 200l/h, with intervals of 10 l/h between 10l/h and 100l/h and intervals of 20l/h between 100l/h and 200l/h
- Ambient wind speed was varied from 0.5m/s to 8m/s with intervals of 0.5m/s
- Tower height was varied from 3m to 14m with intervals of 1m
- Various sized tower configurations were also investigated. Two different tower cross-sections and the ratios of wind catcher area to tower cross-sectional area were employed in each-sized tower. The ratios of wind catcher to tower cross-section were 0.75 to 0.25 for the large tower, 1.0 to 0.5 for the medium tower, and 1.0 to 0.75 for the small tower.

Based on the variation of parameters described above, the minimum number of samples collected in the preliminary sampling process was thus 426. In addition to these samples, 412 samples created during the parametric analysis described in the previous chapter were also utilized. Thus, the total number of samples used during this preliminary sampling process was 838.

A systematic approach was necessary to minimize computational time since the computational model predicts dependent variables of individual sample. In fact, a CFD simulation needed its own computational time as well as pre- and post-processing of data, which costs a lot of time. A careful approach to minimize time constraints was thus necessary. Once the preliminary data sets were produced, a correlation analysis using general purpose statistical software Minitab 16 was performed in order to determine the impact of the independent variables on the dependent variable, i.e. temperature and velocity. With these samples and independent variables, efforts were made to find an appropriate relationship between the dependent and the independent variables. Once a relationship was found to be effective, a simple model was obtained. A calibration process using a forward selection method, which adds samples to the basic samples until no significant variations were found, was used. The impact of each independent variable was determined by monitoring the differences in each dependent variable between the preliminary CFD samples and regression model predictions. In this process, the sampling process was continued over the ranges or intervals for the different independent variables, and differences were monitored until additional of samples did not improve the coefficient of determination, R^2, value as well as the significance probability of the regression coefficient, P-value. The regression equations obtained were then considered as the final mathematical models when the calibration process showed no impact on these statistical values. The significance probability of each regression coefficient for the independent variables obtained from the regression analysis was then reviewed to verify the decisions made regarding the independent variables.

Table 6.1 Climatic classification for the purpose of regression analysis

Climates	Temperature (°C)		Relative Humidity (%)	
	Max	Min	Max	Min
Hot-dry	42	36	30	10
Hot-humid			50	30
Warm-dry	36	32	30	15
Warm-humid			50	30
Moderate-dry	32	28	30	15
Moderate-Humid			60	30

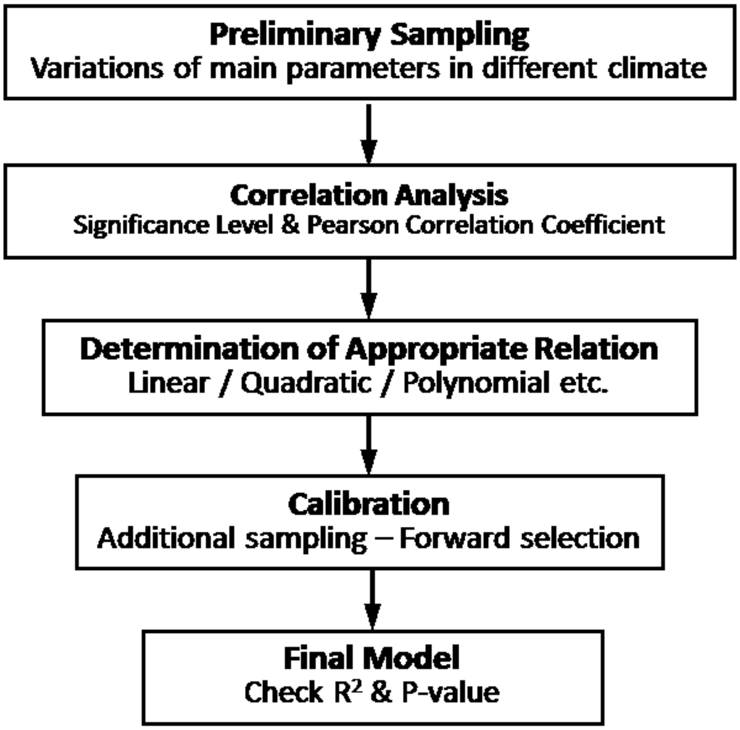


Figure 6.1 Schematic of the overall approach to regression analysis

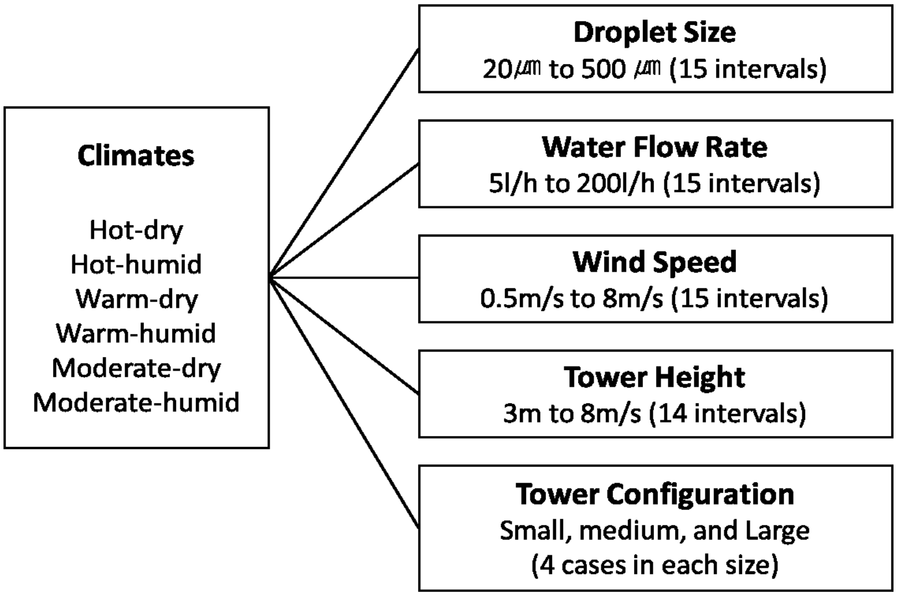


Figure 6.2 Diagram of preliminary sampling method

6.3 Multiple Linear Regression

6.3.1 Correlation analysis

A correlation analysis determined the independent variables for regression analyses. It was expected that the correlation between each dependent variable and independent variables would be considerably different. This was because a number of independent variables were involved, and each individual independent variable has a different relationship to the dependent variables, i.e. temperature and velocity. For instance, ambient wind speed has a strong second-order polynomial relationship to both the temperature and the relative humidity while the water flow rate has a robust inverse relationship to temperature and a linear relationship to relative humidity. In addition, the tower height has a weak inverse relationship to temperature, and the droplet size has a weak linear relation to temperature. The Pearson correlation coefficients, which typically are used to explain correlations between variables, were thus only considered as reference values in this study. Instead, the main parameters defined as key parameters shown in Table 6.2 below were considered as the independent variables when they have a significance probability at the level of 5%, determined by P-value of less than 0.05. Those independent variables were then included in the regression analysis for the dependent variables.

All variables considered were included in the multiple regression analysis for exit temperature. The correlations of each independent variable with temperature were different as shown in Table 6.2. A statistical index that explains the significance between two variables called Pearson Correlation Coefficient (PCC) was employed to determine individual independent variable. This index distributed from -1.0 to 1.0, and indicates -1.0 as perfect negative correlation, 1.0 as perfect positive correlation, and zero as no correlation. The highest PCC corresponding to temperature were displayed by the outdoor wet-bulb temperature at 0.531 and the outdoor dry-bulb temperature at 0.568. It was also found that the droplet size and the water flow rate also showed considerable correlation with the dependent variable temperature. Based on the PCC values for the other independent variables, mass flow rate, wind speed, tower inlet velocity, and tower height were found to have fairly low correlation with temperature. On the other hand, the P-values for all variables considered were found to be zero, which statistically means no probability of saying both variables have no relation. The multiple regression analysis for temperature will thus include all eight independent variables.

Three variables will be excluded in the regression analysis for velocity. A robust correlation and significance between outlet velocity predicted and incoming air velocities was observed. The Pearson correlation coefficient of tower inlet velocity was given as 0.996, which showed an excellent correlation with outlet velocity at the exit. A high value of the coefficient 0.732 was also seen for the outdoor wind speed. The coefficients for mass flow rate and tower height were 0.398 and -0.421, respectively. These values show the importance of these two parameters on exit velocity and were greater than those determined for temperature. On the other hand, very low correlations with velocity for the other variables such as droplet sizes and wet- and dry-bulb temperatures were found. The significance probability of these three variables was also higher than the others. These three independent variables were thus excluded in the regression analysis for velocity even though the P-value for wet-bulb temperature was within the significance probability (less than 5%). In fact, the regression model that included wet-bulb temperature had almost no impact to the two dependent variables. Minimum number of independent variable is likely to improve useability. This field was thus not considered as an independent variable. Consequently, five independent variables (tower inlet velocity, wind speed, air mass flow rate, water flow rate, and tower height) were included in the regression analysis for velocity as independent variables.

Table 6.2 Correlation indexes between each independent variable and dependent variables

Independent variables	Temperature		Velocity	
	PCC	P-value	PCC	P-value
V_i	0.208	0.0	0.996	0.0
V_o	0.118	0.0	0.732	0.0
$\dot{m}$	0.096	0.0	0.398	0.0
WF	-0.286	0.0	0.293	0.0
D	0.338	0.0	0.018	0.704
H	-0.107	0.0	-0.421	0.0
T_{db}	0.531	0.0	-0.041	0.386
T_{wb}	0.568	0.0	-0.104	0.026

* i: tower inlet; o: outdoor; db: dry bulb; wb: wet bulb, and PCC: Pearson Correlation Coefficient

6.3.2 Regression analysis for temperature

A weak linear relation with temperature was displayed in the preliminary samples. As described in the previous section, 838 samples were considered to find the appropriate relationship between the dependent variables exit temperature and velocity and the independent variables obtained during the correlation analysis. Various regression types, provided by the statistical software Minitab 16, were considered, and no acceptable correlations except a linear type were found. An regression analysis for polynomial, exponential, and logarithmic required tremendous relationships expended a considerable amount of computing resources in an attempt to find a correlation (up to 48 hours in some cases) since individual independent variable have different relationships with the dependent variable, resulting of no relevant correlations in these regression types. Only the linear regression type showed a reasonable relationship, resulting coefficient of determination R^2 of 0.62 and a significance probability P-value of zero for the constant and the other regression coefficients regarding independent variables. While the independent variables included were considered appropriate, further numerical samples were necessary to demonstrate whether the relationships were truly appropriate.

Additional samples using forward selection were performed so that a reasonable numbers of data sets can be determined. The forward selection method is to add samples to the model, and then to see how it works with the model, which does not need a perfect set of data for the analysis. This approach was necessary to reduce computational efforts since each sample required a separate run of the computational model. A certain level of accuracy, however, should be maintained. To satisfy these goals, the two dependent variables, temperature and velocity as well as relative humidity, of the basic samples were compared with the predictions from the linear regression equation obtained by the preliminary samples. Initially, considerable differences between the two calculation methods appeared in certain situations such as high wind speed, humid climatic conditions, bigger droplet sizes, lower water flow rates, and cases where the exit conditions were saturated. Samples were thus randomly added in these particular ranges to decrease such differences and thus improve statistical performance of the mathematical model. For instance, such differences were fairly large in the range of larger droplet sizes since the interval in this region was 50 ㎛. Thus, additional samples with smaller intervals were produced. In addition, it was noted that some of these conditions that showed larger differences such as larger droplet sizes, very high of low water flow rates, and high wind speed were not necessarily desirable design conditions for PDEC towers, so that many samples collected in this process were within a certain range such as droplet sizes between 30 ㎛ and 150 ㎛, water flow rate between 10l/h and 200l/h, tower height from 4m to 10m, the ratio of wind catcher area to tower cross-section between 0.75 and 0.25, and ambient wind speed as high as 6m/s and as low as 1m/s.

The preliminary linear equation weakly explained the linear relationship between the response variable, temperature, and the regressors, or independent variables, which means that approximately 38% of the samples for temperature were considered as they have no relation with the dependent variables. Forward selection sampling continued until these additional sampling did not affect the value of coefficient of determination, R^2, or the P-value. As a result, these values maintained constant values after approximately 809 additional samples were added to explain the variability in temperature. The total number of samples collected in addition to the preliminary samples of 838 thus reached 1647. The P-values of the regression coefficients for the independent variables including the constant term in the linear regression equation appeared as zero. The following multiple linear regression equation obtained was thus considered as the final mathematical model:

$$\begin{aligned} T_e = -13.6 + 1.35V_t + 0.386V_o + 0.0958\dot{m}_a - 0.071WF + 0.0222D \\ -0.0865H + 0.686T_{db} + 0.709T_{wb} \end{aligned} \tag{6.1}$$

where a standard deviation of 2.732 and a coefficient of determination $R^2$of 77.1% were observed.

It should be noted that the linear regression equation in the practical range showed a higher value for the coefficient of determination. The linear regression equation given above explained that 77.1% of the population was known as they have a relation. The standard deviation of 2.732 in temperature is fairly high. This is because the model dealt with a very wide range of conditions, so that the variability of the population in certain ranges such as high mass flow, hot-humid conditions, low water flow rate, and big droplet size were likely bigger than in the practical ranges described in the previous section. The statistical values in the practical range, that are important for typical designs of PDEC towers and where the more extreme conditions were eliminated, improved. The value of R^2 reached 82.3%, and the standard deviation decreased to 1.956 in the regression analysis with samples in the practical ranges. It can thus be concluded that the prediction of temperature by the linear regression equation can respond properly to a wide range of fluid conditions and tower configurations while some ranges may cause inaccuracy in the predictions.

6.3.3 Regression analysis for velocity

An excellent linear relationship was found between the exit velocity and the five independent variables. As described in the subsection 6.1, five independent variables (ambient wind speed, tower inlet velocity, air mass flow rate, water flow rate, and tower height) were included in the regression analysis for velocity at the exit of PDEC tower using the 838 preliminary samples. It was found during the correlation analysis that the tower inlet velocity had a robust correlation with exit velocity, showing a Pearson correlation coefficient of 0.996 and P-value of zero. The ambient wind speed had also a strong correlation with velocity. On the other hand, the other main parameters such as droplet sizes, water flow rate, and temperature had a statistically very weak correlation. Efforts were made to find a relevant regression type, and the linear regression type was considered. In the regression analysis for velocity, adding more data samples had no effect on the statistical indexes, and the P-values of the regression coefficients for the independent variables were zero. As a result, the multiple linear regression equation given with the preliminary samples was considered to be sufficient as the final mathematical model. The value of the coefficient determination R^2 was 99.7% with a standard deviation of 0.052, and the linear equation obtained was:

$$V_e = 0.107 + 0.706V_t + 0.217V_o + 0.00413\dot{m}_a - 0.0001671WF - 0.0245H \tag{6.2}$$

6.4 Summary

The overall impact of PDEC towers can be investigated when their ability to save energy and to improve indoor environment is analyzed in detail. To date, no study can accomplish this task since mathematical models that allow accurate predictions of PDEC air conditions were unavailable. It is thus critical to develop such models. In this study, a statistical methodology such as regression analysis was employed to develop mathematical models to characterize the physical cooling processes in the effective area of spray PDEC towers. A correlation analysis was performed to find the independent variables in the regression analyses for temperature and velocity, and different independent variables were found for each regression analysis. A fairly linear relation was found by the forward selection sampling method for temperature while a robust linear relation was found for the prediction of velocity.

This chapter has shown that the linear regression equations were capable of predicting both temperature and velocity with reasonable accuracy, and the temperature in the practical range was more accurately predicted. In the following chapter, various dynamic simulations that employ these mathematical models will be performed so that some problems with PDEC towers and the solutions to resolve these problems will be presented.

CHAPTER 7: DYNAMIC BUILDING ENERGY SIMULATION

The mathematical models that predict temperature and velocity at the exit of PDEC systems were developed as shown in the previous chapter. As a result, the air conditions such as temperature, relative humidity, and flow rate at the outlet of these systems can be accurately predicted. To date, predictions of such conditions were inaccurate because no models that included all variables that significantly change the performance were in existence. On the other hand, new models developed in the previous chapter have the capability of modeling the exit air conditions of a spray PDEC tower since they include all the critical variables such as droplet size, mass flow rate, and physical tower dimensions. The overall impact of the PDEC systems in many situations can now be adequately analyzed. To examine the performance and capability in various weather conditions, these models were implemented into a whole building energy simulation program, EnergyPlus. The influence of the indoor environment and various strategies to achieve a certain level of consistency and cooling capacity will be investigated on a typical summer day in this chapter. The energy performance in different buildings and climates for longer periods of time will be studied in the next chapter.

7.1 Simulation Algorithm

7.1.1 Typical operation of PDEC systems

The mathematical models developed and discussed in the previous chapter were employed in an energy simulation tool, EnergyPlus, to predict temperature, relative humidity, and velocity at the outlet of PDEC systems. In fact, a model employing Givoni's mathematical models for determining cooling capacity of PDEC towers is available in EnergyPlus (Kang and Strand, 2009). The model, however, is only as accurate and reliable as Givoni's model, which is only under particular climatic conditions and for specific physical tower configurations. Predictions of outlet air conditions of PDEC towers in different situations can thus be inaccurate. It is thus necessary to implement a reliable mathematical model that covers a wide range of weather conditions and physical tower configurations in a program such as EnergyPlus.

According to EnergyPlus Documentation (Getting Started with EnergyPlus, 2010), EnergyPlus is an energy analysis and thermal load simulation program. Based on a user's description of a building from the perspective of the building's physical make-up, associated mechanical systems, etc., EnergyPlus will calculate the heating and cooling loads necessary to maintain thermal control setpoints, conditions throughout an secondary HVAC system and coil loads, and the energy consumption of primary plant equipment as well as many other simulation details that are necessary to verify that the simulation is performing as the actual building would. Some of the strong points of EnergyPlus include:

- integrated, simultaneous solution where the building response and the primary and secondary systems are tightly coupled;
- sub-hourly, user-definable time steps for the interaction between the thermal zones and the environment;
- heat balance based solution technique for building thermal loads that allows for simultaneous calculation of radiant and convective effects at both in the interior and exterior surface during each time step;
- Atmospheric pollution calculations that predict CO2, SOx, NOx, CO, particulate matter, and hydrocarbon production for both on site and remote energy conversion.

To utilize these capabilities in EnergyPlus, mathematical models presented in the previous chapter were implemented into EnergyPlus as below. In addition to these models, control algorithms, which will be proposed in the following subsection, were also added to the Fortran code. It is important to note that all zones are modeled as a well-mixed in EnergyPlus, which indicates uniform conditions over the zones. Therefore, the air flows from PDEC systems in conjunction with other natural air flows such as ventilation and infiltration were designed to be immediately mixed with the air in the space, so that the cooling loads that the primary cooling system should meet were determined.

The modeling algorithm starts by checking to see if the outdoor air conditions are appropriate for providing cooling and that cooling is in fact needed by the zone. In other words, the model assumes that any PDEC towers defined in the user input are turned on when the outdoor temperature, the relative humidity, and the wind speed are within an operable range. The model then determines various thermal properties of ambient air, using the following EnergyPlus built-in functions:

$$\varpi_i = \mathrm{PsyWFnTdbTwbPb}(\mathrm{T_{db}}, \mathrm{T_{wb}}, \mathrm{P}) \tag{7.1}$$

$$h_i = \mathrm{PsyHFnTdbW}(\mathrm{T_{db}}, \varpi_\mathrm{i}) \tag{7.2}$$

$$\rho_i = \mathrm{PsyRhoAirFnPbTdbW}(\mathrm{T_{db}}, \varpi_\mathrm{i}, \mathrm{P}) \tag{7.3}$$

where ω_i is humidity ratio of outdoor air [kg/kg-dry-air], h_i is enthalpy of outdoor air [J/kg], and ρ_i is density of outdoor air [kg/m^3]. The incoming air mass flow rate and the inlet velocity at the top of effective tower area are:

$$V_t = \frac{A_{wc}}{A_t} V_o \tag{7.5}$$

$$\dot{m}_a = \rho_i \cdot A_{wc} \cdot V_o \tag{7.6}$$

where V_t is velocity at the top of tower [m/s] and $\dot{m}_a$ is mass flow rate through wind catcher [kg/s], A_{wc} is wind catcher area [m^2], A_t is tower cross-sectional area [m^2], and V_o is wind speed [m/s]. The temperature and velocity at the end of effective tower area can calculated as shown in the previous chapter using:

$$\begin{aligned} T_e = -13.6 + 1.35V_t + 0.386V_o + 0.0958\dot{m}_a - 0.071WF + 0.0222D - 0.0865H \\ +0.686T_{db} + 0.709T_{wb} \end{aligned} \tag{7.7}$$

$$V_e = 0.107 + 0.706 V_i + 0.0217 V_o + 0.00413 \dot{m}_a - 0.000167 WF - 0.0245 H \tag{7.8}$$

where T_e is PDEC outlet temperature [°C], WF is water flow rate [kg/s], D is water droplet size [μm], H is tower height [m], T_{db} is outdoor dry-bulb temperature [°C], and T_{wb} is wet-bulb temperature [°C], and V_e is PDEC outlet velocity [m/s]. Once the air exit temperature is calculated and the enthalpy of the exit air is defined by assuming an isentropic process, the humidity ratio of the air, the relative humidity, and the air density at the exit of the PDEC tower are obtained from the following EnergyPlus built-in functions:

$$\varpi_e = PsyWFnTdbH(T_e, h_i) \tag{7.9}$$

$$RH_e = PsyRhFnTdbWPb(T_e, \varpi_e, P) \tag{7.10}$$

$$\rho_e = PsyRhoAirFnPbTdbW(T_e, \varpi_e, P) \tag{7.11}$$

where ω_e is humidity ratio at the PDEC outlet [kg/kg-dry-air], RH_e is relative humidity at the PDEC outlet [%], and ρ_e is density at the PDEC outlet [kg/m^3]. The air mass flow rate and volumetric air flow rate as well as the velocity at the outlet surface are thus:

$$V_{outlet} = \frac{A_t}{A_e} V_e \tag{7.12}$$

$$\dot{m}_e = \rho_e A_e V_{outlet} \tag{7.13}$$

$$Q_e = \frac{\dot{m}_e}{\rho_e}(1 - F_a) \tag{7.14}$$

where V_{outlet} is velocity at the outlet surface [m/s], $\dot{m}_e$ is air mass flow rate at the PDEC outlet [kg/s], A_e is area of the PDEC outlet surface [m^2], Q_e is air volumetric flow rates [m^3/s]tower, and F_a is fraction of air loss. The evaporation rate can be expressed as:

$$Q_w = \frac{\dot{m}_e(\varpi_e - \varpi_i)}{\rho_w} \tag{7.15}$$

where Q_w is water consumption rate [m^3/s]. The total water and power consumption of water pump are then expressed as:

$$Q_T = Q_w(1 + F_w) \tag{7.16}$$

$$P_p = P_{rated}L \tag{7.17}$$

where Q_T is total water consumption rate [m^3/s], F_w is fraction of water loss, P_p is pump power consumption [W], and Prated is rated pump power [W].

7.1.2 Performance control

Accurate predictions of the air conditions that are delivered to the space by the PDEC tower are critical. PDEC systems have been incorporated in the cooling of buildings but it is important to know with some accuracy how much energy saving can be accomplished before a building is constructed. The cooling capacity of these systems can be inconsistent due to their strong dependence on variable outdoor weather conditions. While it is difficult to immediately respond to outdoor weather conditions such as wind speed, temperature, and relative humidity, PDEC systems need to properly deal with such variable conditions so that indoor thermal loads can be properly treated. From this perspective, the cooling performance of PDEC towers must be relatively constant and controllable. In addition, almost all PDEC towers uses as a large amount of water to achieve the best possible performance with no consideration for the variable weather conditions. Excessive water consumption should be avoided, particularly when the air is saturated or in a situation where the evaporative cooling process cannot take place.

Two key factors for the performance control of PDEC towers can be considered. As described in the previous chapter, the performance of PDEC systems varies with a number of parameters such as air mass flow rate, droplet sizes injected, and water flow rate. These three parameters can thus be potential factors that help successfully control the performance based on maintaining consistent conditions within a space. While both the water flow rate and the air mass flow rate are relatively easy to control, adjusting the droplet size as outdoor weather conditions change is difficult. In addition, differences in the cooling performance between droplet sizes of 30 ㎛ and 100 ㎛ were fairly small. Two different control strategies, water flow rate control and air mass flow rate control, are thus considered.

In reality, many algorithms dealing with the optimal performance of the PDEC systems could be considered. The goal of this case study, however, is to verify that PDEC towers are applicable as a cooling component in buildings, providing significant energy savings and also improving indoor environmental quality. An analysis of optimal control algorithms was thus not included in this study.

A simple control algorithm for determining the water flow rate and the air mass flow rate were employed as shown in Figure 7.1. The model calculates the exit temperature and velocity from Equations 7.7 and 7.8, if ambient air conditions are in the ranges defined by user inputs. In the case of typical operation of PDEC systems, the model calculates the air mass flow rate and volumetric flow rate as well as the relative humidity at the outlet based on the temperature and the velocity calculated by Equations 7.7 and 7.8. The control algorithm that was implemented compares the outlet temperature of the PDEC system with the mean air temperature in the space. If the system exit temperature is larger, the model checked again to see if the temperature difference between the calculated exit and the indoor air temperature is within the user-defined range. If this temperature difference is within the user-defined range, the model checks to see if the air temperature in the space was 1.5°C bigger than outdoor wet-bulb temperature to avoid saturation of the air while this low temperature limit should vary with weather conditions. This temperature limit, 1.5°C bigger than the wet-bulb temperature, was imposed when the calculated temperature is bigger than the zone air temperature so that load calculation as well as indoor environment cannot be impacted in this particular situation. Once all these conditions are met at a particular point during the simulation called a time step, the model then set the outlet temperature to 1.5°C higher than outdoor wet-bulb temperature. The requirements of either water flow rate or air mass flow rate can then be determined from Equation 7.7 in the process “A” in the flow chart in Figure 7.1.

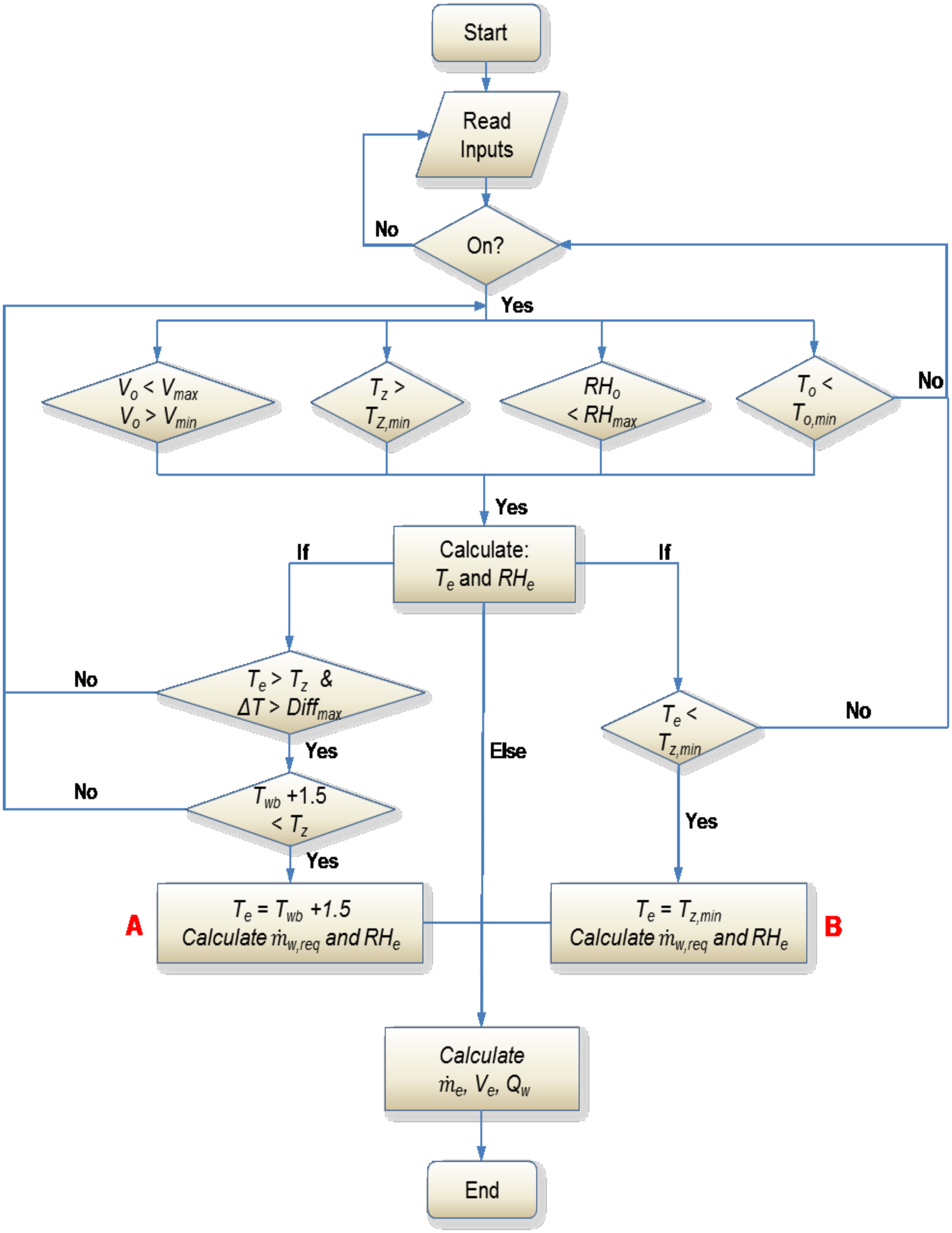


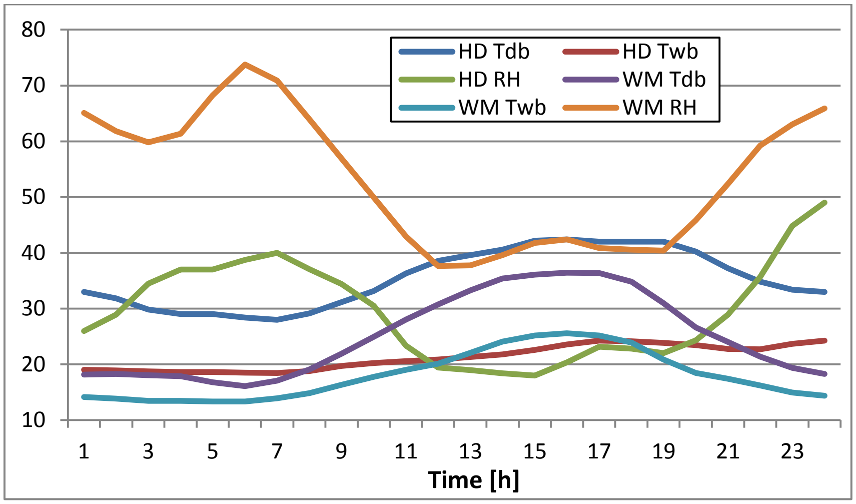
Figure 7.1 Flow chart of simple algorithm for water flow rate control

In contrast, the temperature was set to the minimum temperature defined by the user, if the outlet temperature calculated was less than the user-defined minimum indoor temperature to avoid having the PDEC system overcool the space thus cause heating loads. The water flow rate demand or air mass flow rate demand at the time step can then be calculated from Equation 7.7 as shown by process "B" in Figure 7.1. Finally, the model determines the air mass flow rate, the air volumetric flow rate, and the velocity of the air at the tower outlet.

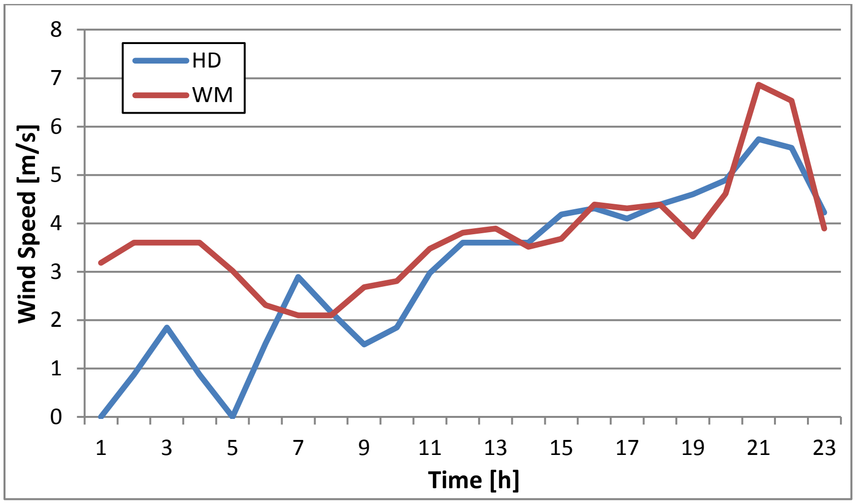
7.2 Case Study

Using the algorithm described in the previous subsection, various case studies were performed to analyze the cooling performance of PDEC towers in different climates and to verify its potential capability as a building cooling system. Two different locations were chosen for a short-term simulation study. These include a hot-dry climate represented by Yuma, Arizona and the warm-moderate climate represented by Sacramento, California. A typical summer day that reflects the characteristics of each weather condition was chosen from the days during run period. It should be noted that the classification of climate in this study was not a typical climate classification provided by weather statistics, but rather a definition based on the different air condition for this specific study. The city of Yuma is classified as a dessert climate, and Sacramento has a hot dry summer with a large variation in relative humidity. The building energy system and envelope of the building were designed based on the climate of Arizona. While overall design components of the building such as building envelope and mechanical systems should vary with climatic regions, these features remained the same over the simulations in this study.

Figure 7.2 depicts the climatic conditions of the two locations that were considered. In contrast, the peak temperatures on the day were approximately 42°C between 3PM and 7PM in Yuma, and approximately 36.4°C between 3PM and 5PM in Sacramento. The wet-bulb temperatures in Yuma peaked at approximately 24.2°C between 5PM and 6PM, and peak wet-bulb temperatures of approximately 25.2°C appeared between 3PM and 5PM in Sacramento. The relative humidity in Sacramento increased up to 73.8% at 6AM and dropped to 37.6% at 12PM while a constant variation was seen between 12PM and 7PM. The relative humidity in Yuma in the morning was higher than the other hours of the day, and it dropped as low as 18% at 3PM. The ambient wind speeds in Yuma in the early morning was approximately 2.5m/s lower than those in Sacramento, and they were fairly similar to each other the other hours of the day.



a) Temperatures (°C) and relative humidity (%RH)



b) Wind speed

Figure 7.2 Ambient air conditions in the two climatic regions investigate

(HD=hot-dry, WM=warm-moderate)

The building that was used for these case studies was a primary school reference building provided by the U.S. Department of Energy (DOE). This building was chosen because its design contains various types of rooms and a high number of occupants. The one story E-shaped school has an area of 6,871m^2 and consists of one main corridor with three wings in which classrooms were placed. The types of spaces include classrooms, an office, corridors, an auditorium, a gymnasium, a cafeteria, a kitchen, and a library. These spaces were divided into 23 individual zones. The primary building HVAC system includes a multi-zone single duct VAV system with reheat for all of the classrooms, the office, the corridors, the auditorium, and the library, and packaged single zone air conditioning (PSZ-AC) units for the gymnasium, kitchen, and cafeteria.

The minimum flow rate of the VAV system was set to 30% of the total design air flow to satisfy the requirement of minimum air flow for indoor air quality standards. This minimum air flow was adjusted to 5% when the PDEC systems were added as a cooling component. Internal heat gains such as occupants, lights, electric equipment, and gas equipment varied according to purpose of spaces. The primary HVAC system and PDEC towers were set to operate 6AM through 9PM. The setpoint temperatures were set to 24°C during occupied hours and 27°C during setback hours. Environmental factors were also defined and included a total carbon equivalent emission factor from carbon dioxide of 0.2727 kg/kg and a carbon dioxide emission factor from fuel of 341.7 g/MJ.

Four different control strategies were considered. Almost all existing PDEC towers have no control options so one control strategy was termed “Normal” to consider typical PDEC operation. A second control strategy that monitored temperature was named “Temp Ctrl.” This algorithm checked only if the outlet air temperature was greater than the minimum zone temperature input to avoid introduction of warm air higher than indoor set point temperature, since this could end up heating the space. This essentially follows the “A” process in Figure 7.1 that looks at whether or not the outlet air temperature calculated was less than the zone air temperature at a specific point in time. The third control option monitored the water flow rate and was named “WF Ctrl.” This option added an additional check to the second control option “Temp Ctrl” to protect overcooling a space when the PDEC outlet temperature was less than the user-defined minimum zone air temperature at each time step. This algorithm follows either “A” or “B” in the flow chart depending on the situation. The fourth control option was named “Mass

Ctrl" and was set to adjust the air mass flow rate by varying the wind catcher area at a fixed water flow rate. Analysis of results using the "WF Ctrl" control option prompted a series of runs labeled "Smaller". These cases reduced the areas of wind catcher and tower cross-section by 50% from the original sizes, and two small towers were placed in each space rather than a single tower per space.

In addition to monitoring standard measures of space conditions like temperature and humidity, the EnergyPlus simulation also allowed the report of the values of the predicted mean vote (PMV) within a space using the Fanger thermal comfort model (Fanger, 1970.) These results were compared to verify how PDEC towers affect thermal comfort of occupants in a space. The Fanger PMV value is determined from six major variables such as activity, clothing, and four environmental variables: air speed, air temperature, mean radiant temperature, and humidity. PDEC towers affect all the environmental variables in the calculation of PMV value. In fact, air speed in the space should be altered for accurate predictions since PDEC towers typically provided large amount of air flows with a space. However, no attempt was made to adjust air speed of the air in a space in this study because of the complexity of the accurate prediction of these values and the time required to properly account for such variations on an hourly or sub-hourly basis. Thus, the air speed in each space remained at 0.2m/s in all simulations.

7.2.1 PDEC without primary cooling system

In one series of runs, the school building was modeled with the PDEC systems as the only cooling system for the building. A number of attempts made to design reasonable input fields that defined the performance of the system, and the resulting inputs for the PDEC towers are listed in Table 7.1. It should be noted that the PDEC towers were not optimized according to climatic conditions, but rather oversized in order to clearly reflect the characteristics of these systems. Different tower heights, water pump power consumption rates, and areas of the wind catcher and the tower cross-section were employed. A water flow rate of 200l/h and water droplet size of 30 ㎛ were used. 5% of the air and water flow rates were assumed to be lost. The minimum zone temperature limit and minimum ambient temperature were set to 20°C and 28°C, respectively. That is, the model assumed that the PDEC systems were turned off when the zone air temperature at a given time step was below the minimum zone temperature, as well as the ambient air temperature was lower than the minimum ambient temperature. These values were used as control setpoints during the PDEC control simulations as well. As for simulations in the warm-moderate climate Sacramento, the two input fields for the maximum relative humidity and the minimum ambient temperature were adjusted to 50% and 26°C. PDEC towers for the "normal" PDEC operation case was set to always be turned on in all climatic ranges.

Table 7.1 Main input parameters for PDEC objects in the short-term simulation

Type of rooms	Class room	Office	Cafeteria
Water flow rate [l/h]	200	200	200
Effective tower height [m]	5	10	8
Minimum indoor temperature [°C]	20	20	20
Water loss [%]	5	5	5
Air flow loss [%]	5	5	5
Rated pump power consumption [W]	150	250	250
Area of wind catcher [m^2]	6.25	9	9
Tower cross-sectional area [m^2]	16	25	25
Diameter of water droplet [μm]	30	30	30
Maximum relative humidity [%]	40	40	40
Minimum ambient temperature [°C]	28	28	28

7.2.1.1 Energy performance

A tremendous reduction in the electricity consumption for cooling was shown in all of the PDEC controlled cases. The energy performance of the different control strategies on a typical summer day was compared to verify how much energy each case could save. Table 7.2 below illustrates the electricity consumed by the cooling systems and facilities, the water consumption, and the carbon dioxide production by the building in the two different climates. The cooling electricity in the PDEC cases was the total energy use of the water pump, which is the only component consuming energy in the PDEC systems. The electricity for cooling was 7100.78MJ in the base case that was served by the conventional forced air systems only in the hot-dry climate and 3994.59MJ in the warm-moderate climate. This value decreased to 258.72MJ in the hot-dry climate and 179.34MJ in the warm-moderate climate, which is a maximum reduction of 96.3% in Yuma and 95.5% in Sacramento. Since no electricity was consumed by fans in any of the PDEC cases, more energy savings was achieved. Percentage reductions in electricity by building facilities were estimated as 57.3% in Yuma and 44.9% in Sacramento. The production of carbon dioxide in the use of building facilities was 2716.45kg in the base case in Yuma and 1174.56kg in PDEC cases, and these values were reduced by 56.7% using the PDEC system. The PDEC systems did consume a large volume of water, up to 437.38m^3 in Yuma and 356.11m^3 in Sacramento in the smaller case, which is a sharp increase over the base case which only used 1.5m^3 in both climates. In Yuma, the water consumption in the Temp Ctrl case was greater than in the Normal case. It was likely that water In addition, a considerable difference in water consumption between each control case was observed, and the water flow rate control significantly decreased water consumption in both climates.

Table 7.2 Comparisons of energy performance along control algorithms in different climates

Hot-Dry Climate

Meters	Normal	Temp Ctrl	WF Ctrl	Mass Ctrl	Smaller	Base
Cooling:Electricity [MJ]	258.72	258.72	258.72	258.72	261.36	7100.78
Electricity:Facility [MJ]	5774.86	5774.86	5774.86	5774.86	5777.50	13529.43
Fans:Electricity [MJ]	0	0	0	0	0	683.77
Cooling:MainsWater [m^3]	223.50	237.73	191.13	218.30	437.38	1.50
CO2:Facility [kg]	1174.58	1174.58	1174.58	1174.58	1175.10	2716.45

Warm-Moderate Climate

Meters	Normal	Temp Ctrl	WF Ctrl	Mass Ctrl	Smaller	Base
Cooling:Electricity [MJ]	264.60	179.34	179.34	179.34	187.11	3994.59
Electricity:Facility [MJ]	5774.86	5685.19	5685.19	5685.19	5692.96	10324.15
Fans:Electricity [MJ]	0	0	0	0	0	614.02
Cooling:MainsWater [m^3]	175.08	139.93	103.52	176.69	356.11	1.50
CO2:Facility [kg]	1173.71	1156.90	1156.90	1156.90	1158.43	2084.69

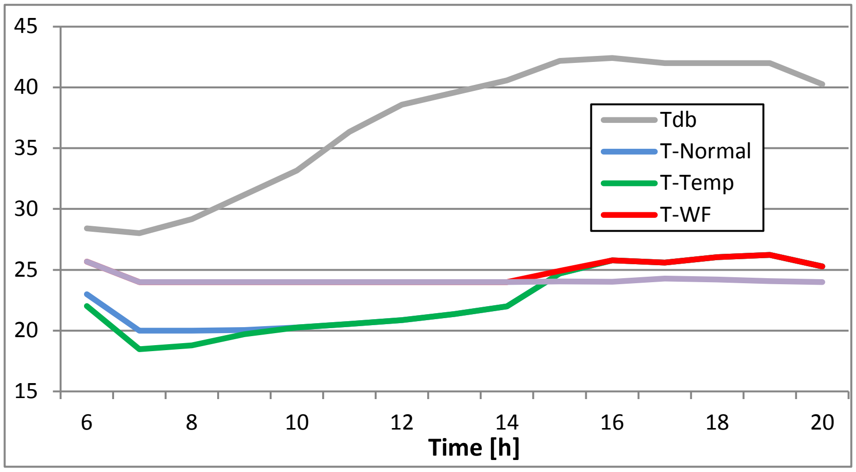
7.2.1.2 Cooling performance

The indoor environment in three representative spaces (the cafeteria, a classroom, and the office) was also compared. The office, which was a relatively large-scale space, has a volume of 1764 m^3. The volumes of a medium-scale space, cafeteria, and the smallest space, classroom, were 1260m^3 and 396 m^3, respectively. The number of occupants and internal heat gains from lights and electric equipment differed for each space. The minimum indoor temperature was set to 24°C in all the PDEC controls cases, and this was considered the setpoint temperature for the PDEC systems. No attempt, however, was made to strictly meet the indoor temperature setpoint in these control types. The model thus adjusted either water flow rate in "Temp Ctrl" and "WF Ctrl" cases, or mass flow rate in "Mass Ctrl" case if the outlet temperatures calculated fell into processes A or B as shown in the flow chart in Figure 7.1.

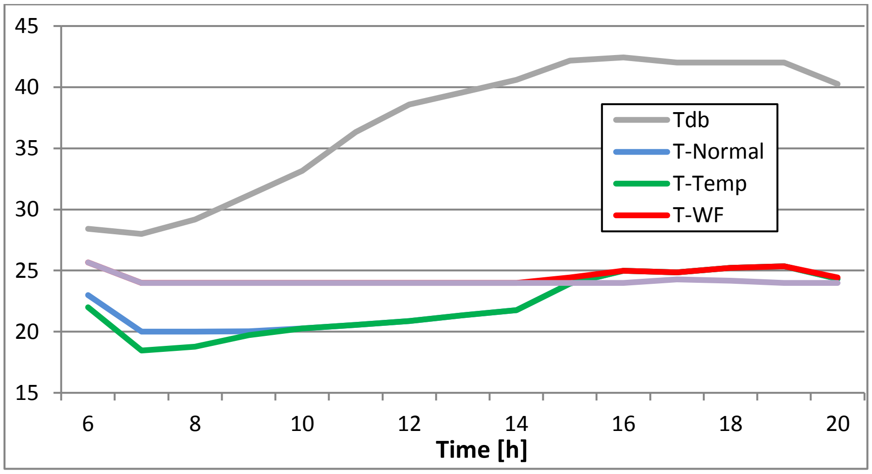
PDEC outlet air conditions

Low temperature with high relative humidity at the exit of the PDEC system was noted in both the normal PDEC operation case and the temperature control case during most of operational hours of the PDEC system. Note that PDEC control cases in Sacramento covered a certain portion of the day since PDEC towers began to run at 11AM. The relative humidity at the outlet of the temperature control case significantly increased and remained fairly constant until 2PM as it started to run in all spaces and climates. In the hot-dry climate, the ambient wet-bulb temperatures were fairly low during the early morning and resulted in a sharp rise in the relative humidity and sudden temperature drop of the outlet air. It was also seen that a large amount of water, maximum water flow rate of 200l/h, was unnecessary if such a low temperature, approximately 20°C, was not required. These two cases, however, maintained a bit lower level of relative humidity between 88.6% and 82% once the ambient air conditions changed under very hot and dry inlet conditions. Similar tendencies were also observed in Sacramento in these cases. In addition, the normal PDEC operation showed a severe increase in relative humidity as it reached the maximum at 7PM in Yuma, and all running hours in Sacramento due to relatively low ambient wet-bulb temperature and high volume of water injected. The temperature of the air in the normal condition then gradually increased as the ambient wet-bulb temperature increased.

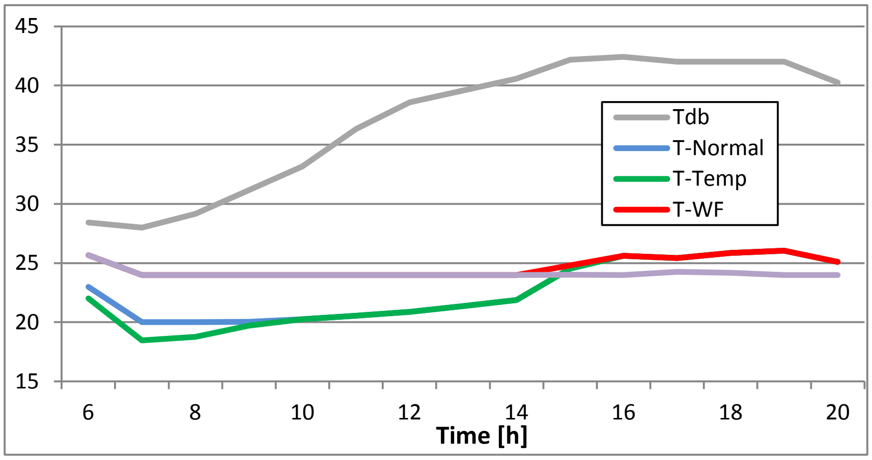
The other three control cases achieved almost the same performance in all cases in both climates. A gradual increase in relative humidity appeared in the other three control types by 2PM in Yuma. They then maintained a relatively constant variation of relative humidity in the range between 80% and 94% in Yuma. A sudden rise in relative humidity, however, was seen in Sacramento as soon as it started to operate from 11AM through 2PM due to a higher ambient relative humidity of approximately 40% and thus higher wet-bulb temperature than early morning hours. Relative humidity in these control types then suddenly dropped starting at 6PM in Sacramento along with the variation of ambient wet-bulb temperature from 23.9°C to 20.9°C. On the other hand, a constant outlet temperature of 24°C, which was the set point temperature of PDEC towers, was shown through 2PM in Yuma and 1PM in Sacramento. Outlet temperatures in these control types then slightly increased since the ambient wet-bulb temperatures was floating around 24°C.



a) Cafeteria – Hot-dry

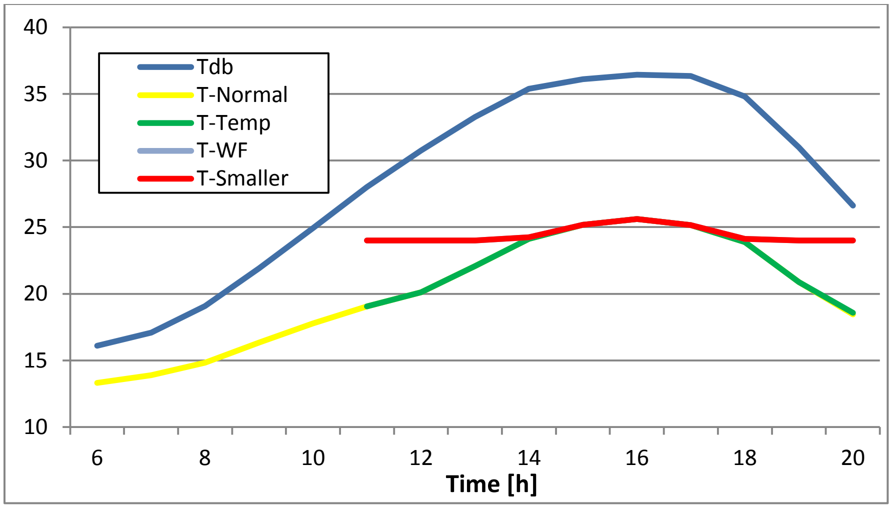


b) Classroom – Hot-dry

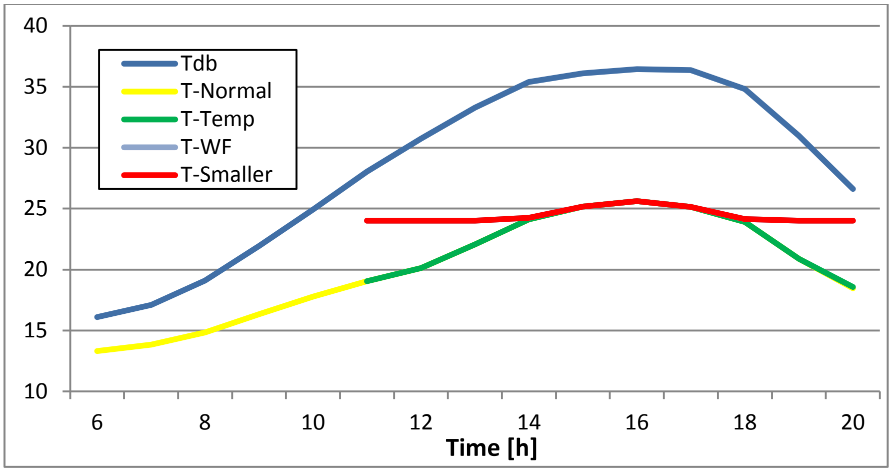


c) Office – Hot-dry

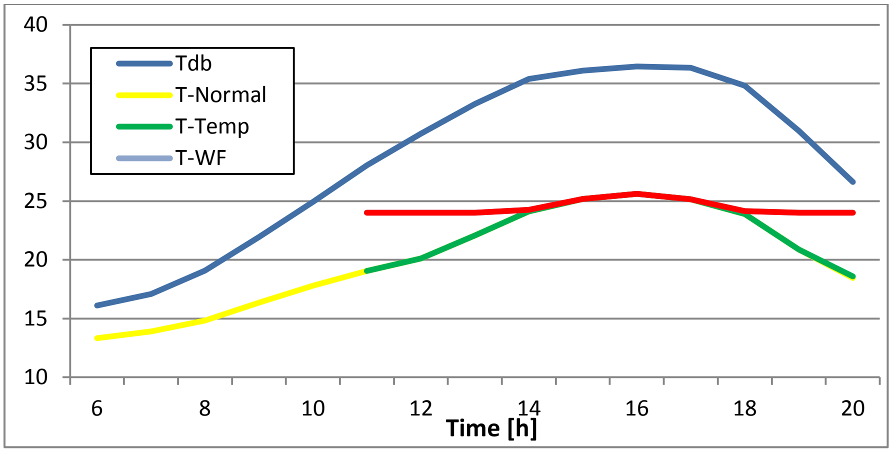
Figure 7.3 Variations of temperature at PDEC towers outlet



d) Cafeteria – Warm-moderate

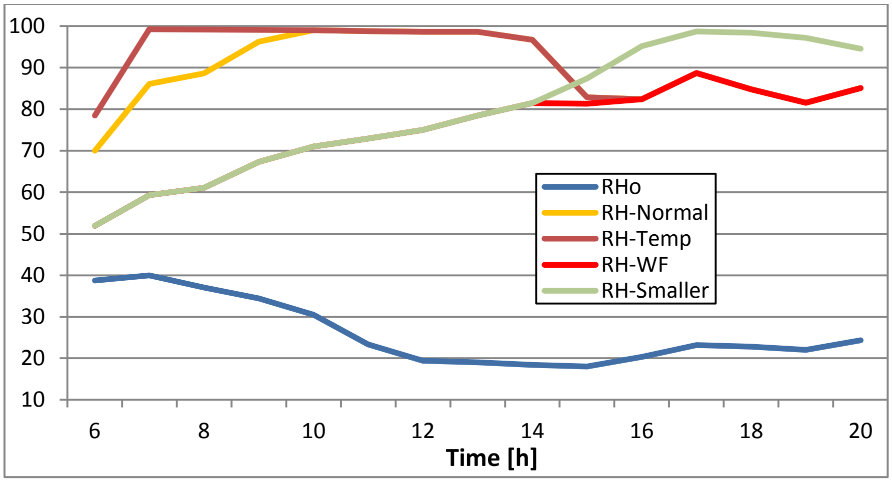


e) Classroom – Warm-moderate

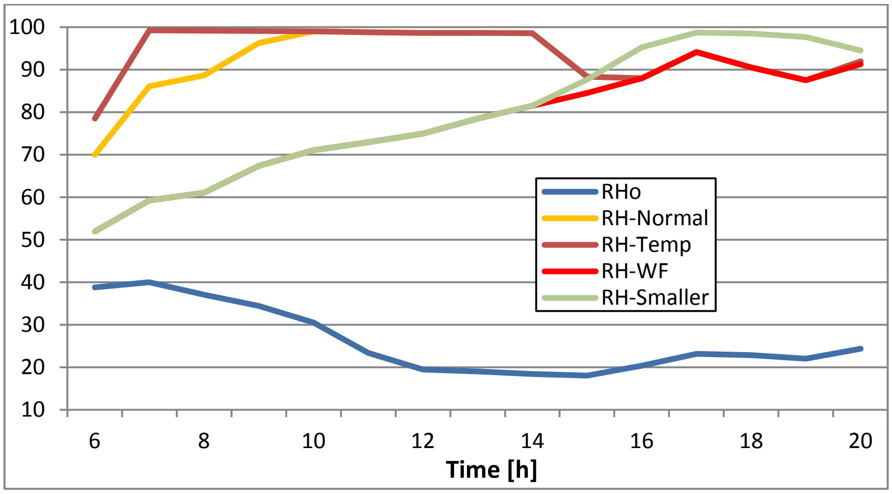


f) Office – Warm-moderate

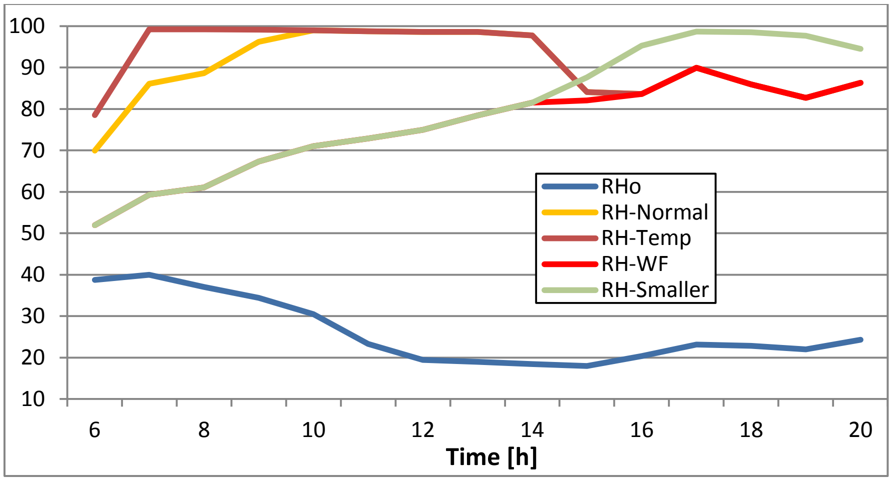
Figure 7.3 Variations of temperature at PDEC towers outlet (con't)



a) Cafeteria – Hot-dry

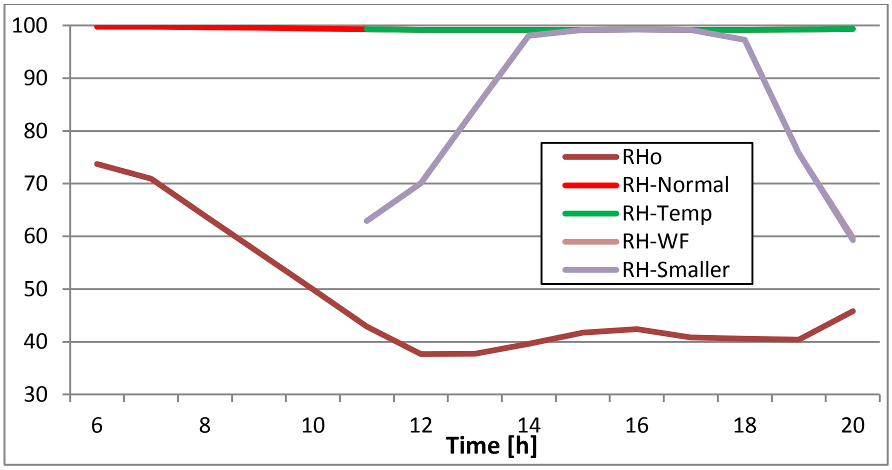


b) Classroom – Hot-dry

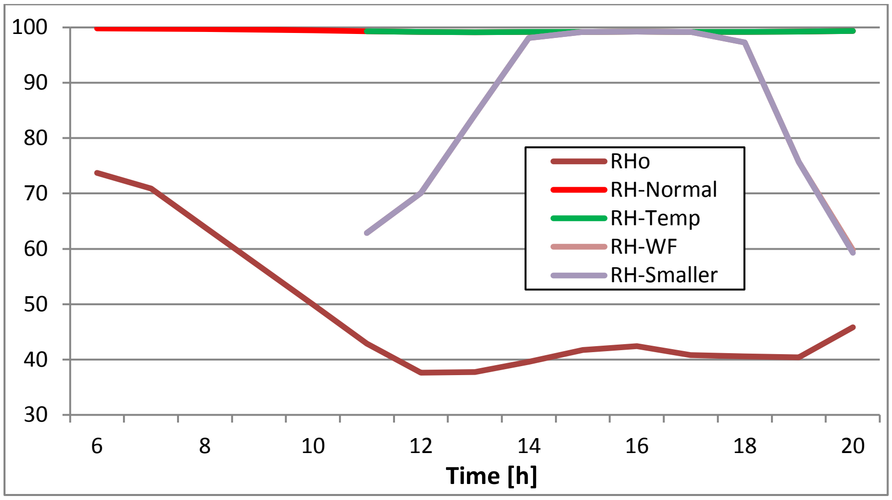


c) Office – Hot-dry

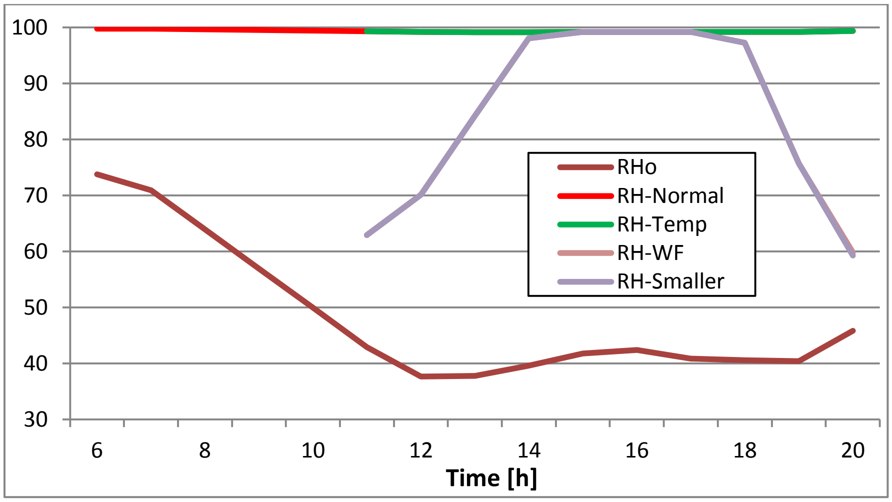
Figure 7.4 Variations of relative humidity at PDEC towers outlet



d) Cafeteria – Warm-moderate



e) Classroom – Warm-moderate



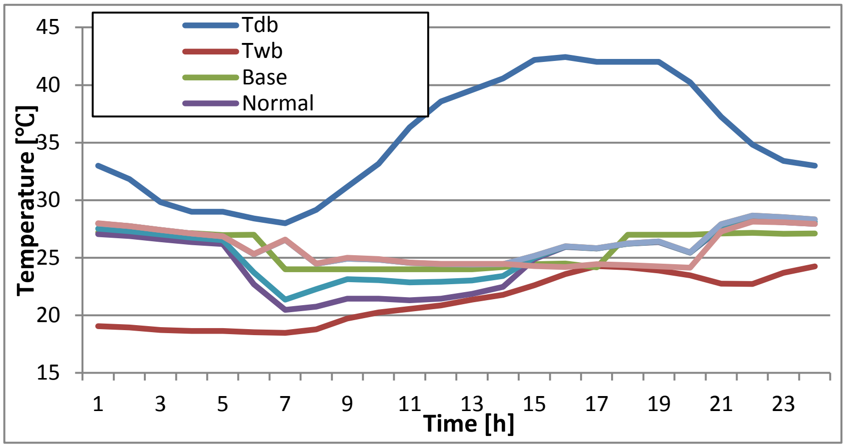
f) Office – Warm-moderate

Figure 7.4 Variations of relative humidity at PDEC towers outlet (con't)

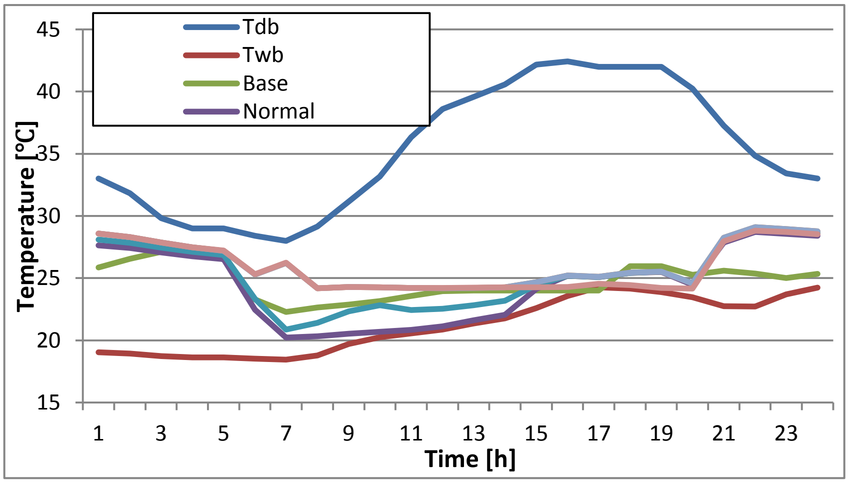
Mean air temperature

Variation in indoor air temperature throughout the day showed large differences for each of the cases. The normal PDEC operation significantly overcooled the spaces in the morning hours in both climates. The temperatures at 7AM dropped to 20.2°C in the classroom in Yuma and 16.7°C in classroom in Sacramento. Temperature differences between the base case and the normal case at 7AM, when the lowest indoor air temperature was predicted, were approximately 4.1°C in the cafeteria in Yuma and 5.26°C in the office in Sacramento. Similarly, the temperature control in Yuma, which only checks if the outlet temperature calculated was greater than the space air temperature at each time step, maintained low temperatures until 3PM. This temperature control in Sacramento also performed worse than the other three control strategies, overcooling the spaces from 11AM when the PDEC systems began operating, but it showed better performance than the normal case. In Sacramento, due to low outdoor temperatures and relatively high humidity, the PDEC systems were turned off by 11AM in the controlled PDEC cases, increasing indoor air temperatures up to 27.6°C in cafeteria.

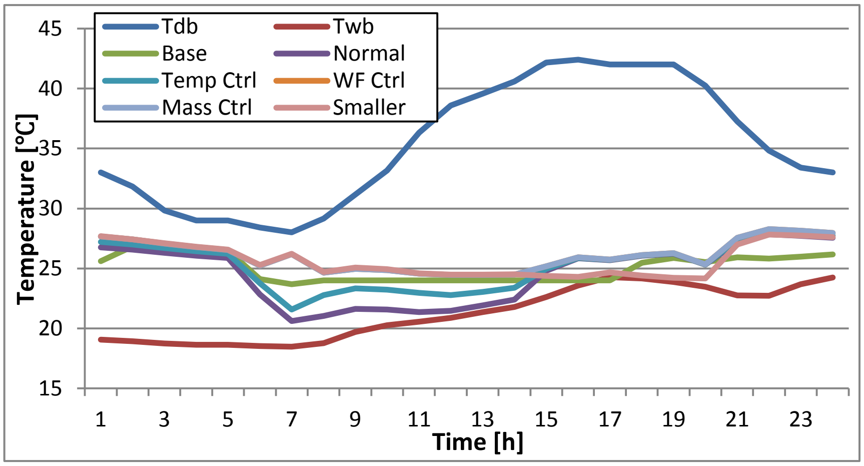
The temperatures in PDEC control cases were more consistent than the base case. However, both the normal PDEC operation and the temperature control cases were unlikely to maintain a constant environment in all spaces and climates. The original cooling system in the base case could not meet the set point temperature between 6PM and 8PM in both cases due to very high outdoor dry-bulb temperatures (up to 42°C in Yuma and 36.5°C in Sacramento.) Conversely, three of the controlled PDEC cases (water flow control, mass flow control, and smaller PDEC tower) showed almost the same variation between 8AM and 8PM in all spaces and climates. This was because the PDEC systems continued to operate during all scheduled hours, providing almost the same cooling capacity between the different control algorithms since the ambient air conditions were within the range of operation. Indoor air temperatures in Sacramento in these three PDEC control cases, however, were variable since the outdoor wet-bulb temperature increased up to 25.6°C at 6PM. They, however, maintained a constant indoor temperature between 5PM and 8PM, which the base case and the other cases could not achieve. In summary, PDEC systems with appropriate performance control may handle all the cooling demands in a space in a hot-dry climate while the PDEC towers will have some difficulty maintaining acceptable indoor conditions in a warm-moderate climate when the outdoor wet-bulb temperature increases above the upper limit of indoor air temperature acceptability.



a) Cafeteria – Hot-dry

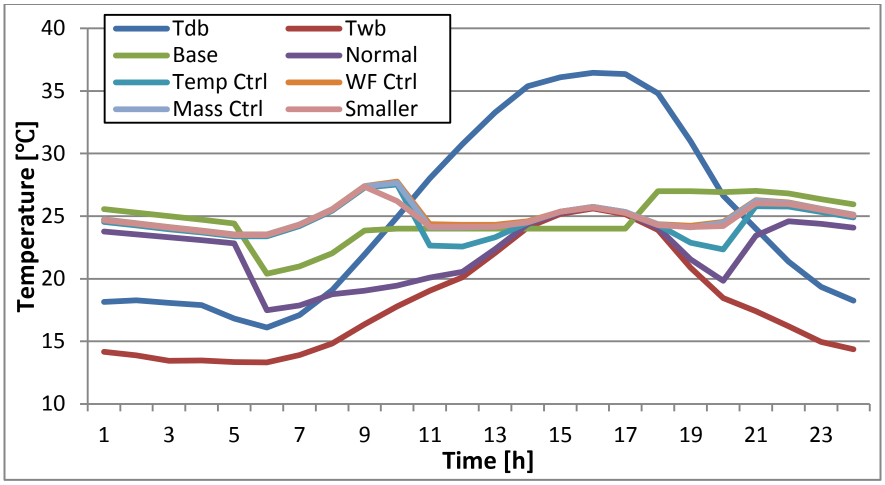


b) Classroom – Hot-dry

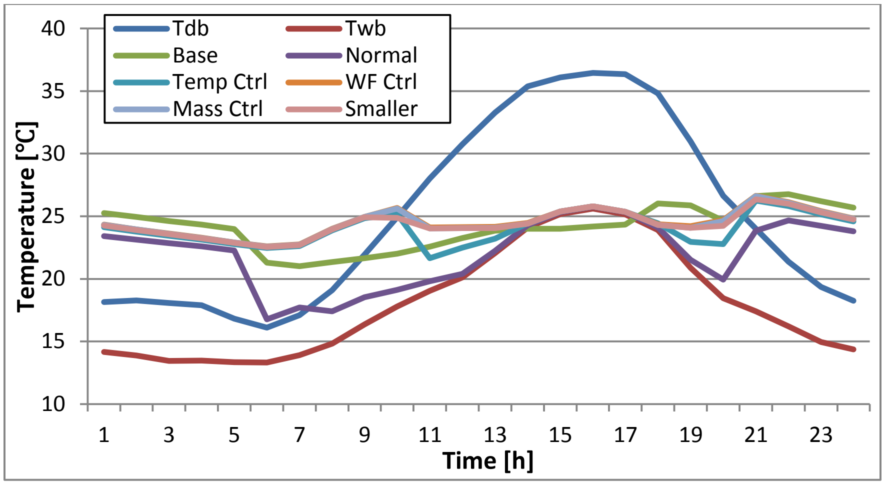


c) Office – Hot-dry

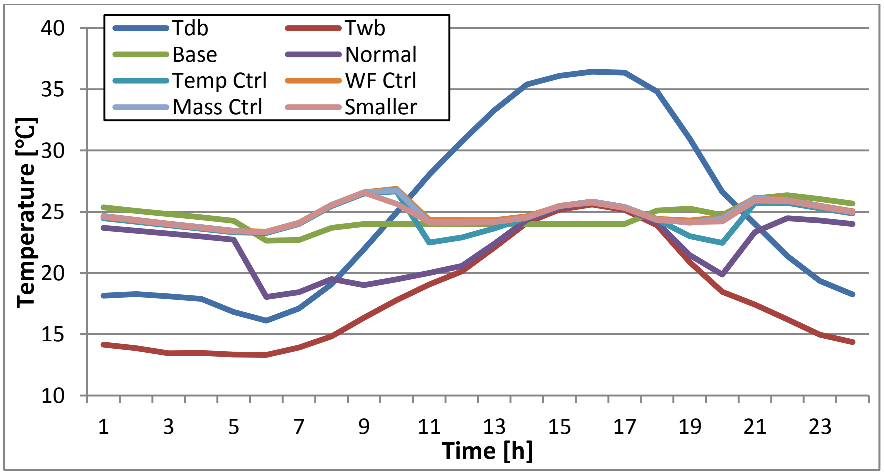
Figure 7.5 Variations of indoor mean air temperature



d) Cafeteria – Warm-moderate



e) Classroom – Warm-moderate



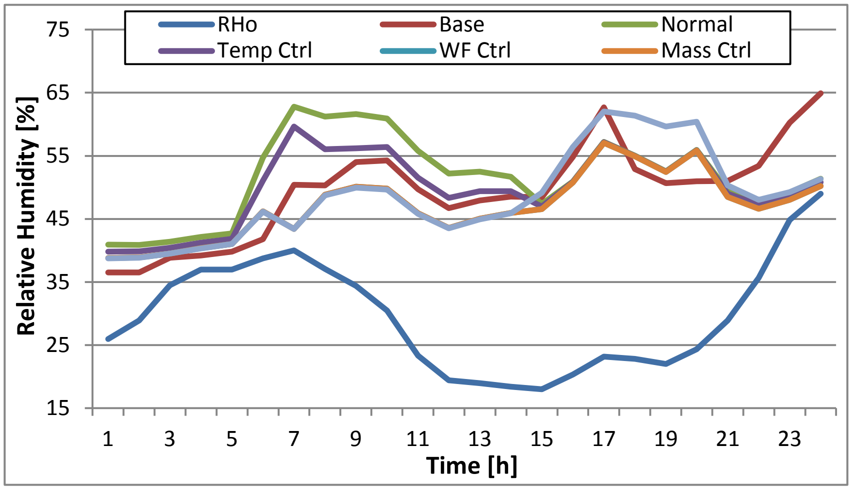
f) Office – Warm-moderate

Figure 7.5 Variations of indoor mean air temperature (con't)

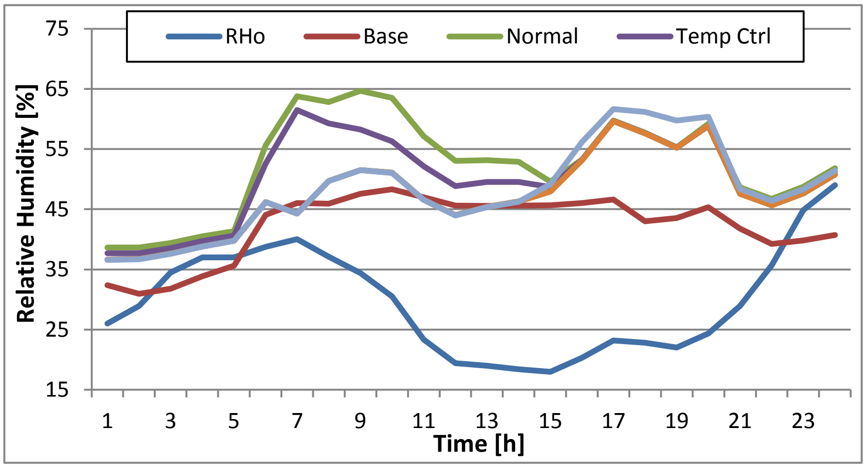
Relative humidity

Relative humidity significantly varied in all cases including the base cases. In the cafeteria, which was controlled by a unitary air conditioning system, PSZ-AC, the relative humidity in all cases and climates varied during all operational hours. In addition, both the normal operation and temperature control cases significantly increased indoor relative humidity level at the beginning of the day with cyclical increases and decreases throughout the day in all cases both in Yuma and Sacramento. The maximum relative humidity was shown to be roughly 65% even in the normal PDEC operation case, and the differences between the maximum and minimum relative humidity were less than 20% in all cases in Yuma. The variations in relative humidity in Sacramento were much greater than in Yuma, which was mainly because of the warm-humid outdoor air conditions.

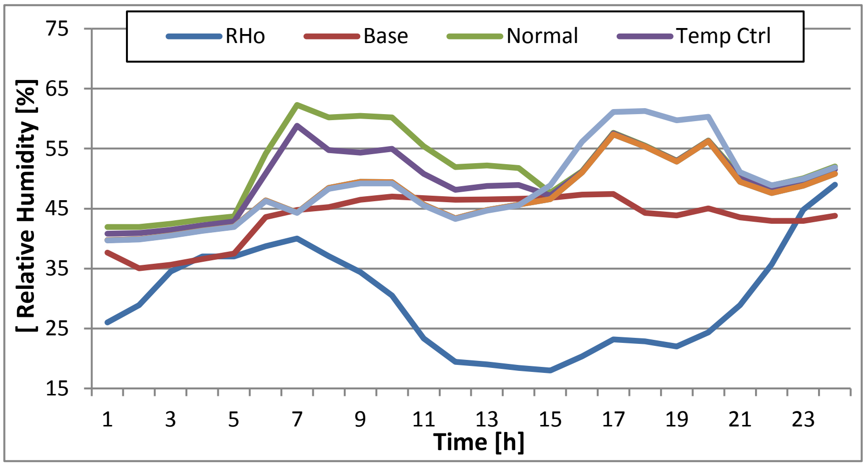
In contrast, relative humidity in the other three PDEC control cases in Yuma was relatively constant within approximately a 7% difference by 3PM as the water flow rates determined to achieve the setpoint temperature did not reach the maximum water flow rate of 200l/h. Relative humidity in these control cases, also including the other cases, sharply increased as the cooling demands of the spaces increased, and the ambient wind speeds also increased, resulting in a large amount of water consumption to treat the large amount of outdoor air flow at a high temperature. In addition, the variation in relative humidity in Sacramento was larger than in Yuma due to the humid weather conditions. The indoor relative humidity increased up to nearly 80% at 4PM in all spaces in Sacramento due to increase of water requirements to meet cooling loads that significantly increased. Thus, it turned out that inappropriately designed PDEC towers can significantly increase indoor humidity level, resulting in excessive water consumption.



a) Cafeteria – Hot-dry

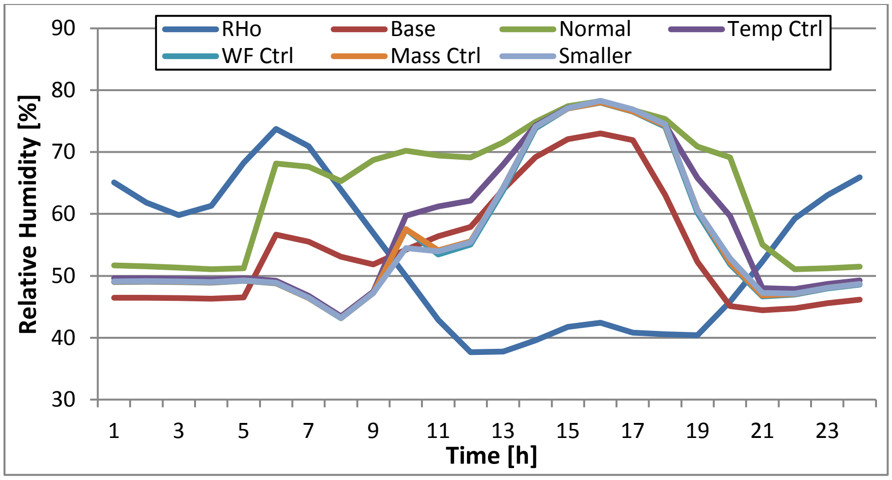


b) Classroom – Hot-dry

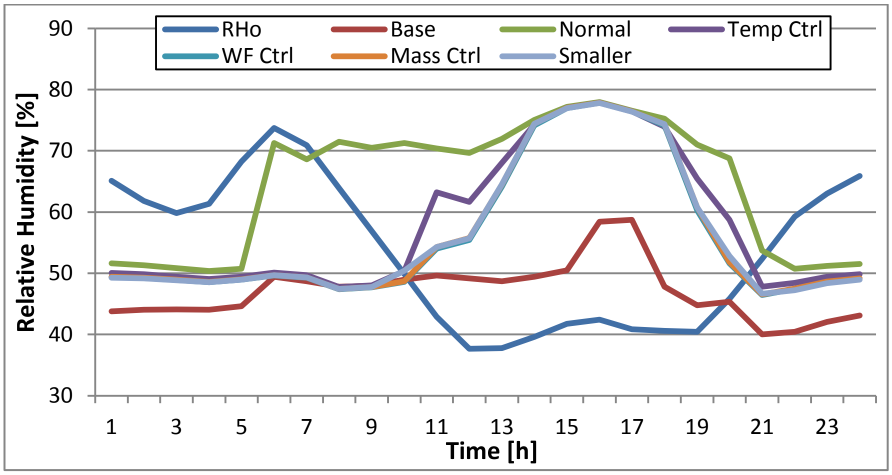


c) Office – Hot-dry

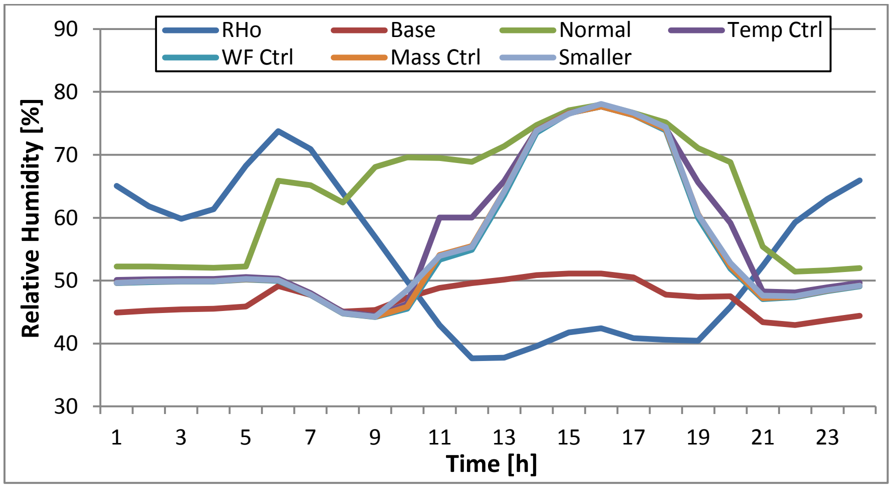
Figure 7.6 Variations of indoor relative humidity



d) Cafeteria – Warm-moderate



e) Classroom – Warm-moderate

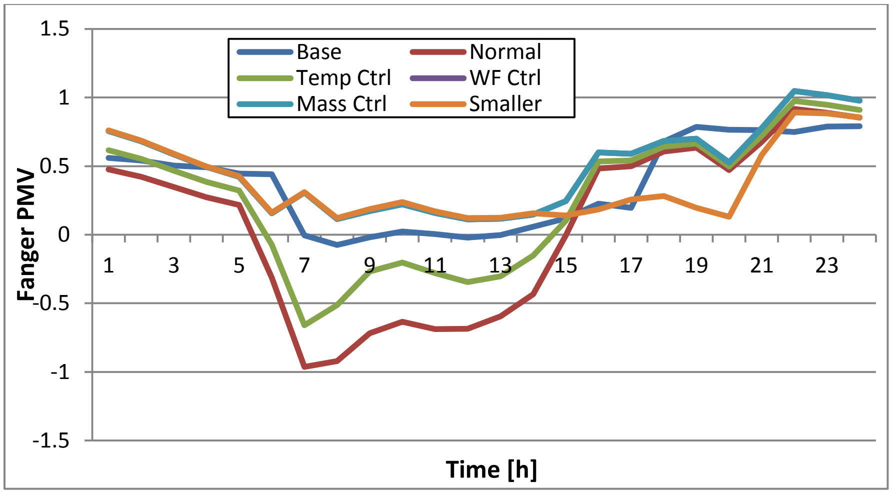


f) Office – Warm-moderate

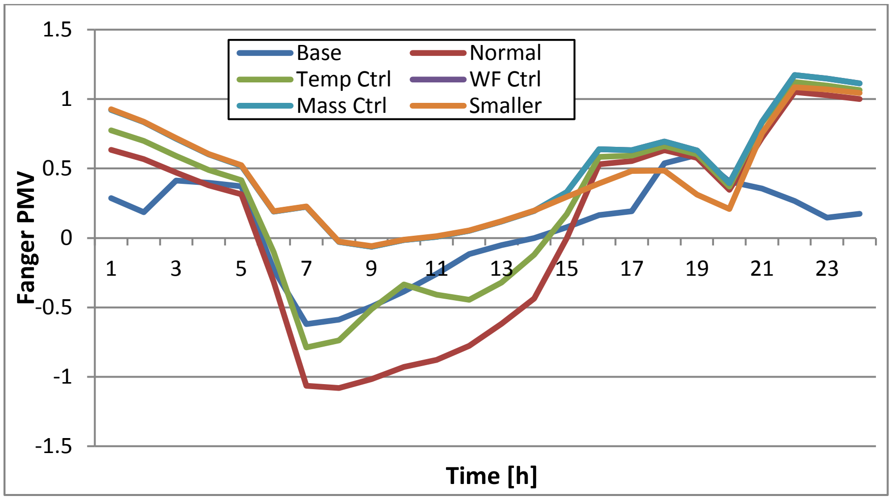
Figure 7.6 Variations of indoor relative humidity (con't)

Thermal comfort

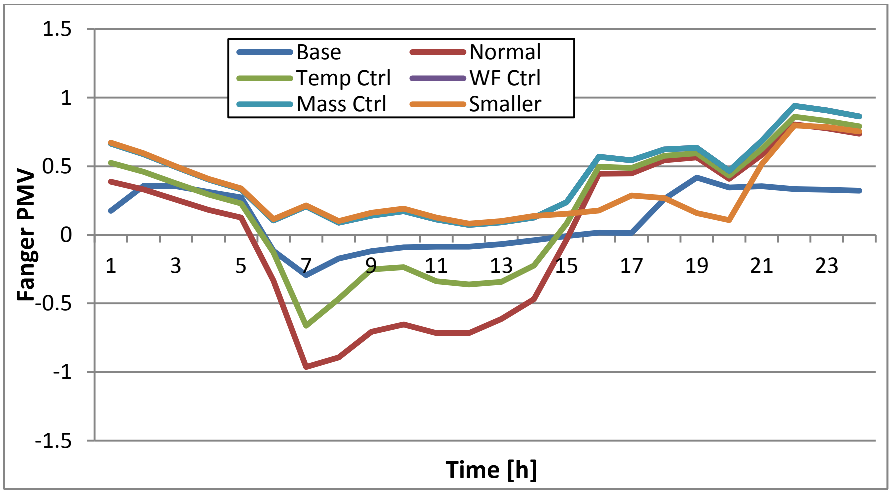
The trends in the thermal comfort levels showed similar tendencies to the variations in the indoor temperature and relative humidity. Since temperature and relative humidity are key factors in determining the thermal comfort indexes, it was expected that variations in these parameters will affect the predicted Fanger PMV values. As described in the simulation description section, no adjustments were made to indoor air speed for the PDEC cases. The Fanger PMV values in classroom at 7AM in the normal case were reported as -1.08 in Yuma, which is classified as slightly cold, and nearly -2.0 in Sacramento, which is classified as cold. These values were because large volume of cold air is flowing from the PDEC towers and this dropped the indoor air temperatures while increasing the relative humidity at this particular time. These values then fall in between neutral (PMV=0) and slightly warm (PMV=1) reaching values up to 0.7 in cafeteria between 3PM and 8PM due to significant variations in the indoor environment. A similar tendency was seen for the temperature control type. The temperature control case, however, improved thermal comfort in the spaces, showing better PMV values than the normal case. In contrast, the Fanger PMV values in the other control cases were very close to neutral with a very small variation in Yuma, and these values were maintained for a longer time than the base case. While these values in Sacramento were more variable than in Yuma, the PDEC towers with these three controls maintained the indoor thermal comfort level within a reasonable range between neutral and slightly warm at the maximum of 0.87 during PDEC operational hours.



a) Cafeteria – Hot-dry

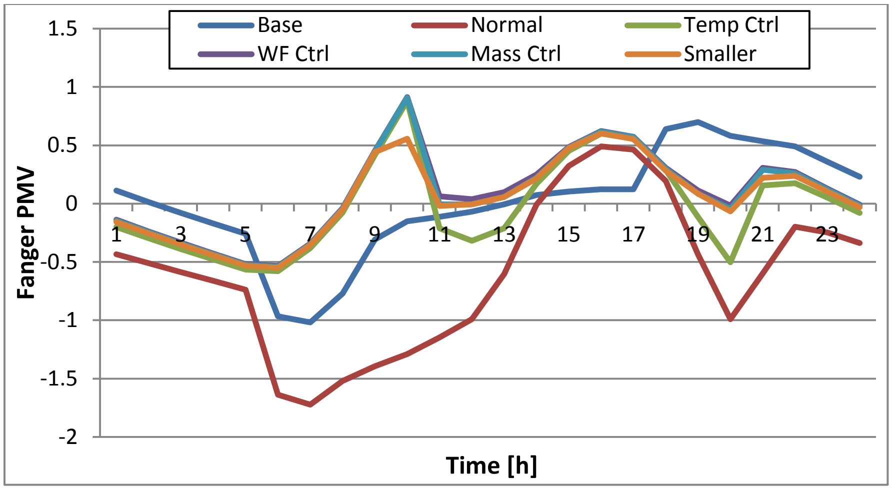


b) Classroom – Hot-dry

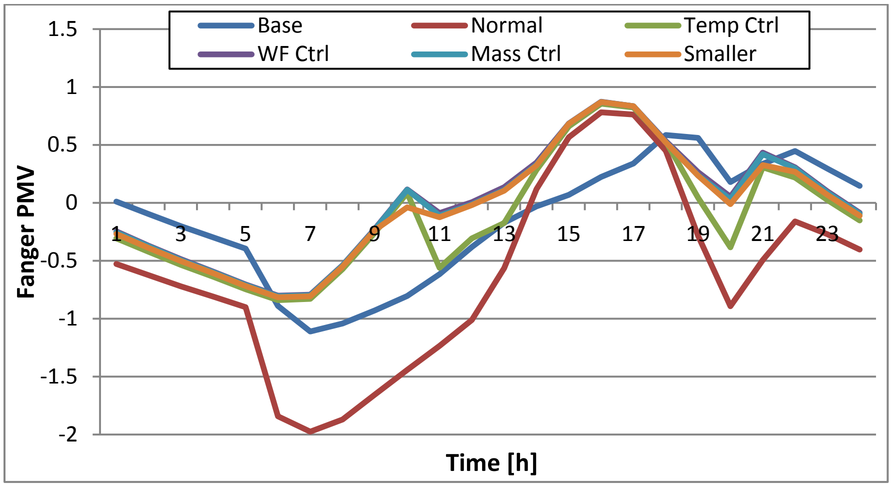


c) Office – Hot-dry

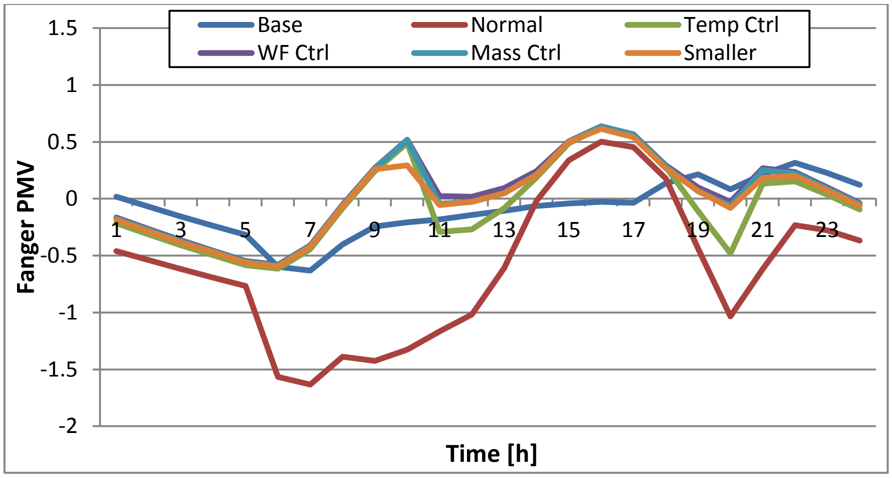
Figure 7.7 Variations of indoor PMV values



d) Cafeteria – Warm-moderate



e) Classroom – Warm-moderate



f) Office – Warm-moderate

Figure 7.7 Variations of indoor PMV values (con't)

7.2.2 PDEC with primary cooling system

PDEC systems are typically a stand-alone cooling system. They, however, may not be capable of meeting all cooling requirements in a space, especially in a humid area, due to their strong dependency on variable weather conditions. To remedy this gap, they could be successfully integrated as a secondary cooling system in conjunction with a primary air conditioning system. They then would meet some of cooling loads while improving the indoor environmental quality. This case study was thus designed to analyze how PDEC towers effectively handle cooling loads in conjunction with a conventional system and achieve their ultimate goal, i.e., energy savings.

An attempt was made to adjust the constant minimum air flow rate of the primary HVAC system, a single duct VAV with reheat, from 30% to 5%. In fact, this minimum air flow rate could be zero in all PDEC running hours. However, PDEC towers could be turned off in some of days during the entire run period occupied hours, which the case where minimum air flow cannot be met by any of these. To avoid such situations, 5% of minimum air flow rate was employed. The other inputs remained the same as the original reference building except for the inclusion of the PDEC towers. In addition, the use of temperature control was excluded in this case study because the purpose of the PDEC system in this series of runs was not to control temperature but rather to provide for outside air. Instead, two different simple comparisons with setpoint temperatures of PDEC towers were included. It was observed in the preliminary studies that the setpoint temperature significantly impacted building load calculations when it differed from indoor cooling setpoint for the primary cooling system. Two different setpoints for PDEC towers (23.5 and 24.5) were thus employed. As a result, the cases considered were “Base”, “Normal”, “WF-23.5”, “WF-24.5”, and “Mass Ctrl.”

7.2.2.1 Energy performance

All of the PDEC integrated cases achieved significant energy savings as illustrated in Table 7.3 below. The electricity for cooling in the base case in Yuma was estimated to be 7100.78MJ. This decreased to 5651.06MJ in the normal PDEC operation case. The normal case achieved an 11.2% reduction in the electricity used by the entire building, a 19.5% reduction in the HVAC electricity use, a 10% reduction in the fan electricity use, and a 33.9% reduction in the carbon dioxide production for the building. In Sacramento, the reductions in electricity consumption in the normal case reached 15.7% for cooling, 6.6% for the building, 14.8% for the HVAC systems, and 8.9% for the fans. The carbon dioxide production in the normal case, however, increased 63.7% in Sacramento, which meant that some amount of energy was consumed for space heating as heating loads appeared during morning hours due to cold PDEC air flows. Similar reductions were seen for both Yuma and Sacramento in the mass flow control case and the water flow rate control at 24.5°C, which is 0.5°C higher than the cooling setpoint temperature. Conversely, carbon dioxide productions by the building in all PDEC cases in Sacramento were greater than those in the base case. This was because the PDEC system tended to overcool as it began to operate in the early morning, resulting in heating needs for the building when the PDEC system was running during those hours. Water consumption in the base cases was estimated less than 0.5% of the total PDEC water consumptions in Yuma and 1.4% in Sacramento.

Water flow rate control at 23.5°C, which was 0.5°C lower than the indoor setpoint temperature of 24°C, achieved the best energy performance as more energy savings were observed in this control case than the other cases. It was interesting that reductions in energy use for cooling and HVAC in Sacramento were greater than in Yuma. This was because the PDEC towers in Sacramento treated relatively large portion of cooling loads in Sacramento since the loads themselves were relatively speaking smaller than those in Yuma. This control case in Yuma achieved a 47.9% reduction in cooling electricity and a 45.6% reduction in HVAC electricity. These percentage reductions in Sacramento increased to 62.1% for cooling and 57.0% for HVAC. On the other hand, carbon dioxide production increased 31% in Sacramento while they decreased 45% in Yuma. This was because, as described previous subsection, an over-sized PDEC tower may cause a heating load if it overcools a space. The 31% increase of carbon dioxide production in the water flow rate control case in comparison with the base case at 23.5°C case, however, was 50% less than that in the other PDEC tower cases.

7.3 Comparisons of energy performance along control algorithms in different climates

Hot-Dry Climate

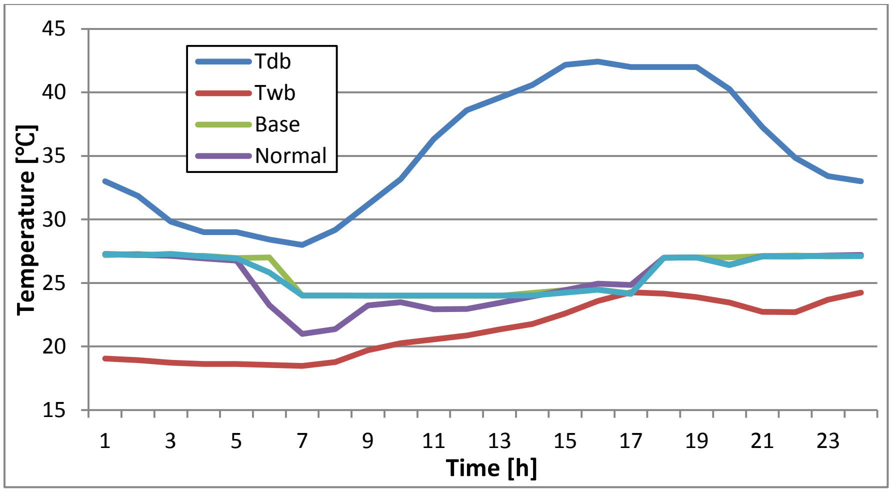
Meters	Base	Normal	WF-23.5	WF-24.5	Mass Ctrl
Cooling:Electricity [MJ]	7100.78	5651.06	3697.97	5692.44	5628.48
Electricity:Facility [MJ]	13529.43	12011.13	9975.70	12056.94	11984.98
Electricity:HVAC [MJ]	7784.55	6266.28	4230.92	6312.19	6240.18
Fans:Electricity [MJ]	683.77	615.23	532.95	619.75	611.70
Cooling:MainsWater [m^3]	1.50	188.31	197.44	109.11	322.75
CO2:Facility [kg]	2716.45	1795.59	1494.15	1802.37	1791.72
Warm-Moderate Climate					
Cooling:Electricity [MJ]	3994.59	3366.99	1514.20	3302.37	3363.35
Electricity:Facility [MJ]	10324.15	9641.72	7695.64	9577.98	9637.26
Electricity:HVAC [MJ]	4608.62	3926.37	1980.11	3862.55	3921.98
Fans:Electricity [MJ]	614.02	559.38	465.91	560.18	558.63
Cooling:MainsWater [m^3]	1.50	92.69	107.47	38.94	185.85
CO2:Facility [kg]	882.60	1444.69	1156.47	1435.24	1444.03

Water consumption in the PDEC towers was directly related to the setpoint temperature. As seen in the previous PDEC-only operated buildings, the water flow rate control at 23.5°C case predicted the lowest water consumption as it adjusted the water flow rate to meet a specific setpoint temperature at a specific time step. While this particular control type achieved the best energy performance, the volume of water consumption was approximately 81% greater than water flow rate control at 24.5°C in Yuma and even 5% greater than normal case, where the indoor setpoint temperature was set to 24°C. In Sacramento, these values increased to 15.9% in the normal case and 176% in the water flow rate control at 24.5°C case. It thus turned out that a 1°C difference in setpoint temperature for the PDEC towers can significantly increase water consumption of these systems while at the same time significantly decreasing their energy consumption. The setpoint temperature for the control of PDEC towers should thus be carefully designed to respond to variable load conditions in a space.

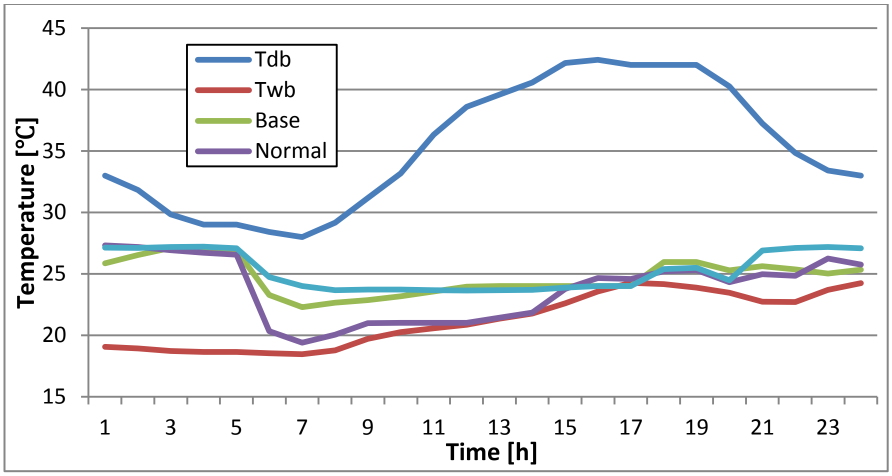
7.2.2.2 Cooling performance

Mean air temperature

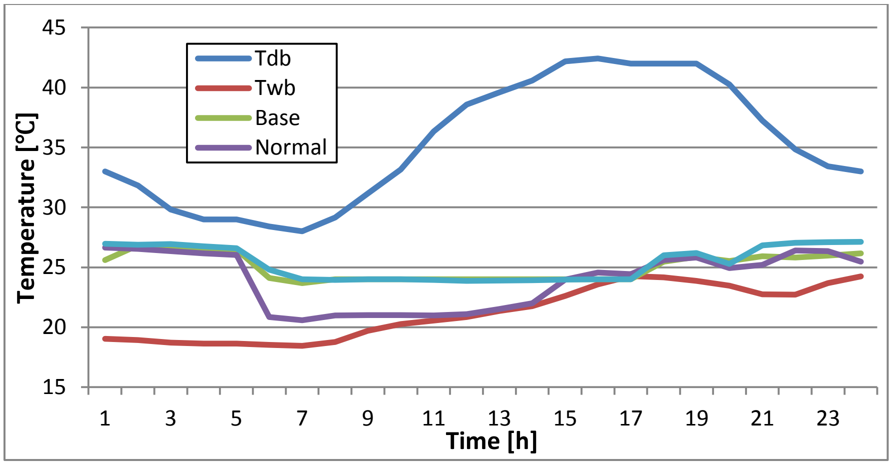
As shown in Figure 7.8, the water flow rate control at 23.5°C maintained the most consistent temperature throughout all of the cases. The base cases without PDEC integration in both climates generally maintained a constant indoor temperature during occupied hours. Conversely, indoor air temperatures in base case between 6PM and 8PM were variable due to changes in the setpoint temperature from the occupied to the setback condition. The temperature in the normal case displayed the most variation as a result of large amounts of cold air from the PDEC towers during the morning hours. The indoor air temperature in the normal case then gradually increased along the outdoor wet-bulb temperature line. This normal PDEC operation provided the coldest temperatures at 19.3°C at 7AM in the classroom in Yuma. This sudden temperature drop also appeared in Sacramento where the temperature dropped to 13.3°C at 7AM in the classroom, causing substantial overcooling of the space for most of the occupied hours. The indoor temperatures in the water flow rate control case maintained a fairly constant value with a little fluctuation between 5PM and 8PM in all spaces in Yuma. These characteristics of temperature variation in the water flow control type were also seen in all spaces in Sacramento, and this case performed better than base case.



a) Cafeteria – Hot-dry

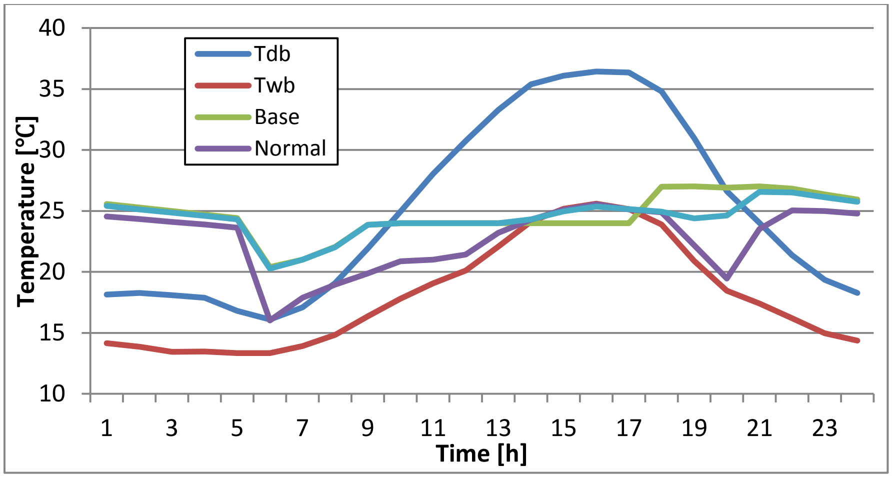


b) Classroom – Hot-dry

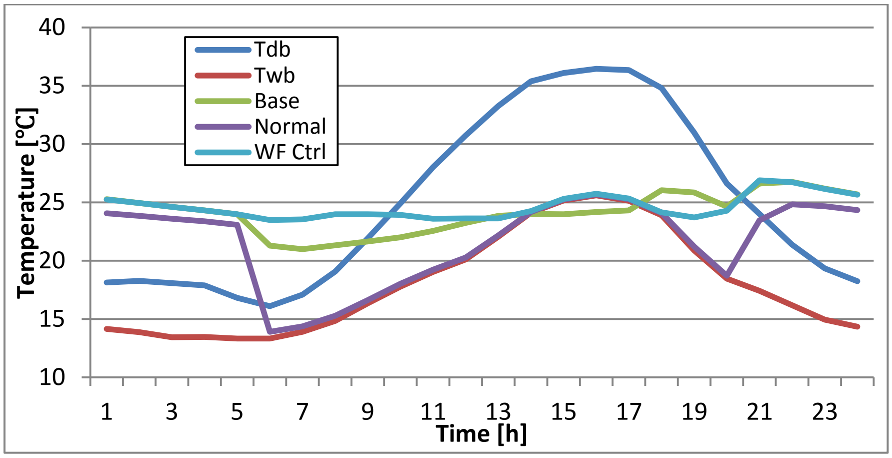


c) Office – Hot-dry

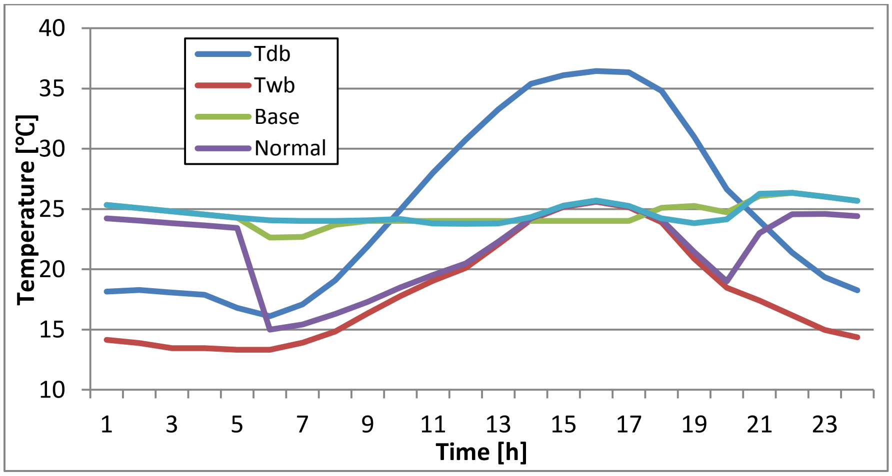
Figure 7.8 Variations of indoor mean air temperature



d) Cafeteria – Warm-moderate



e) Classroom – Warm-moderate



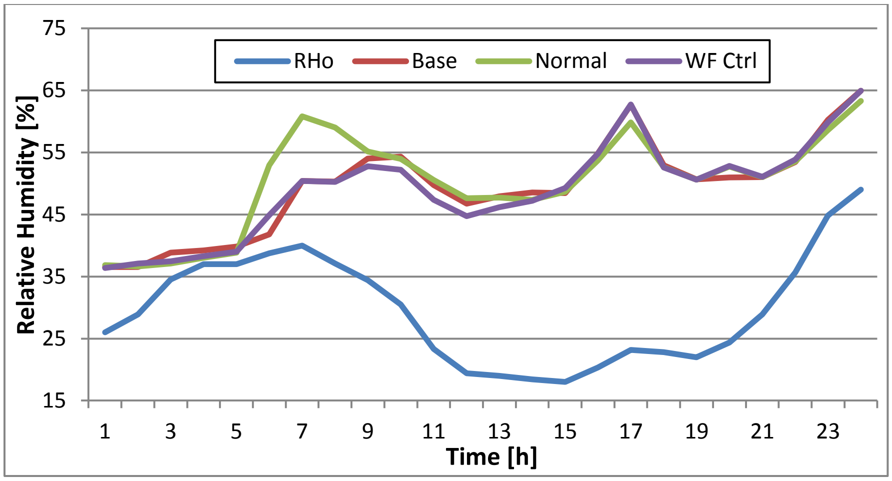
f) Office – Warm-moderate

Figure 7.8 Variations of indoor mean air temperature (con't)

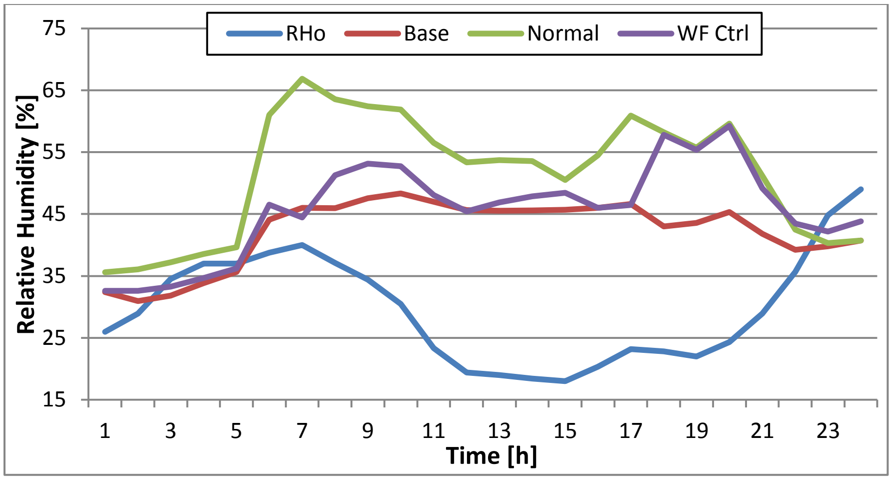
Relative humidity

Indoor relative humidity varied significantly in both climates. The normal case, which was a typical operation of PDEC towers, showed a sharp increase up to 66.8% in Yuma and 84.9% in Sacramento when the PDEC system began to operate. The maximum relative humidity of the normal case in Sacramento was greater than that of the PDEC only cases without any other cooling systems. This tendency seemed to be related to the fact that the air flow rate of PSZ-AC unitary system increased thus humid outdoor air, which was 73.5%RH, increased while that in Yuma was almost the same due to dry outdoor air condition. The indoor relative humidity in Yuma then dropped to 47% in the cafeteria, 50.5% in the classroom, and 49.6% in the office by 3PM while the PDEC only cases gradually increased indoor humidity level. Since the PDEC air flows were mixed with air flows from the primary cooling system in these runs, the relative humidity was lower than that of PDEC air flows. The same tendency was also observed in Sacramento.

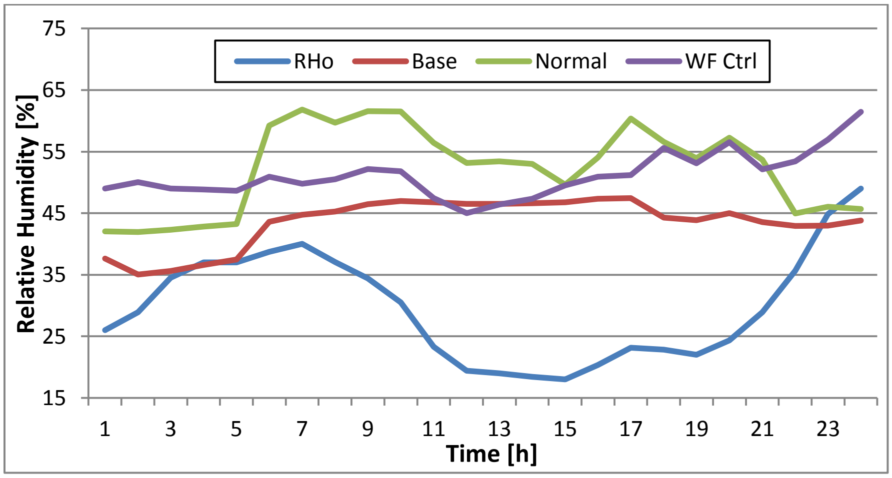
The water flow rate control case showed reasonable variation in the relative humidity. No sharp increase in the indoor humidity level was observed in this particular case since it adjusted the water flow rates according to the outdoor air conditions to achieve the setpoint temperature. This control type increased the indoor humidity level during the afternoon hours when the water flow rate increased. The indoor relative humidity, however, during the afternoon hours in Yuma was within an acceptable range at 59.3% in the classroom, 55.6% in the office, and 62.7% in the cafeteria. It was also seen that this case significantly increased the indoor relative humidity up to 78% in the classroom in Sacramento. The PDEC system in Sacramento showed a tendency to reach saturation due to the humid outdoor air, so that a very high level of indoor relative humidity between 12PM and 7PM was observed in this case. Thus it was necessary to maintain the humidity level of the PDEC air flow below a certain value when faced with a humid climate.



a) Cafeteria – Hot-dry

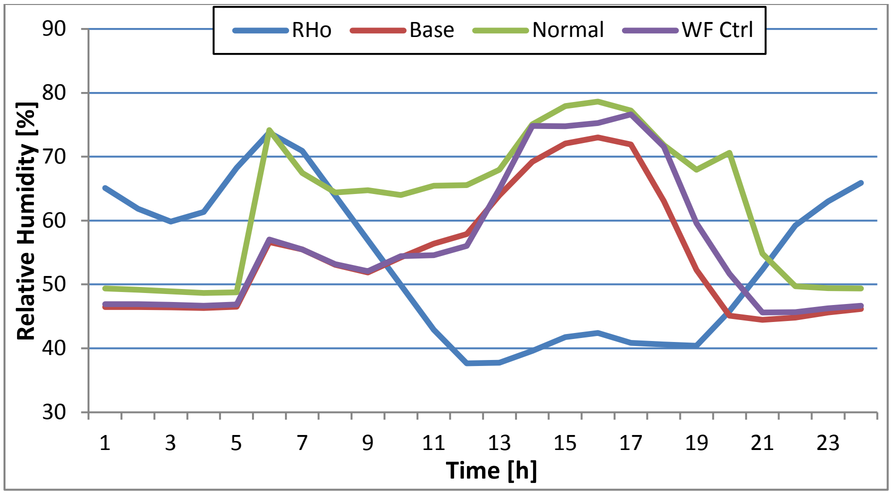


b) Classroom – Hot-dry

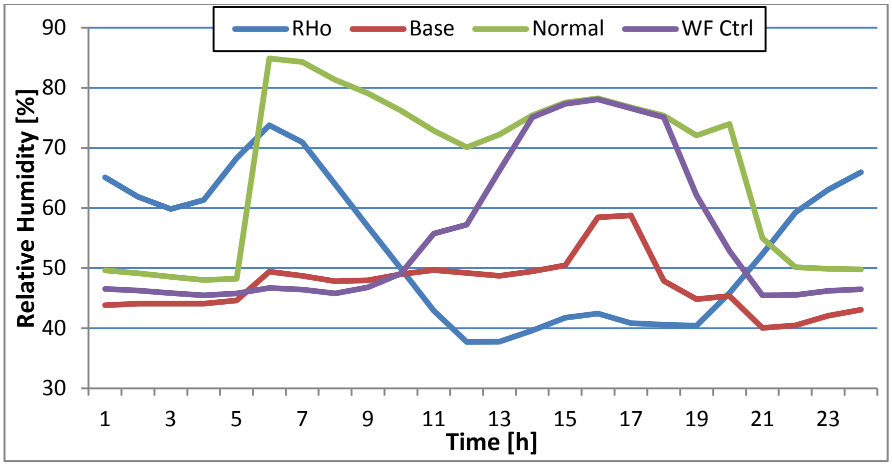


c) Office – Hot-dry

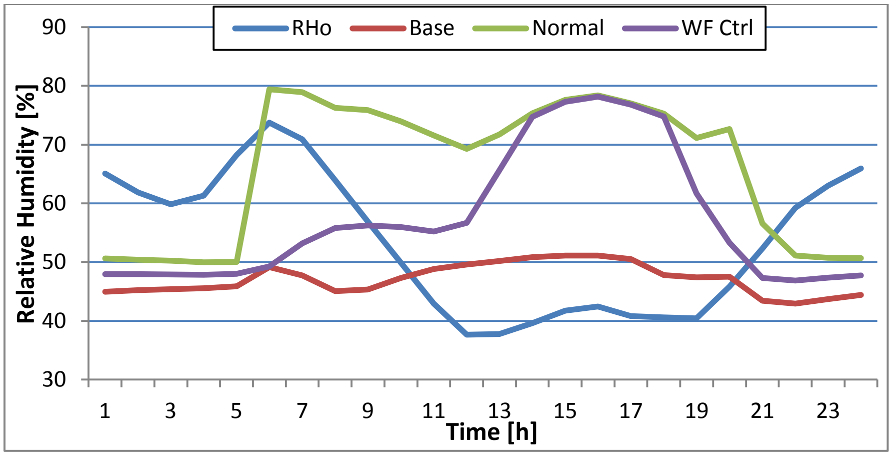
Figure 7.9 Variations of indoor relative humidity



d) Cafeteria – Warm-moderate



e) Classroom – Warm-moderate

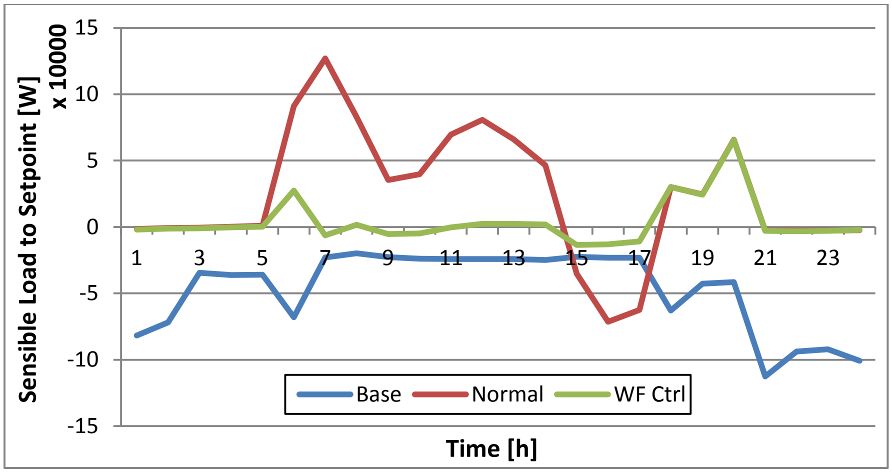


f) Office – Warm-moderate

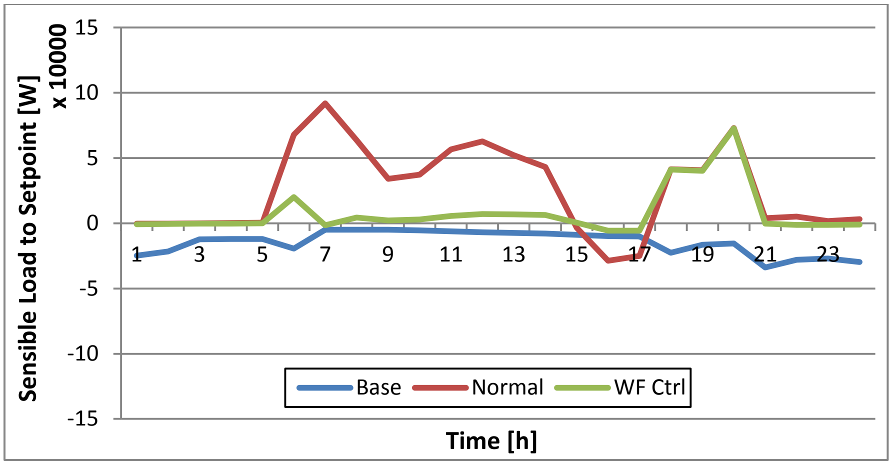
Figure 7.9 Variations of indoor relative humidity (con't)

Sensible cooling load to setpoint

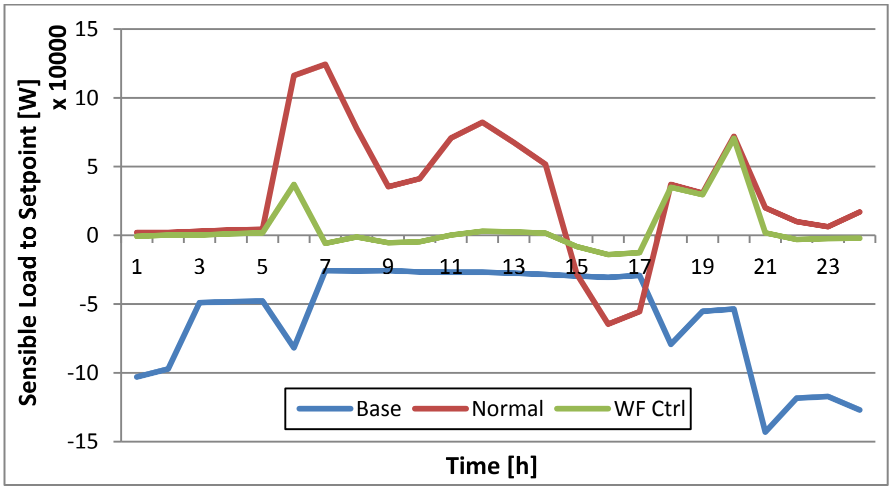
The water flow rate control case substantially decreased the sensible cooling load required to meet the indoor setpoint temperature. The normal case caused a significant increase in the heating loads of the spaces as shown in Figure 7.9. The heating loads for the normal case in Yuma peaked at 7AM at 126.9kW in the cafeteria, 92kW in the classroom, and 124.5kW in the office. It was also observed that the PDEC towers in the normal case resulted in significantly higher space loads between 3PM and 6PM since the water requirements to achieve the maximum temperature drop at these particular hours were greater than the maximum water flow rate of 200l/h in this case, and also the wet-bulb temperatures were floating the setpoint temperature. In Sacramento, the normal case required significantly more heating for the summer cooling day. These heating needs peaked at 8PM at 344.4kW in the cafeteria, 235.8kW in the classroom, and 338.8kW in the office. The normal case also significantly increased the heating loads during the morning hours. The water flow rate control case, however, reduced a large portion of the zonal loads that the primary cooling system should meet. Sensible cooling loads to the indoor set point temperature in this case were the lowest with no significant rises or drops between 7AM and 5PM in Yuma and between 7AM and 2PM in Sacramento. This control type then increased the heating loads late afternoon. Since the wet-bulb temperatures in these hours were greater than the setpoint temperature of 24℃ and the mass flow rate of PDEC towers increased as wind speeds increased. It was thus concluded that PDEC towers with a more responsive control algorithm can achieve more reduction in cooling demands for the primary cooling system.



a) Cafeteria – Hot-dry

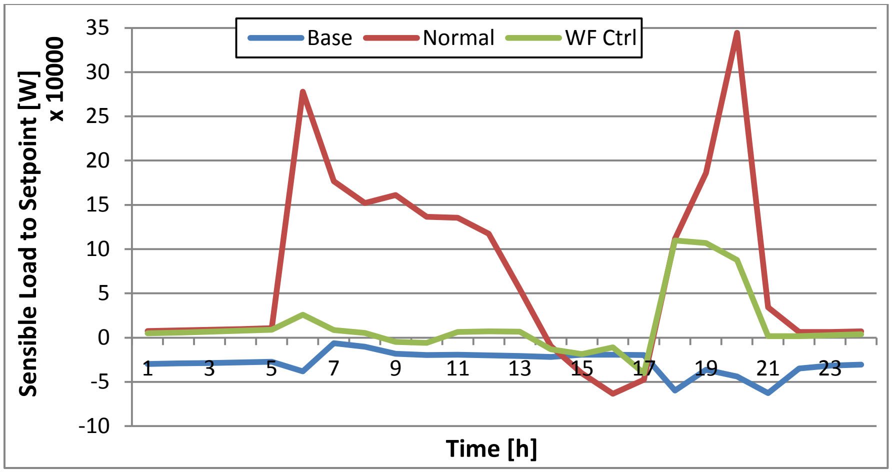


b) Classroom – Hot-dry

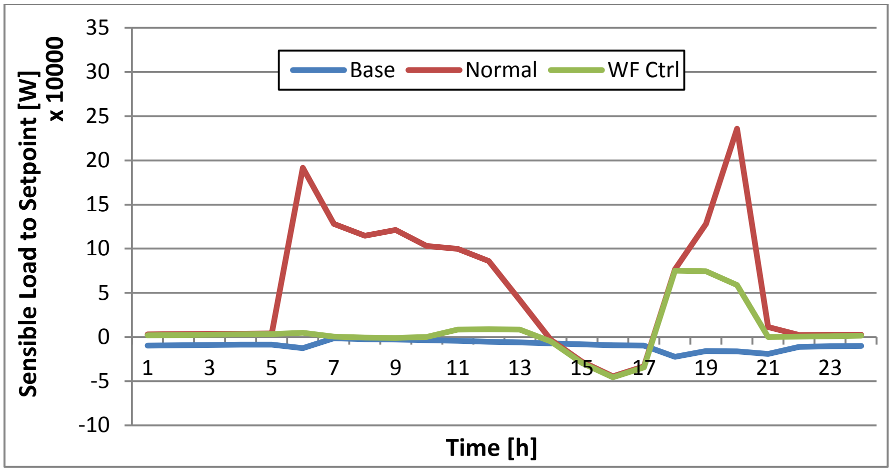


c) Office – Hot-dry

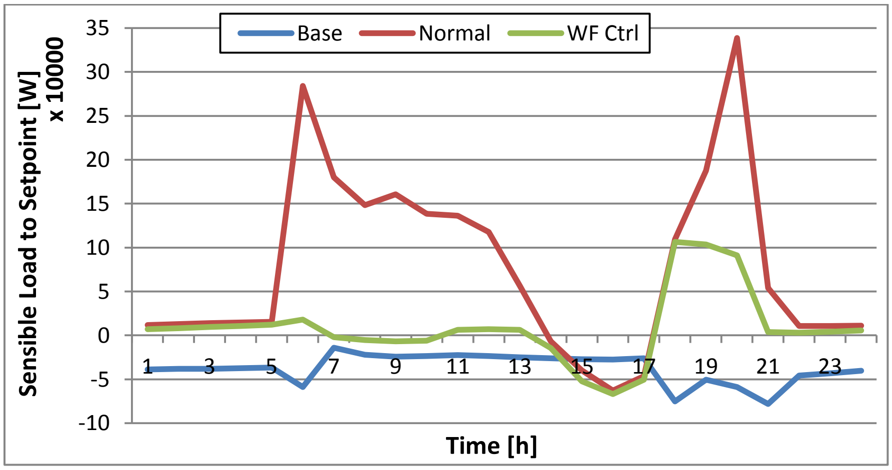
Figure 7.10 Variations of sensible load to indoor setpoint temperature



d) Cafeteria – Warm-moderate



e) Classroom – Warm-moderate

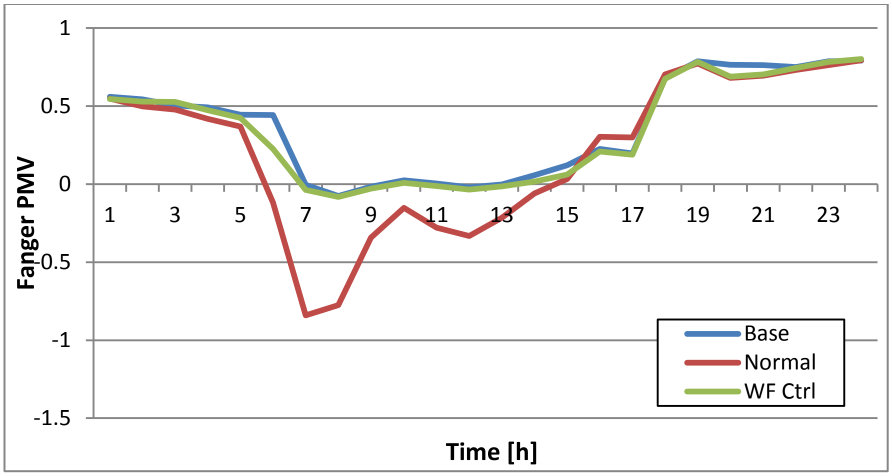


f) Office – Warm-moderate

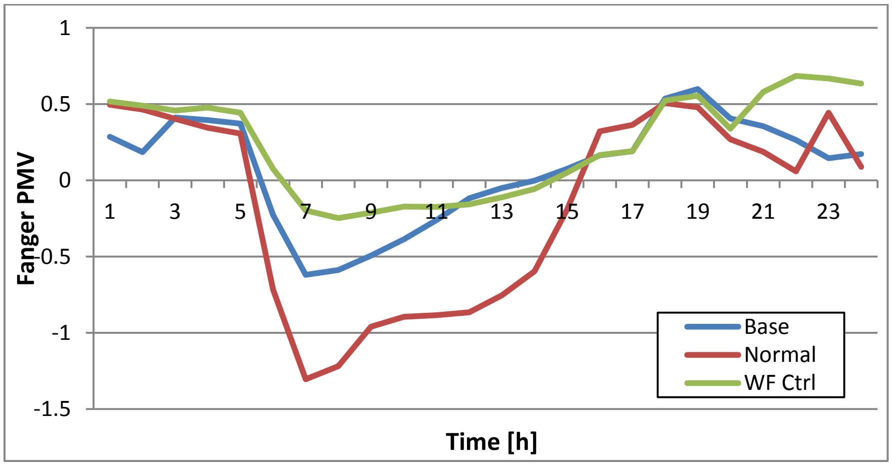
Figure 7.10 Variations of sensible load to indoor setpoint temperature (con't)

Thermal comfort

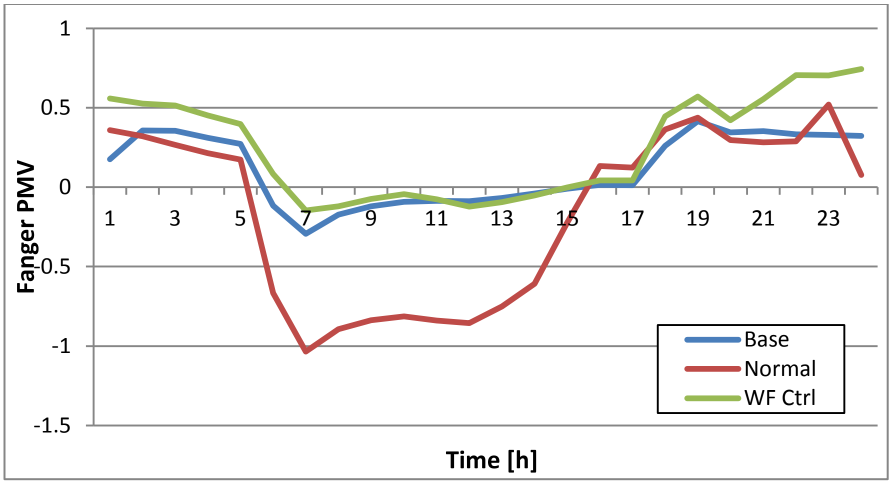
PMVs in the water flow control case showed the best performance overall. When the PDEC towers were controlled in the normal fashion in conjunction with primary cooling system, this combined system could not improve thermal comfort of occupants in the spaces. In Sacramento, the Fanger PMV values dropped to the very cold region (which is classified as -3.0) in the classroom which had a PMV of -2.7 and the office which had a PMV of -2.4. These values were worse than the PDEC only cases described in the previous subsection. Since the primary cooling system also tended to overcool the spaces during the early morning hours, the thermal environment in these spaces was predicted to be very cold. In Yuma, the Fanger PMV values in the normal case showed lower values than in the PDEC only cases. The water flow control case, however, resulted in relatively constant PMVs during most of occupied hours in both Yuma and Sacramento. The PMVs in Sacramento tended to be variable during the afternoon hours due to the very high indoor relative humidity and the larger PDEC air flow than during the morning hours. No considerable difference in the Fanger PMV was observed between base case and water flow rate control case, and these values were maintained at levels that ranged between neutral and slightly warm.



a) Cafeteria – Hot-dry

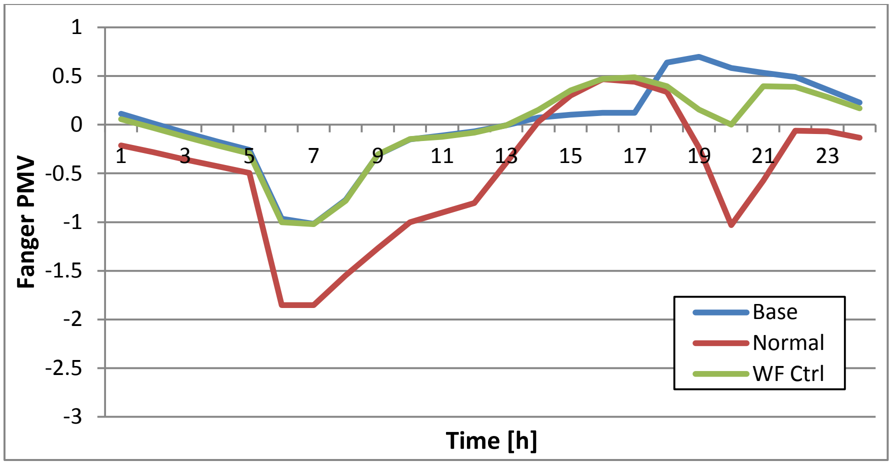


b) Classroom – Hot-dry

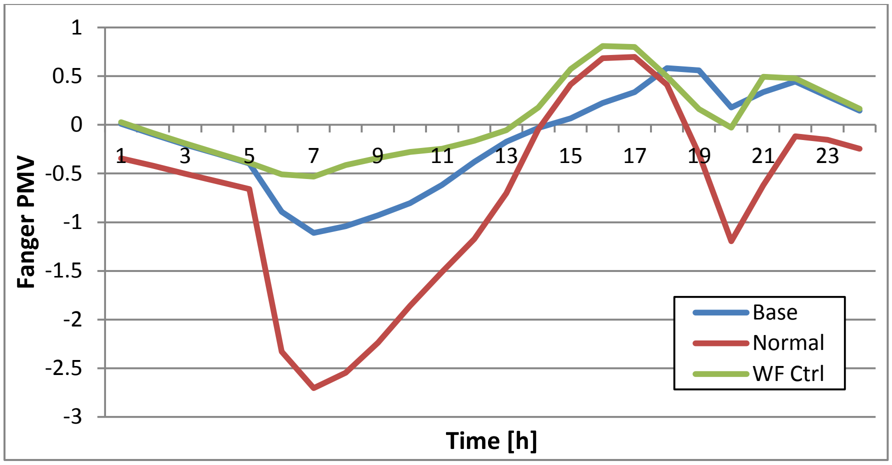


c) Office – Hot-dry

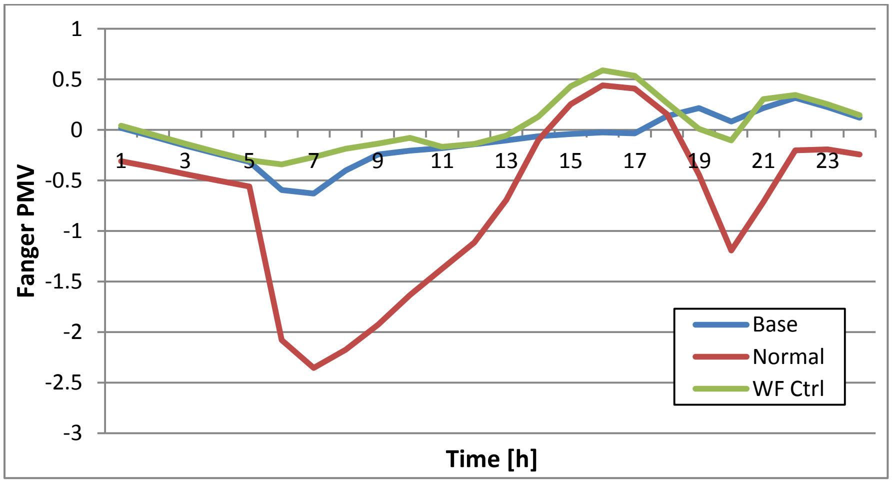
Figure 7.11 Variations of thermal comfort of occupants



d) Cafeteria – Warm-moderate



e) Classroom – Warm-moderate



f) Office – Warm-moderate

Figure 7.11 Variations of thermal comfort of occupants (con't)

7.3 Summary

PDEC towers have been reported to achieve significant energy savings. Many attempts have thus been made to integrate these systems into buildings to improve the efficiency of their cooling systems. Some of the PDEC applications have been successfully integrated into buildings, but there have been also some applications that failed to achieve ultimate goals of energy savings. In addition, the large amount of water consumption of these systems has been reported to be one of the main barriers to the integration of these systems in a more widespread fashion. To investigate solutions that could resolve these problems, the actual condition of the air flow leaving a PDEC system must be determined. Since no models exist in the literature which accurately portrays the conditions of the air leaving a PDEC system, a mathematical model was developed in the previous chapter that is capable of predicting accurate air conditions at the PDEC towers outlet. The equations were then implemented into the whole building energy simulation program EnergyPlus so that various potential solutions can be investigated.

Various case studies on a typical summer day in two different climates were performed to investigate how the PDEC systems affect the indoor environment and energy performance, and to find out what kinds of solutions could be successful to accomplish energy savings in buildings. Meanwhile, a simple control algorithm to enhance the efficiency of PDEC systems was presented, and several control options such as air mass control, water flow control, and temperature control, as well as utilization of a secondary cooling system were considered. Comparisons among a number of alternatives were made to see how each alternative affect the energy performance and indoor environment.

In summary, the typical controls being used for PDEC systems are not as energy efficient as they could be, waste water, lead to heating loads in the summer, and have a high degree of PMV variability. In contrast, the water flow control system presented in this chapter is a definite improvement in that it improves the energy consumption, water consumption and PMV over the typical controls. In fact, it improves everything except water consumption in comparison to a conventional forced air system. Therefore, the performance of PDEC towers should be adequately controlled and carefully designed to immediately respond to the variable cooling demands of a space.

This chapter presents a potential solution that could resolve problems with PDEC towers defined. However, the solution needs to be verified if it could accomplish such improvements in other building types and different climates. Thus, further case studies for a longer period of time will be performed to analyze the overall impact of PDEC towers on energy performance in a number of climatic regions as well as in a number of types of buildings in the following chapter.

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CHAPTER 8: ENERGY SAVING POTENTIAL IN BUILDINGS

In chapter 7, case studies on a typical summer day in two different climatic regions were performed to investigate how typical PDEC systems affect the indoor environment as well as the energy performance in buildings and to examine some potential solutions that might overcome the limitations of PDEC towers. A number of problems with PDEC towers were defined in the previous chapters such as inconsistent cooling performance, high humidity of the air leaving the PDEC tower, and excessive water consumption, and various strategies for controlling the performance were tested. Among those alternatives, the one that utilized water flow rate as a key parameter was shown to be reliable, efficient, and economical.

While the results of the previous chapter are encouraging, the overall impact of these systems could be different from depending on numerous conditions such as climates, building envelope, and building energy systems design. The impact of PDEC systems in these different scenarios on building performance should be analyzed so that they can be successfully integrated into buildings. In this chapter, the energy performance of PDEC systems employing the water flow rate control algorithm for longer time periods will be investigated to verify the applicability of PDEC systems as a cooling system in buildings.

8.1 Simulation Description

In the previous chapter, three control algorithms, temperature control, water flow control, and mass flow control, were proposed and tested in an effort to improve the performance of PDEC towers as well as indoor thermal environment. Based on these results, the water flow rate control was shown to be the most effective in that it performed the best at reducing a large portion of cooling loads and improving thermal comfort of occupants in the spaces. In a very hot-dry region, the PDEC towers were able to maintain a very comfortable indoor environment, achieving tremendous energy savings and minimizing water consumption. In contrast, the PDEC towers could not guarantee a comfortable thermal environment in a humid climate without the aid of conventional HVAC system. Many of the occupied hours in the humid climate were uncomfortable when the PDEC towers attempted to meet the entire cooling loads in a building since the performance of PDEC towers consistently varied with the outdoor weather conditions. Thus, under certain conditions, PDEC towers were more appropriate for reducing a portion of the cooling loads while a conventional cooling system meets the rest of the cooling demands. The impact of PDEC systems on the indoor environment and energy performance on a typical summer day were compared in two different climates such as Yuma in Arizona and Sacramento in California in the previous chapter. The focus of this chapter is to extend the summer single day simulations of the previous chapter to longer-term simulations for different climates and building types to show the applicability and energy savings potential of PDEC systems.

Four different climates within the US were studied. In addition to Yuma and Sacramento, two more climatic regions, Phoenix Deer Valley, Arizona and El Paso, Texas, were also considered. According to the ASHRAE climatic zone descriptions, these climates are classified as very Hot-Dry (Yuma, AZ), Hot-Dry (Phoenix Deer Valley, AZ), Warm-Dry (El Paso, TX), and Warm-Marine (Sacramento, CA). The energy performance of the PDEC system as well as indoor environment that it created in these four different climates was compared to determine how effective PDEC systems were in each particular climate. Table 8.1 and 8.2 list the maximum, minimum, and daily average values for the dry bulb temperature and the relative humidity for an average annual period in each of these locations.

Three different types of buildings were also considered. PDEC towers typically treat a large amount of air, and the air mass flow rate from these systems can be highly variable. Those buildings with high occupancy, high movement frequency, high internal heat gains, large volumes, and adequate water resources can thus be potential candidates for the implementation of this technology because they tend to require high-capacity energy systems to handle their variable load characteristics. The primary school building, which was considered for the short-term simulations in the previous chapter, was included as it exhibits these characteristics. An office building was also included since these buildings have a high occupancy level, high movement frequency, and high internal heat gains. Finally, a strip mall building was also considered because this type has a high frequently of people movement and has a large volume. While PDEC towers can be integrated into many of commercial buildings, these three types of buildings were considered in this long-term energy performance analysis.

The input files used for this study were again based on the US Department of Energy EnergyPlus benchmark files. This study was intended to compare the overall impact of PDEC towers on building performance for particular building types in specific climates. While the performance of PDEC towers can significantly vary with a number of variables, especially outdoor air conditions, this study was intended to be an initial look at the impact of using PDEC towers in buildings rather than an exhaustive, definitive study of implementing PDEC systems in every building type and climate. The modeling of the building envelope, the internal heat gains, and the building energy systems in each individual building was thus set to be almost same between the base cases and the PDEC cases. The most significant change to the input files was the reduction of the minimum air flow fraction for the primary HVAC systems from 0.3 to 0.05 when the PDEC system was used since PDEC towers provided a large amount of fresh air to the spaces. Naturally, weather conditions were a key parameter in the building load calculations in this case study.

Two modifications of the PDEC systems were made to address particular climates. The weather conditions during the morning and evening hours on a typical summer day in Yuma and Sacramento were not favorable to PDEC operations. The running hours of PDEC towers were thus set as 7AM to 8PM in order to reduce the potentially negative impact on indoor environment and building load calculations that the PDEC might have in these climates. In addition, the maximum relative humidity and the minimum ambient temperature were set to be different. These fields were set to be 40% and 28°C in the hot-dry climates, i.e., Yuma and Phoenix Deer Valley, and 50% and 26°C in the warm climates, i.e., El Paso and Sacramento, respectively. In addition, the simulation run period was set to the 6-month period from May 1 through October 31, and all standard holidays or special day rules were applied. The total carbon equivalent emission factor from carbon dioxide was set to 0.2727 kg/kg, and the carbon dioxide emission factor from electricity and natural gas were set to 341.7 g/MJ and 52.1 g/MJ, respectively, for the simulations.

Three parameters were tracked to illustrate the effectiveness of the PDEC towers in maintaining an acceptable indoor environment: the amount of time when the setpoint temperature was not met during occupied hours, the amount of time during which the space conditions were not comfortable during occupied hours, and the amount of time when the relative humidity was below 60% for the entire hours of the run period in a representative space in each type of building. These three parameters were monitored for the entire run period and compared to see how the PDEC systems impacted the overall thermal environment of a space According to conventional wisdom, PDEC towers are known to improve indoor environmental quality in that they deliver a large amount of fresh air into a space and improve thermal comfort levels by increasing air movement within a space. However, PDEC towers can also lower the indoor thermal comfort level since they can significantly increase the humidity level within a space. The focus of this chapter is to determine when the PDEC tower system is beneficial and when it is detrimental to the energy cost of a building.

Table 8.1 Monthly statistics for dry bulb temperature (°C) in four different climates (Adapted from TMY3 weather statistics)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Very Hot-Dry: Yuma AZ												
Maximum	28	27	33.3	34	41.7	42.8	50.6	46	43	38.9	33	22.8
Day:Hour	18:16	17:15	20:15	16:16	6:16	18:14	4:17	10:17	7:17	1:14	13:16	1:14
Minimum	4	5	8.3	11	15	20	21.7	24	18	12.2	8	3.3
Day:Hour	8:07	14:06	12:07	5:06	17:06	1:04	4:06	21:07	22:06	2:07	2:05	11:06
Daily Avg	15.8	14.7	20	22.3	26.5	30.4	34.5	34.2	31.2	24.3	20.2	13
Hot-Dry: Deer Valley, Phoenix AZ												
Maximum	24	24	26.1	37	38	44	45	43	43	36	27.3	23
Day:Hour	2:16	4:15	5:17	2:16	7:16	5:15	2:14	9:17	14:15	1:16	15:14	1:13
Minimum	2	2	4.4	8	16	19	22	23	19	11.6	6	3
Day:Hour	8:07	9:06	17:07	1:05	13:04	14:05	6:02	23:05	0:05	6:07	10:05	12:07
Daily Avg	12.9	12.4	13.5	23.3	27.7	32.3	33.4	33.3	31.5	23.7	16.1	12.5
Warm-Dry: El Paso TX												
Maximum	20.6	23.3	25	32.2	35	38.9	38.3	37.2	33.9	32.8	23.9	18.3
Day:Hour	3:15	20:15	21:16	21:14	19:14	2:16	1:17	7:16	19:14	1:15	3:16	10:15
Minimum	-4.4	-5.6	-3.9	3.3	9.4	15	17.8	16.7	8.3	6.7	-0.6	-4.4
Day:Hour	3:07	3:07	2:05	12:06	2:06	13:05	5:06	7:06	6:06	11:06	17:04	3:07
Daily Avg	8.1	10.3	12.5	19.2	23.8	27.9	27.5	26.3	23.4	18.3	11.2	6.8
Warm-Marine: Sacramento CA												
Maximum	19.4	21.7	25	29.4	34.4	38.9	40	38.3	39.4	31	19.4	15
Day:Hour	21:14	2:16	7:14	13:16	4:15	22:16	1:16	3:16	2:15	16:15	13:16	1:14
Minimum	-1.7	0	1.1	3.3	6.1	10.6	11.1	11.7	10.6	6	1.1	-2
Day:Hour	1:04	5:10	19:06	18:05	0:05	13:05	16:22	23:05	17:06	2:07	21:04	2:06
Daily Avg	8.5	10.3	12	14.2	18.4	21.1	23.5	22.5	21	16.8	10.5	7.5

Table 8.2 Monthly statistics for relative humidity (%) in four different climates (Adapted from TMY3 weather statistics)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Very Hot-Dry: Yuma AZ												
Maximum	81	94	89	100	68	66	82	94	89	89	82	100
Day:Hour	2:05	22:23	15:02	23:17	0:18	14:07	16:05	21:07	4:04	19:05	9:06	5:04
Minimum	12	8	8	8	8	9	7	11	9	11	7	21
Day:Hour	8:14	13:18	19:17	5:18	6:19	23:21	21:13	10:18	3:22	16:16	22:15	15:16
Daily Avg	36	37	33	31	25	22	30	45	35	39	35	60
Hot-Dry: Deer Valley, Phoenix AZ												
Maximum	100	100	96	87	48	83	100	74	61	94	94	54
Day:Hour	11:06	13:23	1:19	1:02	23:06	2:01	6:02	5:21	18:06	18:03	4:23	8:05
Minimum	13	17	11	5	4	8	10	6	9	9	8	5
Day:Hour	2:16	1:13	12:16	2:15	14:18	8:15	2:17	1:15	14:16	9:21	20:16	15:14
Daily Avg	53	55	49	25	17	21	35	27	27	37	38	26
Warm-Dry: El Paso TX												
Maximum	100	93	96	71	83	93	100	97	100	97	97	96
Day:Hour	15:21	13:11	11:01	18:08	1:05	5:01	16:24	14:03	4:05	9:07	3:06	4:02
Minimum	9	9	9	7	11	6	14	14	14	10	12	7
Day:Hour	3:17	21:15	22:13	16:17	14:16	1:16	2:19	3:17	18:18	7:15	18:12	18:13
Daily Avg	49	38	32	25	28	29	50	45	51	53	45	47
Warm-Marine: Sacramento CA												
Maximum	100	100	100	100	100	100	100	97	100	100	96	100
Day:Hour	1:07	13:07	5:17	1:05	1:04	4:06	16:22	9:04	0:24	20:06	1:07	1:03
Minimum	30	28	21	22	12	8	18	11	13	12	34	27
Day:Hour	21:14	10:16	3:16	22:15	7:16	1:18	10:16	19:17	18:17	5:15	20:15	0:14
Daily Avg	83	73	70	72	59	57	53	58	57	62	77	80

8.2 Primary School

The primary school reference building is a one-story 6,871m^2 area building and is divided into 23 zones. The indoor setpoint temperature is defined as 24°C between 6AM and 9PM with 9 hours of set back at 27°C for all week days and 27°C for the entire hours of the weekends and on holidays. The over-sized PDEC towers as defined in the previous chapter cause a significant increase in the building cooling loads and uncomfortable thermal conditions when a large volume of air warmer than the indoor setpoint temperature was delivered to the space by the PDEC towers. The areas of the wind catcher and the tower cross-section were thus set to be smaller than the previous ones to reduce the occurrences of this particular situation as illustrated in Table 8.3 which summarizes the input data for these cases. The minimum indoor temperature, which acts as a set point temperature of PDEC towers, was set to be 23.5°C based on the success with this value in the previous chapter. The PDEC towers were set to operate from 7AM to 8PM for all six months of the simulations. The maximum relative humidity and the minimum ambient temperature were different depending on climates while the other main input fields remained same for all cases.

Table 8.3 Main input parameters for PDEC towers in three representative spaces

Type of rooms	Classroom	Office	Cafeteria
Water flow rate [l/h]	200	200	200
Effective tower height [m]	5	10	8
Minimum indoor temperature [°C]	23.5	23.5	23.5
Water loss [%]	5	5	5
Air flow loss [%]	5	5	5
Rated pump power consumption [W]	150	250	250
Area of wind catcher [m^2]	4	6.25	6.25
Tower cross-sectional area [m^2]	12.25	16	16
Diameter of water droplet [㎛]	30	30	30
Maximum relative humidity [%]	40 (50)	40 (50)	40 (50)
Minimum ambient temperature [°C]	28 (26)	28 (26)	28 (26)

8.2.1 Energy performance

A significant reduction in electricity for cooling was achieved in all climates when the PDEC system was used. As seen in Table 8.4, the percentage reductions in cooling electricity are 33.44% in Yuma, 45.41% in Deer Valley, and 40.76% in El Paso. It is very interesting to note that the greatest energy saving in cooling electricity for 6-month period on a percentage basis was actually achieved in the warm-marine climate of Sacramento where the percentage reduction was 48.27%. It was likely that the PDEC towers in the warm-marine climate were able to meet a larger portion of cooling loads since the cooling requirements in Sacramento were smallest due to the lower temperature differences between the indoor and the outdoor air. In addition, it is also interesting that the lowest reduction of 33.44% was given in the very hot-dry climate. This is because that the weather conditions on many of the days during July and August in Yuma were not appropriate for PDEC tower operation due to the relatively high ambient wet-bulb temperature. Considerable reductions in fans electricity were also seen in all climatic regions since cooling loads in the spaces in PDEC cases decreased.

The savings in HVAC and fan energy also translate into a considerable reduction in the energy end use. Energy savings in the total site energy in the four climates are 12.49% in Yuma, 16.78% in Deer Valley, 11.11% in El Paso, and 10.15% in Sacramento. The greatest reduction in total site energy was achieved in the hot-dry climate of Deer Valley where the use of the PDEC system reduced total site energy consumption by 396.81GJ. Since the proportion of cooling to total site energy in Deer Valley was bigger than the other climates, the greatest reduction in total site energy was given in Deer Valley rather than Sacramento. Similarly, the greatest reduction in the electricity intensities per space floor area was seen in Deer Valley as decrease 43.67%. In addition, similar trend is seen in the percentage reductions in the peak electrical demand where the largest reduction in the peak electrical demand is observed in Deer Valley. Since many commercial buildings have a contract with electric companies at a certain rate, building end use in electricity was necessary to be maintained at least below the rate to avoid over-rated additional cost when it exceeds the contracted rate, which could be seen during summer days due to rise of space cooling demands.

In contrast, the carbon dioxide production and water consumption significantly increase in all of the climates. As seen in the previous chapter, PDEC towers could cause heating loads due to a large mass flow rate and a bigger temperature differences between PDEC flows and the spaces, causing to run heating facilities in this particular case. In fact, reduction of the carbon dioxide production and various by-products from fuels used in buildings is known to be one of the main advantages of PDEC integration.

In addition, PDEC towers can also increase buildings loads when they are inappropriately designed by either overcooling a space or heating a space because the exit conditions are warmer than the space conditions as shown in the previous chapter. The primary school building consists of 23 zones, and a PDEC tower was integrated into almost all of the individual zones. The impact of these tendencies in a building with a large number of zones will likely be greater than with a smaller number. As a result, the carbon dioxide production with the PDEC system increases in all of the climates. The maximum increase in the carbon dioxide production is 52.74% in Sacramento, and the minimum increase is 40.77% in Deer Valley.

Table 8.4 Comparisons of the energy performance of a primary school with a conventional HVAC system and PDEC integrated system under different weather conditions

	Base	PDEC	Reduction (%)	Base	PDEC	Reduction (%)
Climates	Very Hot-dry			Hot-dry		
Electricity: Cooling [GJ]	837.58	557.52	33.44	793.8	433.3	45.41
Electricity: Fans [GJ]	105.69	90.01	14.84	110.93	76.29	31.23
Total Site Energy [GJ]	2403.36	2103.15	12.49	2364.54	1967.73	16.78
Intensity: HVAC [MJ/m^2]	137.28	94.24	31.35	131.67	74.17	43.67
Peak Electrical Demand [GJ]	2210.35	1914.6	13.38	2171.64	1776.49	18.20
Water Supplied by Utility [m^3]	436.9	8890.64	-95.09	436.9	10127.56	-95.69
CO2: Facility [kg]	445937.1	664186	-48.94	438297.4	616991.7	-40.77
Climates	Warm-dry			Warm-marine		
Electricity: Cooling [GJ]	458.94	271.87	40.76	342.84	177.36	48.27
Electricity: Fans [GJ]	103.05	68.39	33.63	77.72	64.77	16.66
Total Site Energy [GJ]	2029.21	1803.73	11.11	1914.78	1720.45	10.15
Intensity: HVAC [MJ/m^2]	81.79	49.52	39.45	61.21	35.24	42.43
Peak Electrical Demand [GJ]	1827.7	1605.98	12.13	1683.28	1504.86	10.60
Water Supplied by Utility [m^3]	436.9	5001.19	-91.26	436.9	4513.43	-90.32
CO2: Facility [kg]	370921.7	559065	-50.72	344004.4	525442.1	-52.74

A huge increase in the water consumption in the PDEC cases appeared in all of the climates as expected. A large amount of water use is one of main limitations of PDEC towers, so a control algorithm must be employed to achieve the maximum cooling output with the minimum water use. While the performance control did save a large quantity of water, all of the PDEC cases still increased water consumption. The water consumption in base cases was 436.9m^3, and this value is approximately 5% of the total water consumption of the PDEC towers in the Deer Valley, 8.74% of the water consumption in El Paso, and 9.68% of the water consumption in Sacramento. Since the PDEC towers in a hot-dry area must meet large cooling requirements for the spaces, the water consumption in this particular climate increases significantly. It was note that the water consumption in Deer Valley was greater than in Yuma because overall running hours in Yuma were considerably smaller than in Deer Valley due to higher ambient wet-bulb temperatures in the afternoons. The water consumption in El Paso was approximately 50% of that in Deer Valley and 56% of that in Yuma. The PDEC towers in the warm climate are able to achieve significant energy savings with less water consumption than the dry climates. Thus, the PDEC systems can be used in various climates and are not limited to hot-dry regions.

8.2.2 Indoor environment

In general, it can be said that the base cases maintained a better indoor environment. The number of hours that the indoor setpoint temperature cannot be achieved during occupied hours decreased 76.1% in El Paso and 17.19% in Yuma when the PDEC system was used. It was because PDEC flow did not have a significant impact to the variation of building loads, so that variable building loads were likely within capacities of the primary cooling system. However, it substantially increased the number of hours during occupied hours where the setpoint was not achieved by 462.3% in Sacramento and 47.05% in Deer Valley. It was because that, in Deer Valley, most of occupied hours were within the PDEC operational range, which PDEC towers continually supplied flows at 0.5°C lower temperature than indoor setpoint temperature, so that they increased cooling loads during some of morning hours, which cooling loads were relatively smaller. The percentage increase in the number of hours that setpoint was not met significantly increased in Sacramento. It was because since outdoor wet-bulb temperature during many of occupied hours was in between slightly lower and slightly higher than the PDEC setpoint, they tended to be turned on and off during afternoon hours, causing large variation in the indoor temperature. In addition, the number of hours not in a comfortable range during occupied hours based on ASHRAE 55-2004 increased in all climates with the highest percentage increase being 78.27% in Sacramento. On the other hand, the total hours for the entire hours of the run period that the indoor relative humidity in a classroom was less than 60% decreased 5.04% in Yuma, 3.15% in Deer Valley, 1.61% in El Paso, and 1.78% in Sacramento when the PDEC system was used. It is interesting to find that these values tended to increase in hot-dry areas rather than the warm-dry and the warm-marine humid areas. This is because the dry areas required much more water to meet the setpoint temperature of 23.5°C, which increased the relative humidity of the air exiting the PDEC system. The PDEC system also operates longer in the dry areas than in the other climates. The biggest difference between the base case and PDEC case was found in Sacramento since relative humidity of PDEC flows during most of PDEC operation hours was greater than 90%.

Table 8.5 Comparisons of the indoor environment between a typical primary school and a PDEC integrated primary school in different weather conditions

	Base	PDEC	Reduction (%)	Base	PDEC	Reduction (%)
	Very Hot-dry			Hot-dry		
Time Setpoint Not Met [Hours]	226.83	187.83	17.19	115.83	170.33	-47.05
Time Not Comfortable [Hours]	1222.83	1333.33	-9.04	1206.67	1303.67	-8.04
RH < 60% in a classroom [Hours]	4298.51	4081.91	5.04	4377.93	4239.86	3.15
	Warm-dry			Warm-Marine		
Time Setpoint Not Met [Hours]	228.33	54.67	76.06	60.17	338.33	-462.29
Time Not Comfortable [Hours]	1113.33	1340.17	-20.37	565.33	1007.83	-78.27
RH < 60% in a classroom [Hours]	4345.93	4275.98	1.61	4401.15	4322.78	1.78

8.3 Medium Office

The medium office reference building is a three-story rectangular 4,932m^2 building with an aspect ratio of 1.5. Each floor is identical and has 4 perimeter zones and a core zone. A multi-zone VAV system with reheat coils serves the heating and cooling loads in the all core zones as well as all perimeter zones. The floor areas of the core zone, east and west zones, and south and north zones were 983.54m^2, 131.26 m^2, and 207.34 m^2, respectively. The HVAC system was set to operate from 6AM to 10PM at 24°C with 8 hours setback at 26.7°C during weekdays, from 6AM to 6PM at 24°C with 12 hours setback at 26.7°C for Saturdays, and setback at 26.7°C for all 24 hours on Sundays and holidays. The PDEC towers were employed in the four perimeter zones in each floor. Since installation of PDEC towers to the core zones needed to model fluid flows through duct or any other facility to deliver the air, the core zones assumed with no PDEC towers in this study. Table 8.6 below shows the input fields used for these cases. The maximum relative humidity and the minimum ambient temperature differed between the dry areas and warm climate as can be seen in this table.

Table 8.6 Main input parameters for two different sizes of PDEC towers

Zones	North & South	East & West
Water flow rate [l/h]	200	200
Effective tower height [m]	12	10
Minimum indoor temperature [°C]	23.5	23.5
Water loss [%]	5	5
Air flow loss [%]	5	5
Rated pump power consumption [W]	250	200
Area of wind catcher [m^2]	9	6.25
Tower cross-sectional area [m^2]	25	16
Diameter of water droplet [μm]	30	30
Maximum relative humidity [%]	40 (50)	40 (50)
Minimum ambient temperature [°C]	28 (26)	28 (26)

8.3.1 Energy performance

The biggest energy saving is achieved in the hot-dry climate (Deer Valley) where the percentage reduction in the cooling electricity is 27.72% and fans electricity is 33.1%. Since most of occupied hours were within the range of PDEC operation, the portions of cooling loads that PDEC towers could reduce increased. A similar percentage reduction of 22.75% in cooling electricity and 31.34% in electricity for fans is achieved in the warm-dry climate of El Paso. Similar to the previous case, outdoor weather conditions in El Paso were suited to run PDEC towers during most of occupied hours. These total cooling energy reductions are 153.5GJ in Deer Valley, 102.89GJ in Yuma, 83.11GJ in El Paso, and 59.57GJ in Sacramento. In conjunction with the reductions in fan electricity, the reductions in the total site energy are 171.77GJ in Deer Valley, 113.43GJ in Yuma, 99.22GJ in El Paso, and 66.15GJ in Sacramento. Since the portion of cooling in Yuma was greater than that in El Paso, the percentage reduction in total site energy in Yuma was the second largest one. Similarly, the electricity intensity for HVAC per floor area and peak electrical demand also decreased.

A small reduction in carbon dioxide production in all climates is achieved while significant increase in water consumption is noted. The PDEC cases achieve small reductions in the carbon dioxide productions in all four climates and are predicted to produce 10.97% less carbon dioxide in Deer Valley, which was the biggest percentage reduction This percentage reduction in carbon dioxide productions is approximately 7.2% in both Yuma and El Paso and 5.26% in Sacramento. In fact, the predictions of carbon dioxide were directly related to the use of electricity and natural gas. Thus, it can be said that PDEC cases increased either electricity use or natural gas consumption. Considering reductions in electricity and much greater carbon dioxide emission factor for electricity such as 341.7g/MJ than that for natural gas such as 52.1g/MJ, percentage reduction in carbon dioxide production should be close to that in electricity. As a result, PDEC towers were likely significantly increased cooling loads. In addition, a large increase in water consumption is observed in all of the climates as expected. The water consumption in the base cases is only approximately 1% in Yuma, Deer Valley, and Sacramento in comparison with that in the PDEC cases. In addition, the PDEC towers in El Paso achieve significant energy saving with approximately 50% of the water consumption of the dry areas.

Similarly, the water consumption in Sacramento was the lowest, but the PDEC case in Sacramento still achieves a considerable energy saving.

Table 8.7 Comparisons of energy performance between typical medium office building and PDEC integrated medium office building in different weather conditions

	Base	PDEC	Reduction (%)	Base	PDEC	Reduction (%)
Climate	Very Hot-dry			Hot-dry		
Electricity: Cooling [GJ]	571.04	468.15	18.02	553.82	400.32	27.72
Electricity: Fans [GJ]	52.67	42.14	19.99	55.22	36.94	33.10
Total Site Energy [GJ]	1594.94	1481.51	7.11	1579.93	1408.16	10.87
Intensity: HVAC [MJ/m^2]	125.22	102.45	18.18	122.27	87.79	28.20
Peak Electrical Demand [GJ]	1578.47	1465.05	7.19	1563.47	1391.69	10.99
Water Supplied by Utility [m^3]	88.52	8510.51	-99.0	88.52	9729.28	-99.1
CO2: Facility [kg]	540222.3	501464.4	7.17	535094.5	476399.5	10.97
Climate	Warm-dry			Warm-marine		
Electricity: Cooling [GJ]	365.37	282.26	22.75	266.76	207.19	22.33
Electricity: Fans [GJ]	51.41	35.3	31.34	35.94	29.46	18.03
Total Site Energy [GJ]	1388.62	1289.4	7.15	1272.17	1206.02	5.20
Intensity: HVAC [MJ/m^2]	83.68	63.77	23.79	60.81	47.54	21.82
Peak Electrical Demand [GJ]	1371.9	1272.68	7.23	1255.07	1188.94	5.27
Water Supplied by Utility [m^3]	88.52	4952.43	-98.21	88.52	4350.74	-98.97
CO2: Facility [kg]	469648	435746.2	7.22	429747.4	407149.7	5.26

8.3.2 Indoor environment

PDEC cases appear to have a negative impact on the indoor environment in all of the climates. As seen in Table 8.8, the number of hours where the setpoint temperature was not met and when the conditions were considered uncomfortable significantly increases in all of the climatic regions. The values of these first two fields in the base case in Sacramento, which has the largest percentage increase, are only 11.67 hours and 2.67 hours as shown in Table 8.8. These values in the PDEC case for Sacramento increase to 204.83 hours and 99.33 hours, respectively. As described in the previous section, PDEC towers in Sacramento continued to be turned on and off during afternoon hours since outdoor air conditions were floating the border of

PDEC operational conditions. In contrast, a relatively small difference is noted between the base case and the PDEC case in El Paso where increases of 7.36% and 125.4% in the number of hours where the setpoint is not met and the number of hours where conditions are uncomfortable, respectively. Since cooling demands in El Paso are much smaller than the dry areas and the relative humidity stays fairly dry during occupied hours at this location, both the sensible and latent cooling capacity were relatively constant in comparison with the other climatic regions. In addition, the percentage reductions in the total hours that the indoor relative humidity was less than 60% were slightly greater in the dry areas than in the warm climates.

Table 8.8 Comparisons of indoor environment between typical medium office building and PDEC integrated medium office building in different weather conditions

	Base	PDEC	Reduction (%)	Base	PDEC	Reduction (%)
Climate	Very Hot-dry			Hot-dry		
Time Setpoint Not Met [Hours]	35.5	231.17	-551.18	33.17	143	-331.11
Time Not Comfortable [Hours]	120.33	336.17	-179.37	76.33	233.83	-206.34
RH < 60% in a classroom [Hours]	4144.1	3949.56	4.69	4361.34	4177.94	4.21
Climate	Warm-dry			Warm-marine		
Time Setpoint Not Met [Hours]	54.33	58.33	-7.36	11.67	204.83	-1655.18
Time Not Comfortable [Hours]	72.17	162.67	-125.40	2.67	99.33	-3620.22
RH < 60% in a classroom [Hours]	4294.76	4215.07	1.86	4407.33	4284.68	2.78

8.4 Strip Mall

The single story strip mall reference building has a floor area of 2,090m^2 and is divided into 10 individual zones. The floor area of each of the two large stores is 348.39 m^2, and that of each of the other eight small stores is 174.19 m^2. Each zone was controlled by a Packaged Single Zone Air Conditioner (PSZ-AC) for space cooling and gas furnace for heating. These systems are defined to operate from 6AM to 9AM at an indoor setpoint temperature of 24°C with 9 hours of setback at 30.0°C during the weekdays. On Saturdays, the indoor setpoint temperatures are set to 24°C from 6AM to 10PM with 8 hours set back at 30.0°C. For Sundays and holidays, the setpoint temperature is set to 24°C from 8AM to 7PM with 13hours set back at 30°C. Larger PDEC towers are employed in the two large stores, and the smaller PDEC towers are used in the other spaces as listed in Table 8.9 below.

Table 8.9 Main input parameters for two different PDEC towers

Zones	Larger	Smaller
Water flow rate [l/h]	250	200
Effective tower height [m]	12	10
Minimum indoor temperature [°C]	23.5	23.5
Water loss [%]	5	5
Air flow loss [%]	5	5
Rated pump power consumption [W]	250	250
Area of wind catcher [m^2]	9	7.56
Tower cross-sectional area [m^2]	25	20.25
Diameter of water droplet [μm]	30	30
Maximum relative humidity [%]	40 (50)	40 (50)
Minimum ambient temperature [°C]	28 (26)	28 (26)

8.4.1 Energy performance

The biggest energy savings appear in the hot-dry climate. As with the previous two types of buildings, the PDEC integrated strip mall in Deer Valley achieve the biggest energy savings in electricity since most of occupied hours were feasible for PDEC towers to run. The total reductions in electricity for cooling and site energy in this particular case are 151.57GJ and 154.67GJ, respectively. On the other hand, the percentage reductions in fans electricity were only 0.23% in Yuma, 1.18% in Deer Valley, and 1.25% in El Paso since the power consumption of the unitary fans in the PSZ-AC units operated consistently when the cooling requirements in the spaces were not met. The one exception to this trend is Sacramento where the percentage reduction in fans electricity is 19.85%. This is likely because the PDEC towers in Sacramento meet most of the cooling loads as the ambient air conditions are within the PDEC operational range. The percentage reductions in cooling electricity and total site energy in the PDEC integrated strip malls are much greater than the other two types of buildings. Those values reach 68.18% in Deer Valley, 59.23% in El Paso, 57.61% in Sacramento, and 47.66% in Yuma. It is likely because that overall running hours of HVAC systems were greater than the other types of building, so that possibility of energy saving become high. In addition, since set back temperature was set to be 3024°C, a negative impact, overcooling or heating spaces, of PDEC towers either at the beginning or at the end of operation was smaller than the others. Both the HVAC electricity intensity per floor area and peak electrical demand also significantly decreased in all climates when the PDEC system was used.

Table 8.10 Comparisons of energy performance between typical strip mall building and PDEC integrated strip mall building in different weather conditions

	Base	PDEC	Reduction (%)	Base	PDEC	Reduction (%)
Climate	Very Hot-dry			Hot-dry		
Electricity: Cooling [GJ]	242.9	127.13	47.66	222.31	70.74	68.18
Electricity: Fans [GJ]	99.96	99.73	0.23	105.43	104.19	1.18
Total Site Energy [GJ]	746.13	628.44	15.77	730.23	575.56	21.18
Intensity: HVAC [MJ/m^2]	164.02	108.53	33.83	156.79	83.69	46.62
Peak Electrical Demand [GJ]	743.22	627.22	15.61	727.84	575.04	20.99
Water Supplied by Utility [m^3]	0	7029.1	-100.00	0	8363.21	-100.00
CO2: Facility [kg]	254110.1	214385	15.63	248829.2	196518.1	21.02
Climate	Warm-dry			Warm-marine		
Electricity: Cooling [GJ]	129.6	52.84	59.23	97.4	41.29	57.61
Electricity: Fans [GJ]	84.2	83.15	1.25	86.48	69.58	19.54
Total Site Energy [GJ]	628.52	541.3	13.88	622.75	523.98	15.86
Intensity: HVAC [MJ/m^2]	102.28	65.06	36.39	87.97	53.04	39.71
Peak Electrical Demand [GJ]	614.43	536.62	12.66	582.27	509.26	12.54
Water Supplied by Utility [m^3]	0	4222.18	-100.00	0	3686.56	-100.00
CO2: Facility [kg]	210683.3	183606.9	12.85	201070.2	174780.2	13.08

Considerable reductions in carbon dioxide production are also found in all climates. Carbon dioxide production increases in the primary school building and is slightly reduced in the medium office building. Reductions in carbon dioxide production in the PDEC integrated strip mall are much bigger than the other two types of buildings (21.02% in Deer Valley, 15.63% in Yuma, 13.08% in Sacramento, and 12.85% in El Paso) due to longer running hours and greater cooling demand between set back hours and occupied hours, as described before. In addition, the total water consumption for the full six-month period is predicted to be 8363m^3 in Deer Valley, 7029.1 m^3 in Yuma, 4222.18 m^3 in El Paso, and 3686.56 m^3 in Sacramento. As with the previous two building types, water use in El Paso is approximately 50% of the total in Deer Valley, showing that the warm-dry climate can achieve significant energy savings with a relatively small water consumption.

8.4.2 Indoor environment

As similar to the previous two buildings, the PDEC integrated cases have a negative impact on the indoor thermal environment. The indoor setpoint temperature in base cases is fairly well met by the conventional systems as shown in Table 8.11. The biggest percentage increase in the number of hours where the setpoint is not met and the space comfort is unacceptable is found in the PDEC case in Sacramento where the hours that the indoor setpoint temperature is not met increases from 1.83hours to 11.67hours. In addition, the total hours not within the comfortable range increase by 85.3 hours in El Paso, 43.83 hours in Sacramento, 52 hours in Deer Valley, and 13.66 hours in Yuma. These values are much smaller than for the other building types. No considerable differences are found in the number of hours where the indoor relative humidity level is below 60% between the base cases and the PDEC cases in all climates. Overall, the impacts of the PDEC towers on the indoor environment in strip mall are considerably smaller than the other two building types. It is likely because PDEC towers in this particular building was well sized better than the other cases, so that problems with PDEC towers, which impacts overall indoor environment, were considerably decreased.

Table 8.11 Comparisons of indoor environment between typical strip mall and PDEC integrated strip mall in different weather conditions

	Base	PDEC	Reduction (%)	Base	PDEC	Reduction (%)
Climate	Very Hot-dry			Hot-dry		
Time Set Point Not Met [Hours]	16.5	0.0	100.00	1.67	0.0	100.00
Time Not Comfortable [Hours]	367.17	380.83	-3.72	140.67	192.67	-36.97
RH < 60% in a classroom [Hours]	3526.53	3511.57	0.42	4185.74	4080.48	2.51
Climate	Warm-dry			Warm-marine		
Time Set Point Not Met [Hours]	0.0	0.0	0.0	1.83	11.67	-537.70
Time Not Comfortable [Hours]	304	389.33	-28.07	85.17	129	-51.46
RH < 60% in a classroom [Hours]	3964.58	3966.82	-0.06	4229.97	4172.2	1.37

8.5 Summary

In this chapter, various case studies have been performed to compare the energy performance and the cooling performance of PDEC towers in three different building types in four different climatic regions for a six-month run period. Substantial energy savings are accomplished in all building types and in all climates by integrating a PDEC system into the building. While PDEC towers are known to be especially effective in a hot-dry climates, the warm-dry and warm-marine climates also show a significant potential energy savings when using PDEC towers. The warm-dry climate was particularly known to be a place where PDEC towers can be successfully integrated since such energy savings are achieved with a lower water consumption than a hot-dry climates. In short, the performance of PDEC towers should be controlled depending on local weather conditions, and they should be considered as a low-energy solution in warm climates.

While PDEC towers have a number of sustainable feasibilities, many barriers are still remaining, so that there have been only a few cases that could be successfully integrated in the cooling of buildings. Therefore, this study was designed to advance the performance of PDEC towers so that they could be extensively used in many circumstances. To achieve this goal, efforts have been made to define key barriers with PDEC towers and to find the potential solutions. As a result, poor performance, inefficiency, and strong dependency on weather conditions were found to be some of key barriers.

On the other hand, absence of methodologies that are able to examine various impacts of PDEC towers was defined as one of the key barriers. To remedy this gap, a computational model was developed, and critical parameters as well as their impacts to the performance were investigated. Based on the findings in the computational analysis, mathematical models were developed, which have an ability to provide accurate predictions of PDEC air conditions. Energy performance as well as their definite impacts to the built environment was then analyzed in the dynamic energy simulations. As a result, the performance control with water flow rate can be considered as a main solution that could resolve problems with PDEC towers. Meanwhile, the key findings of this study will be summarized in the following chapter.

List of References

ASHRAE, ASHRAE Standard 90.1-2001 - Energy Standard For Buildings Except Low-Rise Residential Buildings, SI Edition.

Wilcox, S. and W. Marion. 2008. User's Manual for TMY3 Data Sets, NREL/TP-581-43156. April 2008. Golden, Colorado: National Renewable Energy Laboratory.

CHAPTER 9: CONCLUSION

Passive down draft evaporative cooling (PDEC) is designed to capture the wind at the top of a tower and cool the outdoor air using water evaporation. They have been known to achieve significant energy savings, to improve the indoor environmental quality, and to reduce the production of pollution such as carbon dioxide. Many efforts have thus been made to integrate these cooling systems in buildings in recent decades. Some of these PDEC applications have been successfully integrated while some of them have not accomplished their low-energy goals. To date, the potential problems experienced with PDEC systems that have been presented in the literature have not fully been overcome, and the actual impact of PDEC systems has never been studied as no existing model is able to fully account for their performance.

This study was thus intended to define what problems PDEC systems currently have, to understand the fundamentals of evaporative cooling, and to present viable solutions so that PDEC towers can be more widely utilized as a cooling system in buildings. In the literature review, the key barriers that must be overcome to advance these systems were defined. A computational analysis was performed to understand the main physical phenomena that take place in the passive down-draft cooling processes. With this computational model, the influence of each critical parameter that significantly affects the cooling performance of PDEC towers was studied. To support further study on the actual impact of these systems, a mathematical model that allowed the accurate predictions of PDEC temperature and velocity exit conditions was developed using regression analysis with the forward selection method. These models were then implemented into the whole building energy simulation program EnergyPlus in order to investigate the potential problems and the impact of a typical PDEC system on a typical summer day. As a result of this study, an alternative control method that can resolve some of the problems with PDEC towers was presented. The overall impact of PDEC systems in various building types and climatic conditions was finally investigated for a 6-month period during cooling season. The main findings obtained from the results of the computational analysis as well as dynamic energy simulations are summarized below.

The air mass flow rate and the tower configurations were shown in this study to be critical factors in determining the performance of a PDEC system. While almost all of the models that have been presented in the literature do not account for the air mass flow rate or the tower configuration, a model developed by Givoni does include the outdoor wind speed as a key parameter. The Givoni model, however, was developed based on data obtained for a specific tower configuration that held the tower height, the wind catcher area, and the tower cross-sectional area fixed. Based on the computational analysis presented in this dissertation, the cooling performance of PDEC towers significantly varies with both the air mass flow rate and the ratio of wind catcher area and tower cross-sectional area. The performance of the PDEC tower improved as the ratio of wind catcher to tower cross-sectional area decreased, which means that a smaller air mass flow rate in a bigger tower achieved greater temperature drops. Givoni's model would thus be inaccurate for other tower configurations since the outdoor air mass flow rate would be different depending on the wind catcher area. The air mass flow rate and the ratio between wind catcher area and tower cross-sectional area should thus be included in the design process as well as the models that predict the performance of PDEC towers.

This dissertation also showed that it is unnecessary for tower heights to be as high as possible. A trend in initial PDEC tower designs was that their heights were relatively higher than recent PDEC applications as it was expected that the longer residence time of water droplets would result in better performance. However, to date, no study has fully dealt with the effects of tower height. Some studies revealed that the evaporation process takes place mostly at the very top of the tower, and this finding led to the conclusion that a reasonable tower height can be defined. A parametric study regarding this parameter was thus performed in this dissertation, and the findings show that differences in the performance along tower heights considerably decreased after a certain point depending on the tower cross-sectional area. The ratio between the tower height and the width of the tower in a square tower configuration that would result in little variation in air conditions near the bottom of the tower was found to be approximately 2:1, and this ratio could decrease to 1.5 in wider towers with a width greater than 3m.

This dissertation also determined that a reasonable range of water droplet size that should be injected into PDEC towers is between 30 ㎛ and 100 ㎛. It is known that finer water droplets improve overall cooling performance of evaporative cooling components. No previous study, however, attempted to analyze how significant the impact of the size of the water droplets is to the overall cooling performance of PDEC systems. A parametric study was thus performed using the computational analysis, and it was found that the cooling performance of PDEC towers varies significantly with the size of the water droplets. Based on the computational analysis at two different temperature 30°C and 35°C and relative humidity levels of 20% and 40% at basic tower configurations, considerable differences in PDEC air conditions were found when the droplet size is greater than 100 ㎛ while the differences for droplet sizes finer than 100 ㎛ were small. In contrast, droplet sizes finer than 30 ㎛ were found to achieve lower cooling outputs than 30 ㎛. In addition, changing the droplet size during the operation of a PDEC system and forming an exact droplet size are technically difficult. Thus, a reasonable size for of water droplets, which can accomplish the best cooling performance in PDEC towers, is between 30 ㎛ and 100 ㎛.

Careful consideration of the water flow rate and its control is also necessary. Water flow rate is one of the critical parameters that determine the overall cooling performance of PDEC towers. A tendency shown in the literature was that most of previous studies considered it as a way to significantly improve the performance of the system. Thus, these studies tended to increase the water flow rate with no consideration for the other critical factors such as tower configurations, air mass flow rate, droplet sizes, and local weather conditions, causing a significant increase in water consumption and humidity level of the spaces due to the saturation of the air. The effect of this parameter was analyzed in this work using computational analysis to verify how the cooling capacity of PDEC systems varied and what amount of water would be ideal in different situations. As a result, the air conditions at the exit of the PDEC tower were found to vary significantly with an increase in the water flow rate, and the most desirable air conditions, for example those as close to the wet-bulb depression as possible, can be achieved with considerably less water than appeared in the literature. In addition, the water flow rate required to achieve a certain cooling capacity in various situations also varied significantly with the conditions of other critical parameters. While all of those critical parameters must be considered in the overall design process of PDEC towers, a more careful design of the water flow rate should be made in particular when huge water consumption is a key barrier to the selection of a PDEC system.

While typical PDEC towers can reduce the energy consumption of a building considerably, the control of the performance is critical to maximize the efficiency of these systems while minimizing the problems with them. Some problems identified in the literature included inconsistent cooling outputs due to a strong dependency on the ambient weather conditions and high humidity levels within the space even though considerable energy savings were accomplished. These problems with PDEC towers were verified in this study using dynamic simulations. The findings in the simulations show that typical PDEC towers cannot meet all of the cooling loads in a space since their cooling capacities consistently varied with ambient weather conditions. They also significantly increased the indoor relative humidity. To resolve these problems, a number of alternatives were proposed and tested, and the solution that utilized water flow rate to control the overall cooling performance was shown to be effective in providing a consistent cooling output for meeting space loads. As a result, the alternative water flow rate control accomplished significant reductions in both the water consumption and electricity and achieved almost the same level of thermal environment as a conventional HVAC system. The cooling capacity of PDEC towers can thus be controlled appropriately to maintain comfortable conditions while lowering energy consumption despite variations in the local weather and building conditions.

Another conclusion of this study is that PDEC towers can be more widely used in other climates beyond just hot-dry regions. PDEC systems have already been proven to be a good solution to achieve low-energy goals in hot-dry areas. Case studies were thus performed using the dynamic simulations to verify whether PDEC towers can meet the entire cooling demand in buildings when the water flow rate control algorithm was employed. As was seen in the Chapter 7, while they could possibly be a reliable cooling system in hot-dry areas, they worsened indoor environment and increased water consumption in a warm-marine climate. PDEC towers were thus integrated as a secondary cooling system, and further case studies were performed in three different types of buildings and four different climates. The results of the previous chapter showed that PDEC towers with water flow rate control were able to achieve significant energy savings in all types of buildings and all climates. They accomplished significant energy saving in warm-dry and warm-marine climate while using approximately 50% of the total water used in the hot-dry climate. It is thus concluded that PDEC towers can be seriously considered as a low-energy solution in climates beyond the hot-dry climate.

In addition to the findings presented in this study, this study is not without its own limitations and there is additional work that remains for the future. This study defined the current status of PDEC technology and their problems, and the water flow rate control was given as a good solution to overcome those problems. The solution is not definitive because PDEC towers can still cause a negative impact on the indoor thermal environment when they are inappropriately designed. The tendency to cause either overcooling or space heating are still seen in some situations. Thus, more sensitive control algorithms are necessary so that these negative impacts to cooling load and indoor environment can be resolved. As a result, additional energy savings and improvements in the indoor environment may be possible if more responsive control algorithms that factor in local weather conditions as well as building load characteristics are applied.

In this study, the capability of PDEC towers was investigated in three different types of building and four different climates. It is observed that they are viable in all these environments. However, their performances could be different in many other situations such as different types of buildings as well as many other climatic conditions that were not treated in this study. Further studies in these different conditions are thus necessary so that some other possibilities to widely extend their applicability and performance can be demonstrated.

In addition, control setpoint temperature for PDEC towers is directly related to the water consumption and the energy savings. Lowering the setpoints increases the water consumption while achieving more energy savings. The cooling setpoints for PDEC towers should thus be carefully determined according to applicability of the water source and the indoor environment of the space where PDEC air flows are delivered. It is thus necessary to investigate the potential energy savings in an optimal condition in various situations so that PDEC towers completely satisfy all the goals of minimum energy consumption, minimal water consumption, and improved indoor thermal environment.

Comparison of the predictions of this study with actual buildings performance is necessary. This study employed three different approaches to present solutions for advancing PDEC towers' cooling performance. Many uncertainties are typically involved with these analyses since assumptions to simplify the solutions are made. As for the most reliable results, gaps between these computational predictions and actual buildings performance should be properly handled. While almost no data obtained from actual buildings with PDEC towers is available in the literature, this process is necessary to minimize any uncertainties involved with computational methodologies used in this study.

Furthermore, pressure characteristics between PDEC towers and a space should be studied. Overall cooling capacity of PDEC towers may vary when considerable pressure difference between PDEC towers and the space takes place. Pressurization from a space to PDEC towers may affect the volume flow rate of PDEC towers as well as the air conditions within PDEC towers, so that overall cooling capacity of PDEC towers are changed. In addition, significant energy loss through PDEC towers is expected when they are in this particular circumstance. A study describing these situations is also helpful to successfully accomplish the goals of PDEC towers integration in the cooling of buildings.