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Performance Control of a spray Passive Down-draft Evaporative Cooling System

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Keywords: Control, Evaporative cooling, Downdraft, Building simulation, Wind tower, Indoor environment

Abstract

A spray passive down-draft evaporative cooling system has been regarded as a low-energy cooling system that leads significant energy savings in the cooling of buildings. While the energy saving capability of the system has been proven, the ability to control a comfortable indoor environment is still inadequate due to strong climatic dependency. This study seeks viable solutions to advance the control competence of the system by mitigating critical problems of the system to be a reliable cooling application in the cooling of buildings. It proposes potential control strategies for the system and alternative operations. It develops a control algorithm for the proposed control strategies and implements the algorithm in EnergyPlus. A simulation analysis follows to examine the functionality of each proposed control strategy and alternative operations. The results of the simulations ascertain that a spray PDEC system with a water flow control performs better. In addition, a spray PDEC system contributes most when it operates as a secondary cooling system to abate space cooling loads and to maintain a steady thermal environment by reducing 62.1% electricity for space cooling and 47.9% water consumption in a warm-moderate climate.

Keywords: Control, Evaporative cooling, Downdraft, Building simulation, Wind tower, Indoor environment

Nomenclature:

A : areas of tower cross-section or tower outlets in m^2
 A_i : area of surface i in m^2
 C_p : zone air specific heat in $J/kg \cdot K$
 $C_z \frac{dT_z}{dt}$: energy stored in zone air in J/h
 D : water droplet size in μm
 DBT : outdoor air dry bulb temperature in $^{\circ}C$
 H : effective height of a tower of a spray PDEC system in m
 HD : hot dry climate
 h_i : convective heat transfer coefficient of surface i in $W/m^2 \cdot K$
 h_m : inside moisture transfer coefficient in $kg/m^2 \cdot s$
 $Kg_{mass_{sched\ load}}$: internal latent loads in kg_{air}/s

$\dot{m}$: air mass flow rate in kg/h
 $\dot{m}_i$: air mass flow rate of the air in thermal zone i in kg/h
 $\dot{m}_a$: air mass flow rate of the outdoor air in kg/h
 OA : outdoor air
 $RCMD$: recommended values for indoor relative humidity and PMV
 $\dot{Q}$: evaporation rate in m³/s
 $\dot{Q}_i$: the convective internal load from internal heat source i in watts
 $\dot{Q}_w$: water evaporation rate in kg/h
 T : dry bulb temperature of air in °C
 T_{db} : outdoor air dry bulb temperature in °C
 T_s : supply air temperature at the outlet of a spray PDEC system in °C
 V : air velocity in m/s
 V_i : air velocity at the top of PDEC tower in m/s
 V_o : wind speed in m/s
 WBT : outdoor air wet bulb temperature in °C
 WF : water flow rate in liter/min
 WM : warm moderate climate
 W : humidity ratio of air in kg_{water}/kg_{air}
 W_z^t : humidity ratio at time t in the thermal zone in kg_{water}/kg_{air}
 X : temperature difference between the supply air and wet bulb temperature in °C

Greek:

ρ_{air} : density of air in kg/m³
 ω : humidity ratio of the air in kg_{water}/kg_{air}
 ω_i : humidity ratio of the inflows in kg_{water}/kg_{air}

Subscript:

e : outlet of spray PDEC systems
 inf : infiltration
 max : maximum
 min : minimum
 o : outdoor air
 req : required water mass flow rate
 s : supply air from a spray PDEC system
 sl : sensible load in a zone
 sup : supply air from air systems
 $surf$: surface
 sys : air systems
 t : tower cross section
 w : water
 wb : web-bulb
 z : zone
 ∞ : outdoor air

1. Introduction

A spray passive down-draft evaporative cooling (PDEC) system is a component that is designed to capture the wind at the top of a tower and cools the outdoor air using water evaporation [1]. It is often described as a reverse thermal chimney as the air flows downward through chimney-like tower rather than upward as in a thermal chimney [2]. The air flow through the PDEC tower is natural as the momentum of the inflows through a wind catcher pressurizes in conjunction with an increase in the density of the inflows during the down-draft evaporative cooling process. The down-draft evaporative cooling process causes the air to fall through the tower downward and into the space without the aid of a fan. The principle of a spray PDEC system is water evaporation for cooling ambient air, the momentum of the inflows, gravity difference for establishing natural air flows from the top to the bottom, and momentum transfers from water droplets to the air [3-5].

Wind towers have been used as a means of comfort cooling for decades [6-9]. Adoption of evaporative cooling devices such as water sprays and wetted pads significantly improve the cooling performance and different forms of wind towers with evaporative devices have been developed [6,10-13]. A spray PDEC system has been used for cooling open spaces or large scale spaces since a direct evaporative cooling system deals with a large volume of air and discharges the conditioned air at a low velocity [6,12,14-17]. As the enhancement of energy efficiency has been one of the key areas in building sectors that consume energy most, a spray PDEC system has been adopted in the cooling of buildings in order to utilize the benefits of the direct evaporative cooling [5,6,12,18-22]. To date, many studies focused on this particular system and advanced the performance of the system [1,5,6,12,23-25].

Many benefits have been reported. Energy saving capability is the key benefits as it utilizes water evaporation. It also has a positive impact on indoor air quality (IAQ) since it delivers a large amount of fresh outdoor air. Another important benefit of the system is that it improves the indoor thermal environment as the cool humid supply air affects a number of environmental variables that determine occupants' thermal comfort [4,5,15,17-19]. A spray PDEC system conditions warm outdoor air immediately while conventional air-conditioning systems require a longer time to complete the vapor compression refrigeration cycle and process the outdoor air at the desired supply temperature. It could also remove particular matters in the inflows during the direct evaporative cooling process. It produces a greater cooling capacity during the on-peak hours since a greater wet-bulb depression is attainable.

A number of problems have also been reported. The climatic dependency is often regarded as a benefit of a passive technology in that it actively utilizes the climate. It could also be an obstacle when a spray PDEC system plays a role of a primary cooling system, which requires meeting all the variable cooling loads. In that point of view, one of the obstacles of a spray PDEC system is that the cooling performance is limited to the wet-bulb depression [1,5,12,24]. As the cooling capacity of a spray PDEC system is constrained to the climatic conditions, it may not be able to respond all space cooling demands that vary with time significantly. It causes a significant variation in the indoor thermal environment as the maximum capacity of the system varies with outdoor air conditions [5,25]. A spray PDEC system is typically suitable for a hot dry climate and water resources are fairly limited in this region [4,5,8,12].

2. Literature review

Bajwa, Aksugur, and Al-Otaibi investigated the potential of a pad PDEC system as a means of comfort cooling in the Kingdom of Saudi Arabia [22]. It was perhaps the first study to monitor thermal comfort in a building that a PDEC system served. The 2.2m long square tower mounted

operable louvers on the supply outlets. Measurements were undertaken for nine days between July and September in 1987. The pad PDEC system operated once in the morning from 5 to 10 and once afternoon from 3 to 6. Outdoor air temperature remained above 40°C during the occupied hours in July 1987 and the supply air temperature ranged from 26°C to 32°C. The calculated Fanger's Predicted Mean Vote (PMV) values without evaporative cooling were ranged from +1 to +2, which indicates slightly warm to warm. The PMVs varied between ± 1 except a few hours of the experimental period in September. The study suggested on-off control along with outdoor relative humidity and wind direction.

Yaghoubi, Sabzevari, and Golneshan examined occupants' thermal comfort in a space to which a wind tower, which had no evaporative cooling device, is attached [26]. They measured environmental variables near the outlet of the work is one of the early studies and measured environmental variables on a selected summer day and calculated the Fanger's Predicted Mean Vote (PMV) in three buildings. A sedentary level of metabolic rate (58W/m^2) with a light summer clothing (0.5 clo) was used for occupants. The calculated PMV values throughout the selected summer day were relatively stable. The PMV values fell into a narrow range between approximately 0.7 and 1.5 most of the day. The study found that solar radiation strongly affects the supply air temperature. A higher wind tower received more solar radiation and resulted in a warmer supply air temperature than the outdoor air temperature.

Brian Ford et. al. monitored Torrent Research Center building in Ahmedabad, India during the period of April 5-8, 1997 [20]. Spray PDEC systems conditioned laboratories and offices and applied on-off control. The daily maximum temperature was above 35°C and the minimum relative humidity during the hot and dry season was 20%. This long-term monitoring campaign confirmed that the spray PDEC systems performed generally well, maintaining 10-14°C temperature drops. The results of the measurement also revealed inconsistent supply air flows, due to moderate wind speed. The results showed that the spray PDEC systems immediately impacted on the indoor thermal environment. The study also summarized the results of other measurements and post-occupancy evaluations throughout the year. The monitoring campaign during the first year confirmed 64% reduction in electricity and 36% reduction in the expense of the plant, maintaining acceptable comfort conditions.

Dehghani, Mazidi, and Aghanajafi measured the indoor thermal environment in multiple buildings served by wind towers in Yazd, Iran [27]. The measurements were conducted August 14 through August 17 in 2002. The wind towers distributed air to multiple rooms in the building and also to a basement, rejecting heats and absorbing moist from the air in the basement. The results of the measurements indicated 4°C to 15°C temperature drops. The other type of wind towers in a different building was used for cellars and cisterns. These wind towers ventilated the storage spaces and the dry outdoor air lowered the humidity of the air in the spaces. The experimental results showed the inflows through the wind towers reduced the indoor temperatures by 3°C to 5°C. The authors concluded that the wind towers effectively ventilated the storage spaces.

Elmualim investigated the indoor thermal environment and ventilation performance in a small building to which a wind tower was attached [28]. The work measured ventilation rates through a wind tower and the indoor environment. The main characteristics of the climate were a low daily temperature difference and a large variability of relative humidity between approximately 65% and 99%. The indoor temperature was floating within a very narrow band and remained below 26°C except for a few hours. The measured indoor relative humidity was also fairly constant. It also surveyed occupants' satisfaction when the building was naturally ventilated April 2002 through September 2002. The occupants' responses to the sensation of indoor temperature

represented 40% of the occupants felt neutral, 16.7% of the occupants felt slightly warm, and the rest felt significantly warm. The study found that the combination of a wind tower and operable windows resulted in a better cooling effect.

The design source book also introduced a case study in Federal Courthouse, Phoenix, AZ, USA in 2007 [5]. The building is a six-story building with the floor area of 46,500m². It uses a spray PDEC system to control a large open atrium and ventilates the air through a bottom and top outlets. The water supply system for the spray PDEC system is connected to the building management system (BMS) and the water supply was modulated in response to the BMS system. The average daily water consumption was approximated as 6,317 liters in October 2007. The spray PDEC system led a temperature drop of 11°C as predicted. A significant temperature variation was also observed throughout the space. Many occupants reported that the indoor thermal environment was unsatisfactory in the responses to the post-occupancy survey in a seven-scale questionnaire. The installation of the PDEC system in the building resulted in 24kWh/m² of electricity, 5 million US dollars of capital cost for cooling systems, and 75% of annual operating costs.

Many building applications using direct evaporative cooling technology have been also developed. Calautit et al. [29] conducted a CFD analysis to study a new design of wind tower incorporating heat transfer device. The study found that the new design achieved a temperature drop up to 15°C and supplied the recommended ventilation rate. Montazeri H. and Montazeri F. [30] studied the performance of a cross-ventilation method using combinations of a wind catcher and a window. The CFD study suggested that the combination of one-sided wind catcher and window showed the best ventilation performance. Haghighi et. al. [31] investigated a new system consisting of a wind catcher and a water adsorption chiller. The inflows through a wind catcher were cooled by cooling plates that an absorption chiller provides chilled water. The study found that the new system can lower the supply air in the range from 10°C to 20°C. Calautit et al. [32] undertook a CFD study to see the ventilation and cooling potential in a hot climate in the United Arab Emirates. An experiment was also done and the results of the experiment showed both a positive cooling effect and some issues in the indoor thermal environment for certain periods.

The literature review showed that a few studies investigated how the cool humid supply air that a spray PDEC system discharges affect the indoor thermal environment [5,12,19-21,26,28,32]. The majority of the building applications using PDEC technology operated with no performance control, or applied a simple on-off control, rather than immediately responding to the variable cooling loads [5,12,20,22]. The studies proved that a spray PDEC system accomplished great energy savings and that a spray PDEC system lowered the temperature of the inflows to some extent. However, the cool humid supply air generally entailed inconsistency of the indoor thermal environment. Advancement of the cooling performance to maintain better thermal environment is of great importance for the current form of a spray PDEC system. As performance control for a spray PDEC system has not been well studied to date, the cooling performance of the system should be adequately controllable so that the energy efficiency of the system can be maximized as much as it could be.

3. Objective

Many building applications using evaporative cooling have been developed and they presented the solutions for resolving issues. This study focuses on the advancement in the performance of a spray PDEC system that is a direct evaporative application in the cooling of buildings. It is designed to present active solutions for maximizing the cooling performance of a spray PDEC system as much as it could be and mitigating the problems with the system. Figure 1 illustrates the

workflow of the methods and approaches to analyze the performance control and other potential operations. It discusses practical control parameters and presents performance control strategies for a spray PDEC system. It develops an algorithm to apply the proposed control strategies and implements the developed control algorithm into a whole building energy simulation program EnergyPlus. With the new module in EnergyPlus, it explores which control strategy performs best and how the performance control mitigates the critical problems with a spray PDEC system. In addition to the analysis of the proposed performance control strategies, it also searches for the alternative operations of a spray PDEC system, which is useful to ameliorate the indoor thermal environment in thermal zones.

Figure 1 Schematic of the workflow of the study

4. Performance control

4.1 Overview of a spray PDEC system

Figure 2 illustrates the down-draft evaporative cooling process. A spray PDEC system typically comprises a wind catcher to introduce outdoor air, a tower to treat warm inflows, and bottom openings to discharge the conditioned supply air. The water spray system at the top of the tower forms misty of water. The water absorbs heats from the warm inflows when the water droplets change the phase into the vapor during the evaporation process. The temperature of the air decreases during the PDEC process, depending mainly on water flow rates and water droplet sizes. The moist content of the supply air thus increases significantly. The temperature of inflows turns to the wet bulb temperature of the air when the air is saturated. This is the greatest temperature drop that a PDEC process theoretically can achieve. A spray PDEC system then discharges the supply air through the bottom openings to the space where it conditions.

Figure 2 Schematic of a spray PDEC system

Many conditions should be known to predict the capacity of a spray PDEC system. The outdoor air conditions such as temperature (T_{db}) and humidity ratio (ω_o) are needed to predict the supply air conditions. The wind speed of the outdoor air is also needed to specify the mass flow rate of the inflows ($\dot{m}_a$) through a wind catcher and the cross-section of a PDEC tower. The model reads the outdoor air conditions from the weather file at each time step during the simulations. The geometry of a wind catcher, a PDEC tower, and bottom openings are to be known for calculating the mass flow rates of the inflows and the supply air flows ($\dot{m}_s$). The model calculates the mass flow rates by the continuity equation. The water flow rate and droplet sizes are also essential for the model to predict a supply air temperature, relative humidity, and velocity. The geometry of a spray PDEC tower, a water flow rate, and a droplet size are required inputs for the simulations. The model determines the thermal properties of the supply air by using EnergyPlus built-in functions. It processes all necessary inputs and predicts the supply air conditions and water consumptions.

The supply air conditions of a spray PDEC system should be controllable to respond to the variable cooling demand. An accurate method that predicts the performance of a spray PDEC system is essential to address problems of a spray PDEC system. There has been a lack of such methods that can accurately investigate various influences of a spray PDEC system. The authors conducted a series of works in order to improve the accuracy of the predictions of the performance of a spray PDEC system. As a result, the authors formulated the most accurate analytical models that predict the supply air temperature and velocity as follows [24]:

$$T_e = -13.6 + 1.35V_i + 0.386V_o + 0.0958\dot{m}_a - 0.07WF - 0.022D - 0.0865H + 0.686T_{db} + 0.709T_{wb} \quad (1)$$

$$V_e = 0.107 + 0.706V_i + 0.21V_o + 0.00413\dot{m}_a - 0.00016WF - 0.024H. \quad (2)$$

These analytical models embrace such key variables as a water droplet size and velocities over a wind catcher and a cross-section of a spray PDEC tower. They are validated against experimental data and the details of the development of the models can be found in [24]. They are the only

models that adequately account for air mass flow rates and water droplet sizes, which are critical in the prediction of the performance of a spray PDEC system. These models are particularly important in that they enabled proper control of the supply air conditions. With these models, a number of control strategies can be developed.

4.2 Control parameters

Three parameters for the performance control can be thought. The down-draft evaporative cooling process is complicated by many factors. The cooling performance of a spray PDEC system varies with a wind speed and its direction, a water flow rate, a water droplet size, the wet-bulb depression, and a physical tower dimension [1,5,16,12,23-25,33]. While a number of parameters can be controllable, three parameters are practicable as they substantially affect the cooling performance of a spray PDEC system. The air mass flow rate through a wind catcher and bottom openings can be modulated. Some building applications using PDEC technology applied the modulation of air mass flow rates [5,22]. The water spray system may control the size distribution of water droplets and the water flow rate. These three parameters are potential variables to control the cooling capacity of a spray PDEC system, which would enhance the system response to variable cooling loads.

Two flow controls are viable among the three potential variables. Modulation of water droplets or formation of a certain size of water droplets is technically difficult. These processes require a sensitive pressure control throughout the water spray system and a compound nozzle. The authors found that the cooling performance of a spray PDEC system is fairly constant when water droplet sizes are within a narrow range between 30 μm to 100 μm [24]. The down-draft evaporative cooling with a water droplet size within the range accomplished the highest temperature drop. The study also found that the cooling performance of a spray PDEC system varied significantly when a water droplet size is greater than 100 μm [24]. It can be said that a fixed water droplet size between 30 μm to 100 μm is the most energy efficient as one particle size distribution avoids the required pressure control and components. On the other hand, the water flow rates and air mass flow rates are possible to modulate with no significant technical difficulties. A spray PDEC system can be effectively responding to variable space cooling demands when these two parameters are appropriately modulated.

The water flow rate is suitable to treat variable outdoor air. A spray PDEC system typically consists of two openings: a wind catcher at the top and outlets at the bottom of a PDEC tower. The down-draft evaporative cooling process in conjunction with the momentum of the inflows forms natural air flows throughout the PDEC tower from the top to the bottom. The modulation of air mass flow rates also substantially affects the down-draft evaporative cooling process. The incoming airflows involve the pressure profiles throughout the PDEC tower and the corresponding space. The mass flow rate of the inflows determines the conditions of the supply air as well as the indoor air. A preliminary simulation was completed to confirm the competence of the air flow and water flow controls and the results of the preliminary simulation indicated that a water flow control on a typical summer day in a hot dry climate performs better than a mass flow control. To that end, this study focuses on the water flow control.

4.3 Control Algorithm

A temperature control and one water flow control are introduced. An overcooling trend typically appears in the morning when the wet-bulb temperature of the outdoor air is low. A spray PDEC system may heat the space when the supply air temperature is higher than the zone air temperature and the indoor setpoint temperature. A temperature control named as “Temp Ctrl”

checks whether the calculated supply air temperature is lower than the zone air temperature. The “Temp Ctrl” is intended to avoid a situation that a warmer supply air heats the conditioning space. It is also needed to provide cooling if the zone air temperature is greater than the indoor setpoint temperature and the supply air temperature is lower than the zone air temperature. It follows either the path A or B.

A water flow control named as “WF Ctrl” is proposed to enhance the energy efficiency and the cooling performance of a spray PDEC system. The “WF Ctrl” control checks the zone minimum temperature ($T_{z,min}$) and the zone air temperature (T_z). It follows one of the three paths, depending on the calculated supply air conditions. It increases the water flow rate when the calculated supply air temperature can be lowered and follows the path B. It also reduces the water flow rate when the calculated supply air is expected to overcool the conditioning space on the path C. The water flow control follows all three paths.

The algorithm starts to check whether a spray PDEC system is scheduled to operate and whether the outdoor air conditions are within the operational limits as defined by the inputs. It checks the following outdoor air conditions: a maximum wind speed, a minimum wind speed, a minimum air temperature, and maximum relative humidity. It also confirms whether the zone air temperature (T_z) is greater than the setpoint temperature. It recognizes the operation of a spray PDEC system when all the conditions are within the operational range. It reads all the operating conditions from the weather data and inputs. It then calculates the supply air temperature (T_s) by applying them to the analytical models when all the conditions are met for the system operation. It determines the relative humidity of the supply air assuming the adiabatic cooling process. Depending on the calculated supply air conditions, it follows one of the three paths A, B, and C. It confirms the supply air conditions at the end of each path. It reversely calculates the adjusted air conditions when the initially calculated ones are to be adjusted when they are controllable on the path B and C. It produces the outputs in terms of the calculated supply air conditions on the path A as the supply air is expected to be satisfactorily responsive to the cooling loads.

The path A indicates the calculated supply air temperatures (T_s) by the analytical models is suitable to provide cooling at the time of simulations. The algorithm checks the system is scheduled and weather conditions and the indoor air temperature are well suited for the operation. It calculates supply air temperature and relative humidity within the given conditions at the time step. At this point, it confirms whether the calculated supply air conditions are appropriate to provide cooling. As all conditions are met, no adjustment in the controllable variables is needed. It uses the calculated supply air conditions and produces the following outputs: the supply air mass flow rate ($\dot{m}_s$), the supply air velocity (V_s) by the analytical model, and the evaporation rate ($\dot{Q}_w$). From the conservation of mass, these variables can be express as:

$$V_s = \frac{A_t}{A_e} V_e \quad (3)$$

$$\dot{m}_s = \rho_s A_e V_e \quad (4)$$

$$\dot{Q}_w = \frac{\dot{m}_s (\omega_e - \omega_i)}{\rho_w} \quad (5)$$

The path B prevents a space heating by the warmer supply air. The algorithm uses the analytical models to calculate the supply air conditions when the operating conditions are met. It then checks whether the calculated supply air temperature (T_s) is greater than the zone air temperature (T_z). If

the calculated supply air temperature is warmer than the zone air temperature, it looks whether the temperature difference between the supply air and the zone air is within the given range (ΔT_{max}). This condition is designed to avoid a space heating when the wet-bulb temperature is greater or very close to the indoor setpoint temperature. It follows the next step on the path B as it confirms a spray PDEC system can lower the supply air temperature. It gives the flexibility to preclude the saturation of the supply air. It sets a temperature tolerance (X) to manage the indoor humidity level. The lowest supply air temperature is $X^\circ\text{C}$ higher than the outdoor wet-bulb temperature. A tolerance of 1.5°C is used in this study based on the results of a preliminary simulation. The algorithm determines the required water flow rate for the water flow control by applying the adjusted supply air temperature to the analytical models. This control path minimizes unnecessary water use when a spray PDEC system cannot provide cooling. It also allows a spray PDEC system provides cooling as much as it could when the water flow rate is low.

Figure 3 Control algorithm for a spray PDEC tower system

The path C has two benefits. The algorithm always confirms whether the operating conditions are within the range at the beginning of the time step. It calculates the supply air conditions when

all the checks for determining the system operation are passed. It checks the lower limit of the zone air temperature ($T_{z,min}$) since a large amount of the cool supply air may overcool the conditioning space. The authors confirmed an overcooling trend in the morning that strongly affects the indoor thermal environment [25]. In this particular case, the algorithm adjusts the supply air temperature (T_s) to be the lower temperature limit ($T_{z,min}$) as defined by the input. It then applies the adjusted supply air conditions to the analytical models and reversely determines the required water flow rate ($\dot{m}_{req}$). This path C is needed to mainly preclude the occurrence of overcooling to the allowable limit by the input. It also prevents an excessive water supply when a spray PDEC system should stop.

5. Simulation

5.1 Climatic conditions

This study conducts a case study to evaluate the proposed control strategies. This study uses a simulation method by implementing the developed control algorithm in a whole building energy simulation program EnergyPlus. This study simulated control cases and analyzes the cooling performance of a spray PDEC tower system with different control strategies. Two cities were chosen: the city of Yuma, AZ, USA and Sacramento, CA, USA. The ASHRAE Standard 90.1-2010 classifies the former as climate zone 2B and it is defined as “Hot-Dry” with the cooling degree days (CDD) at 10°C between 3500 and 5000. The ASHRAE Standard classifies the latter as climate zone 3B and it is defined as “Warm-Dry” with the CDD at 10°C between 2500 and 3500 [34]. Both climates in this study are named the city of Yuma as hot-dry (HD) climate and the city of Sacramento as warm-moderate (WM) to clearly distinguish the two climates.

Figure 4 shows daily temperature variations and daily wind speed variations on a typical summer day in the two climates. A typical summer day that shows the highest daily wet bulb depression is selected from the TMY3 weather data to reflect the characteristics of the selected climates [35]. The wet bulb depression in Yuma is much greater than in Sacramento. The peaks of the temperature curves in Yuma are much smoother and lower. The outdoor air temperatures remain above 40°C much of the occupied hours of the day. The temperature curves in the city of Sacramento are bell-shaped and the peaks of the curves are relatively sharper and higher. The maximum wet-bulb depression in the warm-moderate climate is approximately 11°C while that in the hot-dry climate is 19.57°C. The daily variations of the wind speed during the occupied hours in the two climates are very similar during the occupied hours. The wind speed gradually increases throughout the day in the two climates. These trends of the daily variations in the two climates clearly show that the hot-dry climate has a greater potential in the evaporative cooling.

a) Outdoor temperatures

b) Wind speed

Figure 4 Ambient air conditions on a typical summer day in the two climatic regions

5.2 Simulation description

The authors implement the control algorithm in EnergyPlus. The EnergyPlus program has been extensively validated and widely used in that it is capable of modeling various physical phenomena simultaneously taking place in buildings and their surroundings [36-39]. The authors implemented the analytical models (equation (1) and (2)) that predict the supply air temperature and velocity in the EnergyPlus program [25]. The implementation of the analytical models enabled the prediction of the cooling performance of a spray PDEC system and also the predictions of all physical phenomena in buildings and their surroundings. The authors fully coupled the proposed performance control strategies, as discussed in the subsection 3.2, with the existing heat balance algorithm in EnergyPlus.

It is important to note that the EnergyPlus program assumes that natural airflows in a thermal zone such as infiltration, ventilation, and airflows through a thermal chimney and an earth tube are well mixed while multiple room air models are available. The supply air flows of a spray PDEC system is assumed as one of the natural air flows. To that end, the supply air of a spray PDEC

system is immediately mixed with other natural air flows available at the time of simulation. The program formulates energy and moisture balances as follows [36]:

$$\sum_{i=1}^{N_{IntLoad}} Q_i + \sum_{i=1}^{N_{Surface}} h_i A_i (T_{surf,i} - T_z) + \sum_{i=1}^{N_{Zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_{\infty} - T_z) + \dot{Q}_{sys} = -\dot{m}_{sys} C_p (T_{sup} - T_z) \quad (6)$$

$$\sum_{i=1}^{N_{IntLoad}} K g_{mass_{sched\ load}} + \sum_{i=1}^{N_{Surface}} A_i h_{mi} \rho_{air_z} (W_{surf,i} - W_z^t) + \sum_{i=1}^{N_{Zones}} \dot{m}_i (W_{zi} - W_z^t) + \dot{m}_{inf} (W_{\infty} - W_z^t) = -\dot{m}_{sys} (W_{sup} - W_z^t). \quad (7)$$

On the left-hand side of both energy and moisture balance equations, each term represents individual energy and moisture inputs in a thermal zone such as internal heat gains, convective heat transfers from the interior surfaces, inter-zone air flows, natural air flows, and system outputs. The model for a spray PDEC system predicts the supply air conditions. The heat balance algorithm of the program sums natural airflows in a thermal zone at each time step as expressed in the fourth terms of the energy and moisture balance equations (3) and (4).

The heat balance on the zone air is formulated as [36]:

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} Q_i + \sum_{i=1}^{N_{Surfaces}} h_i A_i (T_{surf,i} - T_z) + \sum_{i=1}^{N_{Zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_{\infty} - T_z) + \dot{Q}_{sys} \quad (8)$$

The program employs mass balance between supply air by air systems to the zone and leaving air from the zone. With the third order backward difference approximation, the numerical solution estimates the temperature of the air in the zone. The Engineering Reference document describes the details of the zone air heat balance and numerical scheme [40].

The simulations use the US Department of Energy (DOE) Primary School Reference Building model as a baseline simulation [41]. A school building typically consists of different types of spaces and the density of occupants in thermal zones is also high. A spray PDEC system is suitable to condition a school building since the PDEC process occurs as soon as water evaporates with no vapor-compression cycle. The floor area of the one-story E-shaped school building is 6,871m². The school building model consists of one main corridor with three wings where classrooms are located. The space types in the reference school building include classrooms, an office, corridors, an auditorium, a gymnasium, a cafeteria, a kitchen, and a library. It divided these spaces into 23 thermal zones for simulations. A multi-zone single duct VAV system with reheat system serves all of the classrooms, the office, the corridors, the auditorium, and the library. Packaged single zone air conditioning (PSZ-AC) units condition the other larger spaces.

In PDEC cases, the primary cooling systems in the original reference school model were replaced with a spray PDEC system. All the other design conditions in the PDEC cases remained the same as the baseline simulations. The simulation model defines internal heat gains such as occupants, lighting, and equipment as per ASHRAE Standard 90.1-2004 and 62-1999. The operating time for the cooling systems in the baseline model is set to be 6 AM to 9 PM, and the spray PDEC systems operate 6 AM to 8 PM. The indoor setpoint temperature is 24°C during the occupied hours and 27°C during the setback hours. The reference building model also includes

environmental factors to predict the productions of pollution that is directly associated with the energy consumption in the building.

The reference building model also includes environmental factors to predict the productions of pollution that is directly associated with the energy consumption in the building. The representative environmental factors are 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. The fossil fuel combustion is based on AP-42 Compilation of Air Pollutant Emission Factors by US Environmental Protection Agency (EPA).

The simulations include an additional case named as “Smaller”, other than the two flow control strategies. In the PDEC cases, the simulations assume that a single PDEC system serves one thermal zone. A smaller system may be beneficial to maintain constant supply air conditions in that it deals with a lower amount of outdoor air. The “Smaller” case is designed to see the difference in the energy performance and indoor thermal environment between a single larger spray PDEC system and two smaller PDEC systems. The smaller PDEC system reduced the areas of the wind catchers and the tower cross-section by 50% of the normal one, which results in the reduction of air mass flow rates. This case applies the water flow rate control and the other parameters remained the same.

The simulations also report thermal comfort index in the thermal zones in addition to predicting standard measures for the indoor thermal environment. Among multiple thermal comfort models in EnergyPlus, the simulations predict the Fanger’s thermal comfort model and the PMV as it is widely used. The spray PDEC systems affect all the environmental variables such as air velocity, air temperature, mean radiant temperature, and humidity [42,43]. The variation of the indoor air speed should thus be taken into account in the simulations as the supply air flows of the spray PDEC systems affect the indoor thermal environment. However, the simulations use a fixed value for the indoor air velocity in this study since no accurate method to predict the variation of the variable in a thermal zone is available, due to the inherent limitation of the heat balance method in the prediction of airflows within the thermal zone.

Adapted from [44]

Figure 5 Thermal zones in the primary school building

6. Results

6.1 Primary cooling system

In one series of the simulations, the US DOE reference primary school building was modeled with a spray PDEC system as a primary cooling system. The modified model replaces the mechanical cooling systems in the original reference building model with spray PDEC systems. The simulations categorize the 25 thermal zones as shown in Figure 5 into three groups by their physical sizes. Preliminary simulations have been run in order to properly size the spray PDEC systems so that they are able to meet the space cooling loads in the three different space groups as much as they can. The simulation inputs were determined based on the results of these preliminary simulations as listed in Table 1.

Table 1 Main input parameters for the spray PDEC systems in the simulations

Type of Rooms	Classroom	Office
Maximum water flow rate [l/h]	200	200
Effective tower height [m]	5	10
Minimum indoor temperature [°C]	24	24
Water loss [%]	5	5
Air flow loss [%]	5	5
Rated pump power consumption [W]	150	250
Area of wind catcher [m ²]	6.25	9
Tower cross-sectional area [m ²]	16	25
Diameter of water droplet [μm]	30	30
Maximum outdoor relative humidity [%]	40 (50)	40 (50)
Minimum outdoor temperature [°C]	28 (26)	28 (26)

Table 1 summarizes main simulation inputs. The simulations use a water flow rate of 200l/h and water droplet size of 30 μm for all spray PDEC systems. A portion of the supply air flow rate and water flow rate are assumed to be lost during the down-draft evaporative cooling process. The simulations set the minimum zone air temperature of 24°C, which would be the setpoint temperature of the supply air if the calculated supply temperature by the analytical models is below the input. The model determines system-off when the zone air temperature and the outdoor air temperature are below the minimums at the time of simulation. These input values can also be used as performance control variables as a supply air setpoint in the simulations. The physical sizes in the height, the area of wind catcher, and tower cross-section differ from each space.

The simulations account for differences in the outdoor conditions in the two climates. The performance of a spray PDEC system is strongly dependent on the climatic conditions. The operable hours and the cooling capacity of the system are thus directly related to the weather conditions in each climate. The simulations set a wider climatic condition for a warm-moderate climate to characterize the difference between the two climates. The input values in the parentheses for the last two fields are applicable only to the simulations for the warm-moderate climate.

6.1.1 Energy performance

This study evaluated the energy performance of the primary school building. A typical summer day was selected, which was one of the most suitable days for evaporative cooling in the two climates. It compared the results of the simulations to see the differences in energy and water consumptions along with the change of the control strategies and a case that two smaller spray PDEC systems condition a thermal zone in two different climatic conditions. Table 2 and 3 show electricity consumptions by the primary cooling systems and building facilities, the water consumption, and the carbon dioxide production in a baseline case and three PDEC cases. Two of the three PDEC cases adopted a temperature control (Temp Ctrl) and a water flow control (WF Ctrl). The other PDEC case sets two smaller spray PDEC systems (Smaller), which are identical, instead of a larger one.

Table 2 Energy performance and carbon production in the hot-dry climate

Meters	Temp Ctrl	WF Ctrl	Smaller	Baseline
Cooling:Electricity [MJ]	258.72	258.72	261.36	7100.78
Electricity:Facility [MJ]	5774.86	5774.86	5777.50	13529.43
Fans:Electricity [MJ]	0	0	0	683.77
Cooling:MainsWater [m ³]	237.73	191.13	437.38	1.50
CO ₂ :Facility [kg]	1174.58	1174.58	1175.10	2716.45

Table 3 Energy performance and carbon production in the warm-moderate climate

Meters	Temp Ctrl	WF Ctrl	Smaller	Baseline
Cooling:Electricity [MJ]	179.34	179.34	187.11	3994.59
Electricity:Facility [MJ]	5685.19	5685.19	5692.96	10324.15
Fans:Electricity [MJ]	0	0	0	614.02
Cooling:MainsWater [m ³]	139.93	103.52	356.11	1.50
CO ₂ :Facility [kg]	1156.90	1156.90	1158.43	2084.69

The spray PDEC systems consumed approximately 4% to 5% of the electricity for space cooling that the multi-zone single duct VAV system with reheat in the baseline models required in the two climates. This tremendous energy saving stems from the fact that the PDEC system operates with one single energy device, i.e., water pump, while it demands significantly water supply to treat a large amount of inflows at a high temperature. The air distribution system in the baseline model also includes fans to deliver the conditioned air to the thermal zones. The simulations predicted that fans consumed approximately 10% to 15% of the cooling energy in the baseline models. The PDEC systems discharged the supply air by natural forces with no aid of fans and the PDEC cases saved the entire electricity for the fan operation. The reduction in the electricity also led significant reductions in the carbon emission, which is directly determined by the fuel factors.

The water flow control “WF Ctrl” was found to be the most energy efficient control strategy. The spray PDEC systems demanded a significant amount of water, which is one of the main impediments of a spray PDEC system. The “Smaller” case used water most as both smaller spray

PDEC systems operated at the same water flow rate of 200l/h. The electricity consumptions in the “Temp Ctrl” case was the same as the water flow control case since the spray PDEC systems operated for the same amount of the time. However, the “Temp Ctrl” case used a large amount of water as it checks the upper-temperature limit only in a thermal zone. The water flow control demanded the least water in both climates as it modulates the water flow rate as much as a spray PDEC system needs. The water flow control lowered the supply air temperature by consuming the least water to the indoor temperature limit, resolving the overcooling trend.

the simulation results show that the spray PDEC systems accomplished significant energy saving in the warm-moderate climate, requiring much less water. Table 3 shows that the spray PDEC systems in the warm-moderate climate required much less water consumption than in the hot-dry climate since the operating hours in the warm-moderate climate were shorter. Given that a spray PDEC system typically performs best in hot-dry climates, the magnitude of the energy savings for space cooling in the two climates was almost same. The moderate weather conditions delayed the operation of the spray PDEC systems in the morning. The total operating hours were also limited by the outdoor wet-bulb temperature, which was greater than the indoor setpoint temperature of 24°C for a number of afternoon hours. The spray PDEC systems demanded much less water to treat the inflows by the indoor temperature limit.

6.1.2 Cooling performance

This study compared the indoor thermal environment in the two representative spaces: a classroom and the office among 23 thermal zones. The majority of the thermal zones in the school building is classrooms and the office is occupied during the entire occupied hours. It ran a series of the simulations to analyze how each control strategy improves the indoor thermal environment. The volumes of the smaller space classroom and the larger space office are 396 m³ and 1,764 m³, respectively. The number of occupants and internal heat gains from occupants, lights, and equipment differed from space type.

PDEC outlet air conditions

A noticeable difference in the operating hours between the two climates was observed as shown in Figure 6. The spray PDEC systems in the hot-dry climate operated throughout the entire operating hours as the outdoor air conditions were suitable for the operation. The smaller PDEC case maintained the supply air temperature at the indoor temperature limits in the hot-dry climate. The supply air temperature of the smaller case in the warm-moderate climate was greater than the indoor temperature most of the afternoon hours as the wet-bulb temperatures of the outdoor air were above the indoor setpoint temperature of 24°C. The operation of the spray PDEC systems in the warm-moderate climate was delayed 5 hours as the outdoor air and the indoor air conditions were out of the operable conditions.

The temperature control addressed the afternoon heating trend. The “Temp Ctrl” case was originally designed to prevent the introduction of warmer supply airflows that heat the conditioning space. It typically occurs when the outdoor air conditions are above the upper-temperature limit as the outdoor wet-bulb temperature is close to or greater than the indoor setpoint temperature. The supply air temperature in the temperature control case was the lowest in the morning in both climates. In the hot-dry climate, it was the same as that in the water flow control case during the afternoon hours. The results of the simulations indicated that the temperature control can effectively address a heating trend in the hot-dry climate. However, the overcooling trend in the morning and late afternoon still remained, resulting in excessive water consumption.

The water flow control was successful to maintain consistent supply temperatures in both climates. Both “WF Ctrl” and “Smaller” cases adopted water flow control. The temperature variations in both cases in the warm-moderate climate were the same. In the hot-dry climate, they were better in the smaller PDEC case as it treats the smaller amount of inflows at the same water flow rate. The water flow control mitigates overcooling and heating trends in both climates. It modulates the water flow rate when the supply air temperature was greater than the indoor air temperature in the hot-dry climate and when the supply air temperature was lower than the indoor air temperature in the hot-dry climate. The results of the simulations showed that the water flow control can maintain a constant supply air temperature when a spray PDEC system is well designed.

The physical size of a spray PDEC system resulted in a different performance in the hot-dry climate. The spray PDEC systems were sized along the size of the spaces. The simulations applied a bigger spray PDEC system to the larger space office. In the hot-dry climate, the supply air temperatures in the office remained slightly higher than those in the classroom throughout the afternoon hours when a greater water supply was demanded. The smaller systems in the hot-dry climate achieved a greater temperature drop in the spaces and maintained the most constant supply air temperature. The variations in the supply air temperature in the warm-moderate climate were the same in the classroom and the office as the down-draft evaporative cooling process lowered the inflows’ temperature at a lower water flow rate.

a) Classroom – HD

b) Office – HD

c) Classroom – WM

d) Office – WM

Figure 6 Variations of temperature at PDEC tower outlet

Figure 7 shows notable differences in relative humidity between the temperature control and the water flow control. The temperature control caused a hike as soon as the spray PDEC systems operated in the warm-moderate climate and remained almost the same over the rest operating hours. The relative humidity of the supply air in the hot-dry climate reached to the highest level within the first operating hour and decreased as the spray PDEC systems treated drier inflows. The water flow control moderated the humidity level throughout the operating hours. The relative humidity of the supply air in the water flow control cases in the hot-dry climate steadily increased since the spray PDEC systems supplied the minimum water flow due to relatively moderate outdoor weather conditions. The smaller case in the hot-dry climate showed a higher level as it demanded more water supply in total for the two smaller systems with the water flow control over the last five operating hours. The trends in the water flow case and the smaller case in the warm-moderate climate were the same since the supply air was nearly saturated at a low water flow rate. Depending on the volume of the supply air and the volume of the spaces, the humid supply air may significantly increase the indoor humidity level. The influences of the supply air flows will be discussed in the following sections.

a) Classroom – HD

b) Office – HD

c) Classroom – WM

d) Office – WM

Figure 7 Variations of relative humidity at PDEC tower outlet

Indoor mean air temperature

The temperature control case overcooled the spaces as shown in Figure 8. In the hot-dry climate, the mean air temperature in the case decreased by 20.9°C in the classroom and by 21.6°C in the office after two hours of the operation. It was also decreased by 21.7°C in the classroom and 22.5°C in the office as soon as the spray PDEC systems operated in the warm-moderate climate. It was the lowest in the classroom due to a higher air exchange rate. However, the variation in the mean air temperature was fairly stable throughout the day within a narrow band. In the warm-moderate climate, the mean air temperature dropped in the morning and afternoon as the spray PDEC system started. It floated above the indoor setpoint temperature of 24°C in the morning in the climate as the spaces remained unconditioned due to the delay of the system operation. The results of the simulations indicated that the temperature control may be effective in the hot-dry climate if a spray PDEC system is well designed.

The water flow control cases, i.e., “WF Ctrl” and “Smaller” cases, showed a steady variation in the mean air temperature within a very narrow range in the hot-dry climate. Figure 7 showed that

the smaller case in the hot-dry climate, which two smaller spray PDEC systems served a thermal zone, maintained the most constant variation. Particularly, the smaller case resulted in a better temperature variation for the last 5 - 6 operating hours while the other cases maintained a higher temperature than the indoor setpoint temperature of 24°C. More importantly, the smaller case showed a better daily variation than the baseline case that the conventional air-conditioning systems served the spaces. The water flow control cases showed slightly warmer temperature than the indoor setpoint temperature as the space cooling loads increased significantly. It was found that the maximum temperature differences between the mean air temperature and the setpoint temperature during the occupied hours were approximately 0.4°C in the classroom and 0.8°C in the office in the hot-dry climate. The results of the simulations showed that smaller PDEC systems are effective to maintain a consistent supply air temperature as they treated a smaller mass of the inflows.

a) Classroom – HD

b) Office – HD

c) Classroom – WM

d) Office – WM

Figure 8 Variations of indoor mean air temperature

Indoor relative humidity

Figure 9 showed that the variation in the indoor relative humidity in the hot-dry climate was relatively better than in the warm-moderate climate. The indoor relative humidity in the temperature control case substantially increased at the beginning of the system operation in the hot-dry climate. This trend is because the spray PDEC systems operated at the fixed water flow rate of 200l/h with no check of the lower temperature limit. It was relatively lower in the office in all PDEC cases than that in the classroom due to a lower air exchange rate. The highest level appeared in the “Smaller” case throughout the afternoon hours since the spray PDEC systems demanded the maximum water flow rate of 200 l/h for a longer time. The water flow control cases limited the indoor relative humidity within a narrow band for more than half of the day. The indoor relative humidity in the hot-dry climate remained below the recommended value of 60% most of the occupied hours though the humid supply air entailed a significant variation of the indoor relative humidity. It can be said that a spray PDEC system may sustain the indoor humidity level within the comfortable range in the hot-dry climate.

The variations in the indoor relative humidity in the PDEC cases in the warm-moderate climate were very similar. The temperature control case resulted in a hike in the morning and showed a higher relative humidity level than the two water control cases. The case also maintained a greater relative humidity in the spaces. The humid supply air increased the indoor relative humidity by approximately 78% in both the classroom and the office. The water flow rate used in the simulations is relatively high for the warm-moderate climate so that the spray PDEC systems conditioned the inflows by the wet-bulb temperature of the inflows. The indoor relative humidity in both spaces showed a bell-shape curve, which is similar to the outdoor wet-bulb temperature trend for most of the occupied hours. As the down-draft evaporative cooling process saturates the inflows at a low water flow rate, spray PDEC systems strongly affect the indoor relative humidity.

a) Classroom – HD

b) Office – HD

c) Classroom – WM

d) Office – WM

Figure 9 Variations of indoor relative humidity

Thermal comfort

The Fanger PMV values in the water control cases in the hot-dry climate were comparable with the baseline. The Fanger's thermal comfort model uses seven scales for thermal sensation -3 (cold) to 3 (hot) and the recommended acceptable PMV range is ± 0.5 [38]. The baseline cases in both climates formed a slightly cold environment in the morning due to the typical overcooling trend as the control mode returned to the occupied mode. The PMV values steadily increased over the day in both climates as the cooling loads increased. The temperature control case showed a significant variation in the PMV values as it overcooled the spaces in the morning and increased indoor relative humidity. Conversely, the PMV values in the water control cases in the hot-dry climate were within the recommended PMV range during the occupied hours. The "Smaller" case showed the most stable variation and the variation in the case was better than the baseline case. One definite trend in the PMV variation was that it was more stable in the larger space that has a relatively smaller impact by the humid supply air. The water flow control cases maintained the

PMV values in between neutral and the upper recommended limit since the indoor air temperature was a little higher than the indoor setpoint temperature for some afternoon hours.

The PMV variation in the warm-moderate climate fluctuated throughout the day as shown in Figure 10. The PMV values in the morning were relatively better than the baseline case since the baseline case lowered the indoor air temperature substantially. It was because the thermal zones remained unconditioned and maintained a constant indoor thermal environment in the morning in the PDEC cases. They varied sharply after a spray PDEC system began to operate by the change in the outdoor weather conditions. They stayed above the upper limit of the recommended thermal comfort range, i.e., +0.5, for a number of afternoon hours since the outdoor wet-bulb temperature remained above the indoor setpoint temperature. While they varied significantly and stayed out of the recommended range ± 0.5 , the PMV values were close to those in the baseline case. These trends can be addressed by strengthening the performance control of a spray PDEC system to some extent, but the operation of the spray PDEC systems should be carefully monitored to keep the indoor thermal comfort within the recommended range.

a) Classroom – HD

b) Office – HD

c) Classroom – WM

d) Office – WM

Figure 10 Variations of indoor PMV values

6.2 Secondary cooling system

An alternative operation of a spray PDEC system is needed. Spray PDEC systems have been used as a stand-alone cooling system since it demands the least energy, unlike conventional air-conditioning systems. It also has environmental benefits to enhance the sustainability of buildings. The results of the simulations in section 6.1 demonstrated that the water flow control improved the performance of a spray PDEC system to a large extent. However, the indoor thermal environment still remained unstable, especially in the warm-moderate climate. It can be said that the spray PDEC system may not be a stand-alone primary cooling system. One of the possible resolutions to address the remaining issue is the combination of a conventional air-conditioning system and a spray PDEC system. As a secondary cooling system, a spray PDEC system meets a large portion of space cooling loads as much as it could and the primary cooling system treats the rest. This approach is expected to maintain a constant thermal environment in conjunction with a prodigious energy saving. In this section, a series of the simulations is designed to investigate the benefits of the combination.

An adjustment was made for the constant minimum air flow rate for the VAV terminal units in the simulations. The baseline model was set to introduce at least 30% of the outdoor air to meet the minimum ventilation requirement during the occupied hours. The simulations modified the input value into 0.05, which is 5% since the spray PDEC systems introduce a large amount of outdoor air. The fraction can be zero in the hot-dry climate as long as the spray PDEC systems operate throughout the occupied hours and also in the warm-moderate climate during the period of the PDEC system operation. The operation of the spray PDEC systems may vary with the outdoor weather conditions as seen in the results of the simulations in the warm-moderate climate in the previous section. To that end, the fraction was set to be 0.05 since a zero may overestimate the benefits of the alternative operation when a spray PDEC system operates intermittently. The other simulation inputs remained the same as the original reference primary school building.

A spray PDEC system with the water flow control was modeled in the combined case. The results of the simulation in the previous section 6.1 showed that the temperature control may be partially effective in a particular situation that warmer supply air from a spray PDEC system than the indoor setpoint temperature heats the conditioning spaces. The overcooling trend in the temperature control case remained, which caused the significant variation in the indoor thermal environment. The temperature control was unlikely to be a reliable control method to resolve key impediments of a spray PDEC system. In contrast, the water flow control case resolved such problems to a large extent as long as the climatic conditions are suitable for the operation of a spray PDEC system. Thus, the simulations applied the water flow control to the spray PDEC system in the combined operation simulations.

The minimum limit of the supply air temperature of the spray PDEC system in the combined case was set to be 0.5°C lower than the indoor setpoint temperature. The results of the simulation in the previous section showed that the PDEC cases formed a warmer indoor temperature during the afternoon hours. The minimum supply air temperature in the previous simulations was set to be the same as the indoor setpoint temperature of 24°C as long as a spray PDEC system discharged a colder air than the zone air temperature at the time of simulation. A case study was done in order to find a reasonable value of the minimum supply air temperature and it suggested that the supply air temperature of 0.5°C lower than the setpoint temperature was beneficial in energy savings and the indoor thermal environment. The input value for the minimum indoor temperature was thus set to be 23.5°C in this series of simulations.

6.2.1 Energy performance

The warm-moderate climate showed a greater potential for energy efficiency. The combined cases resulted in a substantial energy saving in both climates and a large reduction of carbon dioxide production as illustrated in Table 4. The energy reduction rate in the cooling energy by the combination of the conventional air-conditioning systems and the spray PDEC systems in the warm-moderate climate reached 62.1%. The combined case in the hot-dry climate saved 47.9% of the electricity for space cooling. A lower reduction rate in the hot-dry climate can be explained that the primary cooling system responded the increasing cooling demands throughout the afternoon hours since the indoor mean air temperature was warmer than the desired temperature in the spaces. It indicates that the primary cooling system operated relatively a longer time to meet the increased cooling loads during the afternoon hours. The spray PDEC systems in the hot-dry climate also consumed almost twice the water consumed in the warm-moderate climate. These results demonstrated that a spray PDEC system can reduce a large portion of cooling loads in both climates and be more energy-efficient in the warm-moderate climate.

Table 4 Energy performance in the baseline and the combined cases in both climates

Meters	Hot-dry		Warm-moderate	
	Baseline	Combined	Baseline	Combined
Cooling:Electricity [MJ]	7100.78	3697.97	3994.59	1514.20
Electricity:Facility [MJ]	13529.43	9975.70	10324.15	7695.64
Electricity:HVAC [MJ]	7784.55	4230.92	4608.62	1980.11
Fans:Electricity [MJ]	683.77	532.95	614.02	465.91
Cooling:MainsWater [m ³]	1.50	197.44	1.50	107.47
CO2:Facility [kg]	2716.45	1494.15	1882.60	1156.47

6.2.2 Cooling performance

Mean air temperature

Figure 11 illustrated that the variations in the indoor mean air temperature were more consistent in the combined case in the hot-dry climate. The space cooling loads increased as the control setting for the conventional air-conditioning system changed to the occupied mode from the unoccupied mode. That is, the indoor setpoint temperature changed from 27 °C to 24 °C. The indoor mean air temperature during late afternoon hours stayed above the indoor setpoint temperature of 24°C. This particular period of the day likely entailed a significant rise in the cooling loads since the spray PDEC systems failed to meet the space cooling loads. It was also because of the fact that the west side surfaces in the building gained relatively higher direct solar radiation. The indoor temperature variations during the unoccupied hours in the spaces were also much more stable. The spray PDEC systems increased the space cooling loads to some degree but the combined operation maintained more steady variation in the indoor mean air temperature throughout the occupied hours.

In the warm-moderate climate, the combined case also showed a better daily variation in the indoor mean air temperature. As shown in the previous simulations, the larger space maintained a better variation as the humid supply air had a lower impact on the indoor thermal environment. The combined case also showed a smoother variation in the morning as it resolved the overcooling trend. However, the supply air temperature followed the outdoor wet-bulb temperature curve when it went over the indoor setpoint temperature during a few afternoon hours. The supply air temperature remained above the indoor setpoint temperature for this particular period of the day and the space cooling loads greatly increased. The results of the simulations indicated that the combined case not only met a large portion of the cooling loads most of the day but also led a rise in the cooling loads as a spray PDEC system discharged a warmer supply air.

a) Classroom – HD

b) Office – HD

c) Classroom – WM

d) Office – WM

Figure 11 Variations of indoor mean air temperature

Relative humidity

In the hot-dry climate, the time series of the indoor relative humidity in the combined case showed a better variation than in the water control case. Figure 12 shows the variations in the indoor relative humidity in the baseline case and the combined case. The variations in the baseline cases were better. The variation in the combined cases in the hot-dry climate was also fairly stable within approximately a 9% narrow band for most of the occupied hours. As expected, a hike during late afternoon hours was observed since the spray PDEC systems required the maximum water flow rate in order to lower the supply air temperature by the temperature limit. The variation in the smaller space classroom in the combined case was very similar to that in the water control case in section 6.1. The combined case in the office showed more consistent variation throughout the day than the water flow control case. In general, the variations in the hot-dry climate remained within the recommended range between 30% and 60% and they were stable throughout the day.

The humid supply air from the spray PDEC systems had a strong impact on the indoor relative humidity level in both climates. The variations in the indoor relative humidity in the combined case in the warm-moderate climate were very similar to those in the water control case. The cool humid supply air dominated the indoor relative humidity level as the outdoor wet-bulb temperature varied above the indoor setpoint temperature for some afternoon hours. The indoor relative humidity stayed off from the recommended relative humidity of 60% most of the afternoon hours after the operation of the spray PDEC systems. In addition, the indoor relative humidity level during the unoccupied hours was more stable as the spaces remained unconditioned. The indoor relative humidity in the combined case in the warm-moderate climate needs to be carefully controlled along with the outdoor wet-bulb temperature.

a) Classroom – HD

b) Office – HD

c) Classroom – WM

d) Office – WM

Figure 12 Variations of indoor relative humidity

Thermal comfort

Figure 13 illustrated the time series of the PMV values in the spaces in both climates. In the hot-dry climate, the combined case resulted in the most stable variation throughout the occupied hours. Particularly, the baseline case caused a significant drop by -0.62 in the early morning due to the overcooling trend. The PMV values in the baseline case then increased throughout the occupied hours by +0.55. The PMV variation in the combined case was much better in the morning while it was similar to the baseline case afternoon. It was also better in the larger space office in the hot-dry climate. The PMV values stayed within the recommended range ± 0.5 throughout the occupied hours except for a few afternoon hours in all PDEC cases. The combination was beneficial in maintaining the thermal comfort level in the hot-dry climate. This particular result indicated that the spray PDEC systems met the large portion of the cooling loads in the morning and shortened the operating time of the primary cooling systems.

As expected, the combined case in the warm-moderate climate involved a greater variation in the PMV values. The PMV values in the classroom in the baseline case dropped by -1.11 within two hours of the system operation in the occupied mode. They steeply increased after the drop by 0.58 over the occupied hours. The PMV variation in the baseline case in the office was much more stable. The combined case showed a better variation in both spaces in the morning than the baseline case. As described in the previous section, the operation of the spray PDEC systems delayed most of the morning hours in the warm-moderate climate and the primary cooling system met the cooling loads during the period. The PMV values remained within the recommended range in thermal comfort except for two to three afternoon hours though the combined case involved a greater variation in the warm-moderate climate. The results of the simulation indicated that the combination was beneficial to reduce the space cooling loads, especially when the operating mode returned to the occupied mode.

a) Classroom – HD

b) Office – HD

c) Classroom – WM

d) Office – WM

Figure 13 Variations of thermal comfort of occupants

Sensible cooling load

Figure 14 illustrated that the combined case effectively responded to the variable cooling loads most of the day. The positive values of the sensible cooling loads indicate the space cooling loads that should be removed by the cooling systems to meet the indoor setpoint temperature. The negative values appeared if the cooling system removed heats more than the cooling load at the time of simulations, which may require an operation of heating systems depending on the operating settings of the air-conditioning system. It is noted that this study applied a cooling only mode in the simulations and the heating loads had no impact on the energy consumption.

A definite trend found in the baseline cases was that the cooling systems overcooled the spaces throughout the day. The overcooling trend in the office was stronger as the conventional air-conditioning systems met the larger cooling loads. Interestingly, the overcooling trend in the baseline cases in both climates was clear during the unoccupied hours. It was likely because of the heat storage effect from the building envelope. This particular trend in the baseline cases in both climates also strongly affected the variation in the indoor thermal environment as described in the previous subsections.

The combined case involved significant increases nearly half of the occupied hours in both climates as the spray PDEC systems discharged warmer supply air than the indoor setpoint temperature to the thermal zones. The primary cooling system operated longer since the spray PDEC systems heated the spaces during this particular period. The magnitude of this tendency was stronger in the warm-moderate climate and in the smaller space classroom. The results of the simulations clearly demonstrated that the combined case caused a significant rise in the sensible cooling loads afternoon. The energy efficiency of the combined systems during this particular period could be enhanced if the spray PDEC systems improve the controllability to mitigate the heating tendency. On the other hand, the sensible cooling loads in the combined cases in both climates during the rest of the day stayed near the neutral line. These results suggest a careful treatment of the heating trend in order to improve the energy efficiency of the combined operation.

a) Classroom - HD

b) Office - HD

c) Classroom - WM

d) Office – WM

Figure 14 Variations of sensible cooling load

7. Discussion

The study developed a control algorithm and coupled it with the existing numerical solutions for the heat balance algorithm in EnergyPlus. This two-way coupling enhances the accuracy of the prediction. The analytical models were validated against experimental data and the EnergyPlus program is being extensively validated [36-39]. To that end, this simulation method is currently the most accurate method that can evaluate the impact of a spray PDEC system on building energy performance and the indoor thermal environment. However, the controllability and control stability may be different when it serves a real building. Thermal behavior of a real building and the indoor thermal environment may be different from the predictions of the simulations in this study. The simulations may not characterize all physical phenomena in buildings and their surroundings as they involve with many factors. The results of the simulations need to be evaluated in a real building so that the capability of a spray PDEC system and the alternative operation can be fully verified.

The benefits of a spray PDEC system should be thoroughly analyzed. It is apparent that a spray PDEC system significantly reduces cooling energy consumption as it includes one component that consumes electricity. A spray PDEC system also contributes the indoor air quality (IAQ) and affects the productivity of occupants. This benefit has to be adequately weighed because the productivity of occupants is much more important than energy cost savings. The contributions of the cool humid supply air to IAQ and the indoor thermal environment have not been well studied to date. The combination of a spray PDEC system and a conventional air-conditioning system would meet the minimum ventilation requirement per building codes and it would also increase the system efficiency of the conventional air-conditioning system. The operating cost savings for the entire lifespan of building systems would also be taken into account. A detailed economic analysis is needed to verify the complete benefits of a spray PDEC system.

The implementation of the water flow control for a spray PDEC system is technically practical. The water flow rate can be modulated by control valves at a fixed motor speed, or Variable Frequency Drive (VFD) within a pressure range that can produce the desired size distribution of the water droplets. To apply the performance control in practice, supply air conditions and indoor

air conditions should be monitored to maintain the indoor thermal environment as per building codes and standards. The volume of the supply air should also be sensed in order to properly respond to the sensible cooling load in the conditioning space. The distribution of the sensible cooling loads is particularly important when a spray PDEC system serves as a secondary cooling system. A computational analysis in conjunction with systems commissioning is essential to maximize the energy efficiency of the combination.

8. Conclusion

A spray PDEC system has not been widely used as a low-energy cooling solution in the cooling of buildings though it has a great potential for energy savings. In order to explore practical solutions that can mitigate critical obstacles of a spray PDEC system to its successful integration in the cooling of buildings, this study presents a number of control strategies and developed a control algorithm for a spray PDEC system. It implemented the proposed control algorithm in EnergyPlus. It conducted series of the simulations to see which control strategy works best and how much an alternative operation improve energy performance in buildings. The main findings of the study are as follows:

- The water flow control enhanced the performance most, mitigating much of the inborn problems of a spray PDEC system. However, it led a greater variation in the indoor thermal environment in comparison with the base case.
- The water flow control saved 19.6% of water in the hot-dry climate and 26% in the warm-moderate climate in comparison with temperature control. The warm-moderate climate requires approximately 45.6% less water than in the hot-dry climate.
- Multiple smaller size PDEC systems are better to maintain the indoor thermal environment while demanding more water consumption.
- The combination of a conventional cooling system and a spray PDEC system significantly enhances the indoor thermal environment. A spray PDEC system would be suitable for a secondary cooling system, rather than a stand-alone primary cooling system.
- A careful design of a spray PDEC system is needed to mitigate rises of cooling loads late afternoon. Moderating this particular trend would improve the system efficiency significantly.
- Smaller space in both climates showed a better indoor thermal environment while the differences between the two representative spaces are moderate. The result indicates that a spray PDEC system is suitable for a small space as a direct evaporative cooling system is typically for a large space.
- The feasibility of a spray PDEC system in a climate other than a hot-dry climate is said to be promising. The energy reduction rate of 62.1% in the warm-moderate climate was greater than that of 47.9% in the hot-dry climate.
- Variation in wet-bulb temperature is a critical measure to determine the competence of a spray PDEC system in a climate. The indoor thermal environment in the hot-dry climate was better than the base case.

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