SIMULATION OF PASSIVE DOWN-DRAUGHT EVAPORATIVE COOLING (PDEC) SYSTEMS IN ENERGYPLUS

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ABSTRACT

This paper discusses the development of a new module in EnergyPlus that predicts the cooling performance of PDEC towers with sprays. It introduces an overview of PDEC towers and existing models. A simulation model is employed to design and evaluate PDEC towers, and its modelling algorithm in EnergyPlus is described. An analysis of the capability in different climates and the energy performance of PDEC towers has been performed by using the model implemented, and the main results from various case studies are presented. Overall, the model is capable of predicting air conditions as well as air flow rates from PDEC towers so that EnergyPlus can calculate appropriate indoor air conditions and thermal comfort in a zone.

INTRODUCTION

Passive evaporative cooling technology is generally considered to be suited to hot and arid climates in that it can provide cooling without significant energy use and can also produce a better indoor environment by providing fresh, cool air into a space. With the benefits of energy efficiency, cost effectiveness and sustainability, the demand for passive evaporative cooling systems has grown in hot climates, often competing with or complementing conventional air conditioning systems. A passive down-draught evaporative cooling (PDEC) system, or cooltower, is a passive evaporative cooling technology that is designed to capture the wind at the top of a tower and cool the outside air using water evaporation before delivering the cooled and humidified outside air to a space. The system is able to provide cooling as the conditions of air delivered to the space are cooler than the interior conditions. Models exist for determining the impact of this technology, but in the past, these have not been linked with a whole building energy simulation such as EnergyPlus. As a result, this technology may not be applied correctly in certain situations or may not be considered as a potential design solution when it could be successful.

This paper presents the work that was done to remedy this gap in building energy simulation. A semi-empirical model developed by Givoni was implemented in EnergyPlus in order to model the simultaneous heat and mass transfer that occurs during the natural evaporative cooling in PDEC towers. This algorithm models the PDEC tower as a function of the wet bulb depression, the height of the tower, and water flow rate. The new model is able to determine not only air flow rate and temperature of the air exiting the PDEC tower, but also humidity ratio. This allows the energy simulation program to calculate the correct zone air conditions, i.e. the temperature and humidity ratio, based on an air heat and mass balance. The program can thus evaluate these systems in buildings as well as design and size the systems appropriately.

This study includes an introduction to the PDEC technology, a description of the existing literature and the model taken from the literature, a demonstration of model, and conclusions. In addition, the results of some case studies in different climate types and for various tower configurations will be presented so that the capabilities of this model and the potential impact of these systems can be demonstrated.

OVERVIEW OF PDEC SYSTEMS

Passive downdraught 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 (Cook et al., 2000). A PDEC tower typically consists of an evaporative device, a shaft, a wind catcher, and a water tank or reservoir as shown in Figure 1. Water is pumped over an evaporative device by pump which is the only component consumed power for this system. The applications of this technology can be variously named according to their structure, evaporative devices and geographical locations: wind tower (Bahadori, 1994), shower cooling tower (Givoni, 1994), and cool tower or natural draft evaporative cooler (Givoni, 1993).

The cooling performance of PDEC towers is dependent on various parameters. The performance is largely dependent on climatic conditions, tower configuration such as the height and cross-sectional area, and evaporative devices. Applications of PDEC technology can thus be categorized into three different types: a wind tower, a PDEC tower with pad, and a PDEC tower with spray. A wind tower is the simplest form of PDEC technology without any evaporative devices. To enhance the performance of wind towers, new designs for PDEC systems were developed: PDEC tower with pad or with spray, according to the type of evaporative devices.

Significant energy saving is the potential benefit of PDEC technology (Cook et al., 2000). Large volumes of fresh air from PDEC towers greatly improves the thermal comfort and the quality of the air in a space (Givoni, 1997; Cook et al., 2000). Night ventilation through PDEC towers is also feasible (Cook et al., 2000) and can reduce the cooling demand further. They are also applicable in a region without wind, creating airflow by momentum transfer from water drops to the air and density difference (Cook et al., 2000). On the other hand, climatic limitations are the main disadvantages of PDEC towers (Cook et al., 2000). Due to lack of models that estimate the performance and reliance on weather conditions, control is another deficiency. Additional issues include water use, hardness of the water, microbiological contamination, and sounds from the top (Ford, 2002)

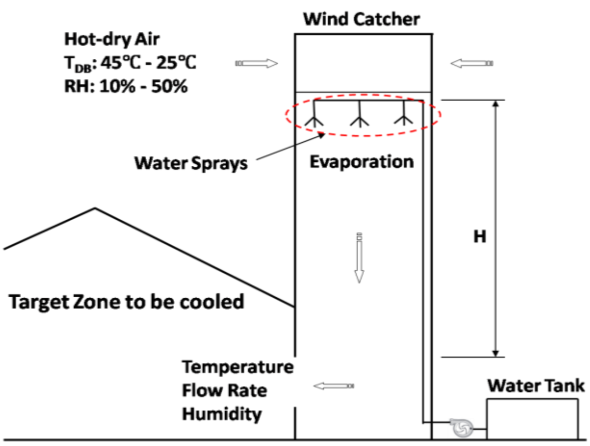

Figure 1 Schemetic of PDEC tower with spray

SIMULATION OF PDEC SYSTEMS

Existing models

Several models have been developed to predict the performance of PDEC towers with pad or spray. Thompson et al. (1994) developed a model for PDEC tower with pad and the model was employed in a simulation program, CoolT, which is intended to design a PDEC tower with pad system. This model, however, is only limited to cases without wind, and also cannot determine the humidity level at the exit, so the water consumption cannot be obtained. Givoni (1993) developed a model that predicts exit air temperature and air volume flow rate of a PDEC tower with pad based on a simple energy balance. This model includes the effect of wind speed. It, however, cannot predict the water content in the exiting air, so that zone air conditions cannot be corrected. Givoni (1994) also developed a model for determining the performance of PDEC towers with spray. This model predicts the exit air temperature as a function of outdoor dry and wet bulb temperature, tower height, and water flow rate. It can also predict the volume flow rate of exiting air and its velocity. It includes the influence of the ambient wind speed and water flow rate, so that the humidity ratio at the exit can be estimated based on an assumption of ideal direct evaporative cooling when the exiting air temperature is available.

Modeling Algorithm in EnergyPlus

Givoni's (1994) empirical model is employed for determining PDEC towers with spray in EnergyPlus in that it is currently the only model that can predict the actual impact of PDEC towers. This model is intended to provide not only air conditions such as flow rate, temperature, and humidity ratio but also water consumption and power consumption by the pump in EnergyPlus. The model is linked into the air heat balance rather than into an HVAC air loop as PDEC towers are typically standalone systems. The air from PDEC towers is assumed to be immediately mixed with the zone air. All components of PDEC towers are executed at the begining of each time step called by HVAC manager, and the air temperature and humidity ratio in the zone is corrected with any other air that enters the zone. The control is achieved by either specifying the water flow rate or obtaining the velocity at the outlet with inputs and weather conditions when the water flow rate is unknown.

The model first determines the temperature and volume flow rate of the exit air. Both parameters are directly determined for the case of the water flow schedule control when the water flow rate is known. With the outdoor temperatures obtained from weather data, the exit air temperature is determined as a function of outdoor dry bulb temperature, outdoor wet bulb temperature, effective tower height and water flow rate by using the following equation:

$$T_{out} = DB - (DB - WB)(1 - \exp(-0.8H))(1 - \exp(-0.15WF)) \quad (1)$$

The volume flow rate of exiting air is also directly determined as a function of water flow rate and effective tower height from the following equation:

$$Q_{out} = 0.0125WF \cdot H^{0.5} \quad (2)$$

In the case where the calculated air volume flow rate is greater than maximum air volume flow rate in this control, which leads to an overestimation of the actual volume flow rate of the exit air, the calculated air volume flow rate is replaced with the maximum. As for the simulation of wind-driven flow control where the water flow rate is unknown, the model determines the exit velocity as:

$$V_{out} = 0.7H^{0.5} + 0.47(WS - 1) \quad (3)$$

The estimated air volume flow rate, Q_{est}, is then calculated by multiplying the estimated velocity by the area of bottom opening, A, as:

$$Q_{est} = A \cdot V_{out} \quad (4)$$

Substituting the air flow rate to the equation (2), the water flow rate is:

$$WF = \frac{Q_{est}}{0.0125 \cdot H^{0.5}} \quad (5)$$

Once the water flow rate is determined, the model checks the limit of the water flow rate that the user inputs so that the model prevents the overestimation of the actual volume flow rate of the exit air. If the calculated water flow rate is greater than the maximum water flow rate, the maximum will be used. The model also replaces the calculated air volume flow rate with the maximum volume flow rate from the user input when the calculated is greater than the maximum. The model then calculates the air volume flow rate and the exit temperature using the equation (1) and (2).

The model allows the user to specify the water loss due to drift or blow down and the loss of air flow. If the user inputs the fraction of water loss or flow schedule, then some amount of air actually does not supply to the space, and the fractional values are applied to previously calculated ones so that the model calculates both actual water flow rate and actual air volume flow rate as:

$$WF_{act} = WF(1.0 + Fraction) \quad (6)$$

$$Q_{act} = Q_{out}(1.0 - Fraction) \quad (7)$$

In this case, the mass flow rates at the inlet and outlet of PDEC tower cannot be correctly calculated because the outlet density is unknown. Assumptions of ideal direct evaporative cooling, i.e. no enthalpy changes, as well as no pressure drops between inlet and outlet are thus made. The model then estimates an initial humidity ratio and densities at the inlet and outlet based on outdoor temperature, the calculated exit air temperature, the enthalpy of outdoor air, and the outdoor barometric pressure using EnergyPlus psychrometric functions. The mass flow rates of the initialized air and outdoor air are then obtained by:

$$\dot{m}_{a,in} = \rho_{a,in} \cdot Q_{act} \quad (8)$$

$$\dot{m}_{a,out} = \rho_{initial} \cdot Q_{act} \quad (9)$$

The model then determines the exit humidity ratio from the relation of the mass balances as shown below:

$$\omega_{out} = \frac{\omega_{in}(\dot{m}_{a,in} + \dot{m}_w)}{\dot{m}_{a,out}} \quad (10)$$

Once the humidity ratio at the exit is determined, the exit air density and the specific heat of exiting air can be obtained by using psychrometric functions. The exit mass flow rate is then:

$$\dot{m}_{out} = \rho_a \cdot Q_{act} \quad (11)$$

Assuming that the water temperature equals the outdoor wet bulb temperature, the model determines the density of the water. The evaporation rate is thus:

$$Q_w = \frac{\dot{m}_{out}(\omega_{out} - \omega_{in})}{\rho_w} \quad (12)$$

MODEL VALIDATION

The model developed determines air conditions from the PDEC tower. These conditions significantly vary with variables such as the temperatures of the air and water, the size of water drops, the weather conditions, and the tower configurations. However, the perfect set of data that includes all these variables or exact solutions is unavailable in the literature. The validation of the model is thus difficult, especially the calculation of the humidity level. As a result, the model was partially validated for temperature against experimental data. Givoni (1997) presented results from experiments in three different climates. Temperatures were predicted in both flow control types: wind-driven flow and water flow schedule. Table 1 shows the results of a comparison between measured and predicted temperatures. Significant agreements were observed, indicating the root mean square (RMS) error of 0.693 in wind-driven flow and 0.374 in water flow schedule. It should note that the RMS error could increase when the user specifies an inappropriate value for the maximum water flow rate in wind-driven flow.

CASE STUDY DESCRIPTION

The cooling capability of PDEC towers in different climates as well as potential impact were investigated through various case studies. Both short-term simulations for comparing the cooling performance and long-term simulations for comparing the energy performance have been performed in three different climates in the US. Simulations were run on a summer design day for the short-term simulation and May through October for the long-term simulation. Three different regions chosen were Phoenix, AZ as hot dry region, Dallas, TX as hot humid region, and Orlando, FL as warm humid region.

A secondary school benchmark model developed by the U.S. Department of Energy (DOE) was chosen as various tower configurations would be feasible in several different types of rooms, and a school is one good place to install PDEC towers because of its high occupancy levels. This two story E-shaped 23,804m^2 building has one main corridor with three wings for classrooms. The main spaces in this building include classrooms, an auditorium, a gymnasium, offices, a cafeteria, a kitchen, and a library. The building is divided into 46 zones. The window-to-wall ratio is 34%, and daylighting in the gymnasium is provied by skylights on 4% of the roof area. The building HVAC systems includes an air cooled chiller, a boiler, and a multi-zone VAV with reheat in most spcaes. Packaged single zone air conditioning (PSZ-AC) units and gas furnaces control the gymnasium, auditorium, kitchen, and cafeteria. The highest internal heat gain from lights is 15W/m^2 in the classrooms, cafeteria, and gymnasium. The other types of heat gains vary with each type of space.

PDEC towers were added as a backup cooling component in this study. That is, all inputs except an addition of PDEC tower were the same as the base cases. The only difference between the base cases and PDEC cases was that minimum outdoor air (OA) was assumed to be 25% of the minimum design OA for HVAC systems in the PDEC cases. PDEC towers were added in all spaces except the kitchen. They were operated 7AM through 8PM in the classrooms, offices, and corridors, and 9AM through 10PM in all the other spaces by scheduled values. Fixed inputs for the PDEC towers included wind-driven flow control, a maximum air flow rate of 10 m^3/s, fractions of 0.05 for water and airflow loss, and a minimum indoor temperature of 22℃. The other inputs for PDEC towers were classified into three different groups so that various tower configurations and variables could be applied. Table 2 describes the main input parameters for PDEC towers. A water flow rate of 12*l*/min and a height of 5m were inputted for smaller spaces such as the classrooms, bathrooms, and corridors. Medium size spaces including main corridors, the offices, and multi-purpose classrooms used a water flow rate of 15*l*/min and a height of 10m. Large spaces such as the gymnasium, auditorium, library, and cafeteria used a water flow rate of 20*l*/min and a height of 20m.

DISCUSSION

Indoor environment

To investigate the variations of indoor temperature and humidity, short-term simulations by using the PDEC tower with spray model have been carried out on a design summer day. Figure 2 illustrates the variations of indoor temperatures and relative humidities in each climatic area. The temperature variation in Phoenix was stable. Almost no difference in temperature between the base and PDEC cases appeared in Phoenix. The PDEC towers were likely to effectively reduce the cooling demand in Phoenix. The variation in Dallas, however, was less stable than the other locations. Temperature differences of about 0.7℃ between the base and PDEC cases appeared. This was because the PDEC towers provided 2℃ to 3℃ warmer air than indoor air during the afternoon, causing late responses from primary HVAC systems. The temperature variation in Orlando was also stable, and difference less than 0.5℃ between the base and PDEC cases were noted. This was mainly due to the relatively low outdoor air temperature while the exit temperature was similar to the indoor air temperatrue in the morning or 1℃ to 4℃ higher than the indoor temperature in the afternoon. Overall, the PDEC towers were effective in reducing the cooling demand in Phoenix while the temperature variation was less stable in Dallas and Orlando because the cooling outputs from the PDEC towers were highly reliant on the wet bulb depression.

Indoor relative humidity (RH) in the PDEC case increased in Phoenix, and the difference between the base and PDEC cases was about 5% in the classrooms and offices. RH in the auditorium, however, in PDEC case was about 3% lower than base case. This was likely due to the humidification of the air from the primary cooling system in the base case as outdoor RH level decreased up to 20%. RH in the classrooms and offices in the PDEC case in Dallas were much higher than the base case. A sudden increase of about 16% between 10AM and 12PM appeared in the classrooms in the PDEC case due to the introduction of saturated air as well as increase of the air volume flow rate from the PDEC towers. RH in the auditorium in PDEC case, however, was about 5% to 7% less than base case. This was because more cooling demand was necessary due to about 1℃ warmer air supply from the PDEC towers than the indoor temperature. Indoor RH level in Orlando were unstable even in the base cases. The differences between each space was relatively large. Sudden increases in RH of about

17% in the offices between 9AM and 11AM and of about 10% in the classrooms between 1PM and 3PM were observed. This was also due to the saturation of air from the PDEC tower and the increase of the air volume flow rate. RH level in the auditorium with a PDEC tower in Orlando was also about 5% less than base case, as in Dallas. Overall, the PDEC towers decreased cooling demand in Phoenix while increasing cooling demand in Dallas and Orlando. The effect of the PDEC towers on RH level was likely significant in a controlled space in all locations, especially in humid regions, increasing the cooling demand in a space.

Cooling performance

The model implemented in EnergyPlus predicted cooling potential from PDEC towers with spray. It estimated various environmetal factors such as temperature and RH at the exit of PDEC towers, thermal comfort, air change rate per hour (ACH), and water consumption in three different climatic regions. Table 3 shows the results from the case studies in three representative spaces: classroom, office, and auditorium. The PDEC towers in the auditorium indicated the lowest average exit temperatures of 21.9℃ in Phoenix and 25.5℃ in Dallas because of greater water flow rate and height than the other two spaces. The lowest temperature of 24.2℃ conversely appeared in classroom in Orlando. The difference in the exit temperature between each space in Orlando was only 0.43℃ while the differences were 1.06℃ in Phoenix and 0.89℃ in Dallas. The maximum temperature differences between the outdoor air and exit air were 17.7℃ in Phoenix, 12.9℃ in Dallas, and 9.4℃ in Orlando. These results supported that the exit temperatures were not proportional to the water flow rate when it reached a certain limit, due to the saturation of the air. The limit that occurs at saturation was also largely dependent on the outdoor wet bulb temperature.

The ACH values in the classrooms, offices, and auditorium in Phoenix were 13.7, 5.06, and 2.49, respectively. The ACH in the classroom was greater than the other spaces while the effective height was 5m. The air volume flow rates in each space were similar in each climatic location, and it greatly increased as the effective height and water flow rate increased. The average RH values ranged from 79.4% to 98.8% in Phoenix. Saturation of the air appeared in Dallas and Orlando, and it occurred most of the time in the classrooms and offices. It, however, appeared only a few hours in the morning in the auditorium in Dallas and Orlando. The PDEC towers were likely to be more effective in large spaces in all locations. It was note that both the height of the tower and the water flow rate significantly affect the air volume flow rate.

The average thermal comfort in the PDEC cases was better than the base cases in all regions. It was noted that the differences in thermal comfort between the base and PDEC cases were greater between 1PM and 6PM when the building had high cooling demands. This was not only because the PDEC towers increased the indoor air velocity but also because it increased the humidity level. Since indoor temperatures in PDEC cases in Dallas were a little higher than the other locations, thermal comfort predicttions were closer to neutral than in Phoenix and Orlando. The daily water consumption of the PDEC towers ranged from 84.86*l* to 142.75*l* in Phoenix. This value was similar to those in Dallas and Orlando, and ranged from 125.29*l* to 232.2*l*. This result supported that the cooling efficiency of PDEC towers would be lower in Dallas and Orlando than in Phoenix. The model estimated the water consumption using the evaporation rate while PDEC towers were operated. It, however, included the water evaporation even when the air was saturated, so that the actual water consumption in Dallas and Orlando would be smaller than the predicted one. The PDEC towers were thus less effective in Dallas and Orlando while those in Phoenix improved the thermal comfort and used less water to cool the space.

Energy performance

Long-term simulations for 6 months, May through October, predicted energy end use in electricity for cooling, water use, and pollutant emissions such as carbon dioxide, carbon monoxide, and sulfur dioxide as shown in Table 4. The effect of energy saving in electricity used for cooling reached 24% in Phoenix, 24.3% in Dallas, and 26.3% in Orlando. It was likely that PDEC towers affected the reduction of cooling loads, which leads to the reduction of the operating time of the primary HVAC systems. In addition, electricity for fans and pumps decreased about 5% while additional pump power for circulating the water for PDEC towers were added. The PDEC towers were not intended to be optimized in this study. There is thus more potential for energy savings when PDEC towers are properly controlled in all three climates.

Additional water consumption in the PDEC cases was 571 tons in Phoenix, 804.1 tons in Dallas, and 1111.35 tons in Orlando. As mentioned in the previous section, the actual water consumption in Dallas and Orlando was likely less than the predicted consumption. Water consumption of the PDEC towers in certain areas where water sources are lacking could be a significant issue as well. While considering buildings where PDEC towers can be applied, a small amount of additional water use may not be critical. In addition, pollutants emission such as carbon dioxide, carbon monoxide, and sulfur dioxide due to system opreation were reduced by

11% in Phoenix, 10.7% in Dallas, and 12.1% in Orlando. This was directly proportional to energy end use in EnergyPlus because pollutant emissions are mostly obtained from energy sources. The PDEC towers reduced by 25% the total electricity for cooling and by 11% the pollutant gas emission while requiring additional water use in all three climatic regions.

CONCLUSION

A module for predicting the cooling performance of a PDEC tower with spray has been developed. An overview of the PDEC system as well as a modeling algorithm were presented. Case studies have been performed to investigate the cooling and energy performance of PDEC towers in different climates. The results obtained from the case studies have shown that the water flow rate significantly affects both the air volume flow rate and the air temperature leaving PDEC towers. The performance of PDEC towers, however, is not proportional to water flow rate, while the height of towers has a linear relationship to air volume flow rate. Appropriate design of the water flow rate is thus required to maximize the efficiency of PDEC towers as well as minimize the water loss and the saturation of the air.

PDEC towers are best fit for hot, dry regions, accomplishing maximum temperature differences of 17.7℃ between outdoor air and the exit air from PDEC towers. They, however, are less effective in hot, humid and warm, humid regions because the cooling performance of PDEC towers varies greatly with weather conditions. Energy performance, however, and reduction of pollutants emission were effective in all climates. Indoor thermal comfort also improved in all climates. With careful design, PDEC towers can thus be used to cool or reduce cooling demand in a space not only in hot, dry areas but also in hot, humid as well as warm, humid areas.

NOMENCLATURE

DB: outdoor dry bulb temperature (℃)

H: effective height of towers (m)

$\dot{m}_{out}$: air mass flow rate from towers (kg/s)

$\dot{m}_{a,in}$: outdoor air mass flow rate (kg/s)

$\dot{m}_{a,out}$: initialized air mass flow rate (kg/s)

$\dot{m}_{w}$: water mass flow rate (kg/s)

Q_w: evaporation rate of water (m^3/s)

Q_{est}: estimated air volume flow rate (m^3/s)

Q_{act}: actual air volume flow rate (m^3/s)

Q_{out}: air volume flow rate leaving towers (m^3/s)

T_{out}: exit air temperature leaving towers (℃)

V_{out}: air velocity leaving towers (m/s)

WB: outdoor wet bulb temperature (℃)

WF: water flow rate (*l*/min)

WF_{act}: actual water flow rate consumped (*l*/min)

ω_{out}: humidity ratio of the air leaving towers

ω_{in}: outdoor air humidity ratio

$\rho_{initial}$: density of initialized air (kg/m^3)

ρ_a: density of air at the exit of the tower (kg/m^3)

$\rho_{a,in}$: density of outdoor air (kg/m^3)

ρ_w: density of water (kg/m^3)

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Table 1
Comparison between predicted and measured temperatures

	Wind-Driven Flow			Water Flow Schedule		
	T_{db}	T_{wb}	T_{out}	T_{db}	T_{wb}	T_{out}
Measured	43.0	19.0	26.0	43.0	19.0	26.0
Predicted	43.0	19.04	25.14	43.0	19.04	25.14
Measured	40.0	18.0	24.3	40.0	18.0	24.3
Predicted	40.38	18.1	23.78	40.38	18.1	23.78
Measured	34.0	16.3	21.0	34.0	16.3	21.0
Predicted	34.0	16.35	20.94	34.0	16.35	20.94

Table 2
Input parameters for PDEC towers

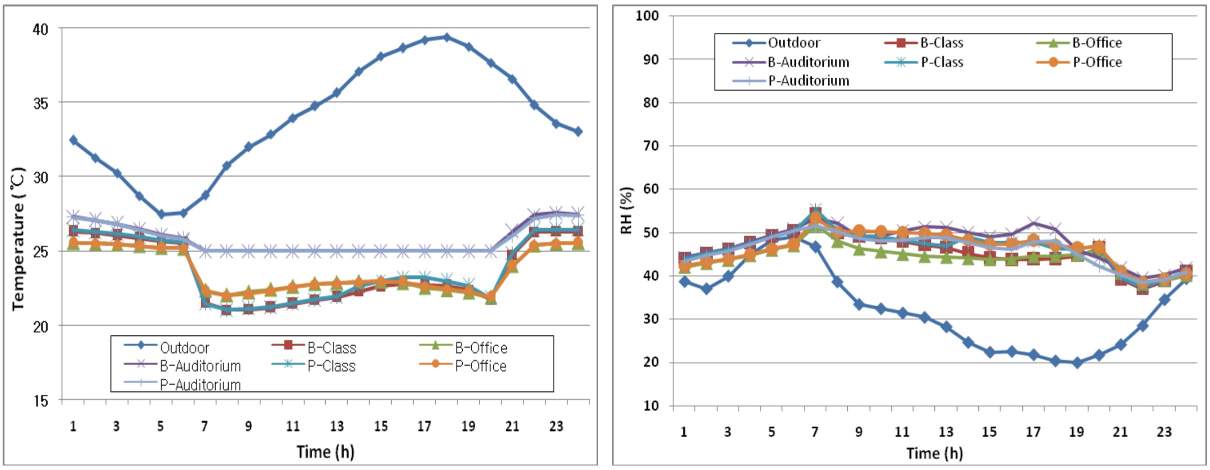
Type of rooms	Classroom	Office	Auditorium	Gymnasium
Water flow rate (m^3/s)	0.0002 (12*l*/min)	0.00025 (15*l*/min)	0.00033 (20*l*/min)	0.00033
Effective height (m)	5	10	20	20
Airflow outlet area (m^2)	1	2.25	2.25	2.25
Pump power (W)	30	50	75	100

Table 3
Cooling performance of different PDEC towers

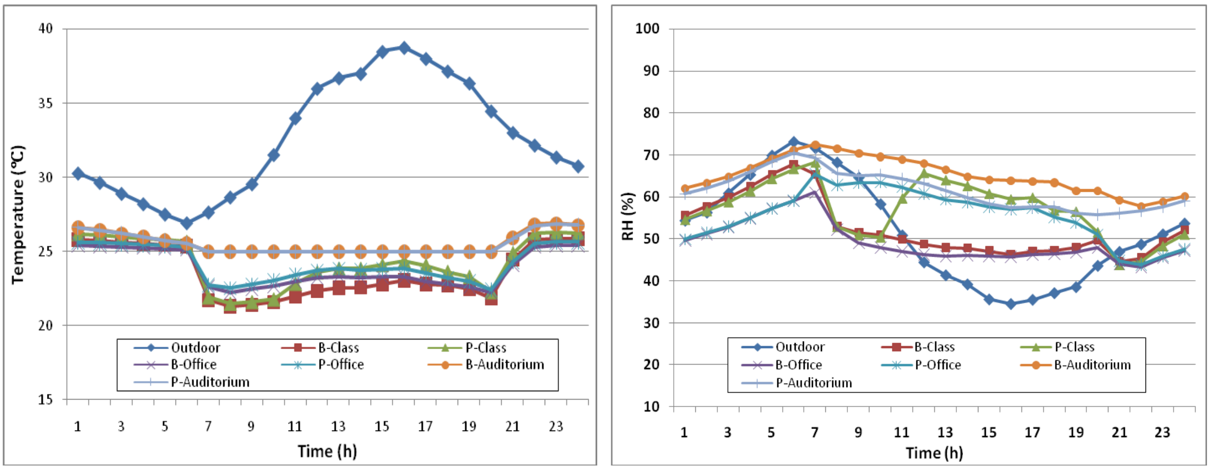
Type of rooms			Classroom	Office	Auditorium
Volume (m^3)			396	2128	7904
Hot-dry	Ave. Exit Temp. (℃)		22.93	22.49	21.87
	Ave. Exit RH (%)		98.8	86.3	79.4
	PMV	Base	-0.290	-0.357	0.271
		PDEC	-0.242	-0.346	0.250
	Ave. ACH		13.7	5.06	2.49
	Water Use (L/day)		84.86	114.16	142.75
Hot-humid	Ave. Exit Temp. (℃)		26.35	25.91	25.46
	Ave. Exit RH (%)		Saturated	Saturated	Saturated
	PMV	Base	-0.267	-0.286	0.316
		PDEC	-0.054	-0.150	0.287
	Ave. ACH		14.65	5.06	2.49
	Water Use (L/day)		133.69	177.45	224.77
Warm-humid	Ave. Exit Temp. (℃)		24.22	24.65	24.61
	Ave. Exit RH (%)		Saturated	Saturated	Saturated
	PMV	Base	-0.569	-0.565	0.186
		PDEC	-0.476	-0.454	0.162
	Ave. ACH		13.54	4.93	2.49
	Water Use (L/day)		125.29	174.43	232.2

Table 4
Energy end use and pollutants emission

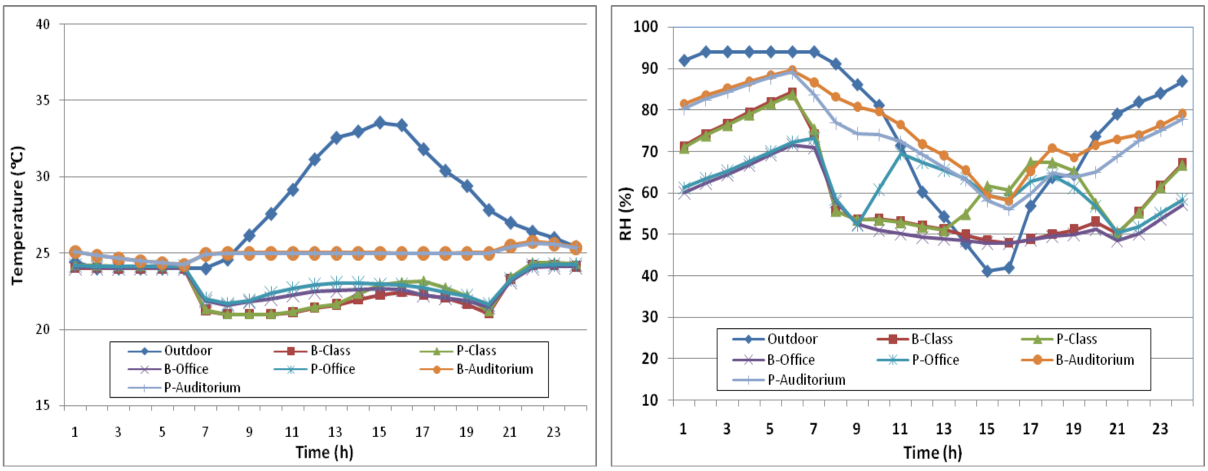
		Electricity: Cooling (GJ)	Water Use (m3)	CO2 (kg)	CO (kg)	SO2 (kg)
Hot-dry	Base	3726.8	338.14	1747271.5	693.3	9796.4
	PDEC	2832.49	909.14	1555903.6	618.2	8711.2
	Reduction (%)	24.0	-268.9	11.0	10.8	11.1
Hot-humid	Base	3501.29	338.14	1629736.1	647.85	9118.13
	PDEC	2650.47	1142.24	1455492.5	579.0	8139.0
	Reduction (%)	24.3	-337.8	10.7	10.6	10.7
Warm-humid	Base	3851.85	338.14	1672935.5	663.5	9384.6
	PDEC	2837.27	1449.49	1470007.6	583.7	8235.5
	Reduction (%)	26.3	-428.7	12.1	12.0	12.2



a) Variation of indoor temperature and relative humidity in Phoenix



b) Variation of indoor temperature and relative humidity in Dallas



c) Variation of indoor temperature and relative humidity in Orlando

Figure 2 Indoor environment variantion in school building with PDEC towers