Summer 6-13-2016

Significance of Parameters Affecting the Performance of a Passive Down-Draft Evaporative Cooling (PDEC) Tower with a Spray System

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Recommended Citation

Daeho Kang and Richard K. Strand. "Significance of parameters affecting the performance of a passive down-draft evaporative cooling (PDEC) tower with a spray system." Applied Energy 178 (2016) 269–280.

Applied Energy 178 (2016) 269–280

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Significance of parameters affecting the performance of a passive down-draft evaporative cooling (PDEC) tower with a spray system

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HIGHLIGHTS

- It demonstrates the significance of main parameters including those have not been well treated in the literature.
- It presents practical design guidelines for main parameters so as to significantly improve the performance of the system.
- It ensures that the performance of the system varies with many factors, rather than one dominant factor.
- It formulates two mathematical models that predict outlet air temperature and velocity.

ARTICLE INFO

Article history:
Received 20 September 2015
Received in revised form 24 April 2016
Accepted 13 June 2016

Keywords:
Evaporative cooling
Wind tower
FLUENT
Water droplet
Passive cooling
Spray

ABSTRACT

PDEC towers with spray systems are known to achieve substantial energy savings. Various parameters such as the wet-bulb depression, the tower height, and the wind speed have been known to be key factors affecting the performance of the system. To date, the significance of these parameters and other important factors have not been adequately treated in the literature. There also has been a lack of models that can successfully investigate potential benefits of the system under various conditions where this particular system could be applicable. To address these critical issues, this study performed a parametric analysis by using a FLUENT model validated against experimental data. It demonstrated the significance of individual parameters including water droplet sizes. As a result, practical design guidelines for important system parameters were presented. A statistical analysis was then used to formulate analytic models that account for all of the relationships found in this study between the parameters and the supply air conditions of the system. Two regression equations were formulated for predicting supply air temperature and velocity.

1. Introduction

Various natural ventilation enhancement strategies that use vertical elements have been used throughout history. One of the simplest of these is a wind tower or catcher. A wind tower is a fully passive system that receives outdoor air at the top of the tower and then delivers it to the interior of a building via an opening at the bottom. The simple wind tower operates without the aid of energy systems such as a fan, a coil, pumps, or evaporative devices such as a water spray [1–5]. One of the disadvantages of wind towers is that the cooling capacity of this particular component is insufficient and strongly dependent on local weather conditions [3,6–11].

A passive down-draft evaporative cooling (PDEC) tower is a variation of a wind tower. It is designed to capture the wind at the top like a wind tower but provides additional conditioning potential by cooling the outdoor air using water evaporation. Different types of evaporative devices such as wetted pads and water sprays are attached to wind towers in order to improve their performance, accelerating the direct evaporative cooling process by expanding direct contact between the incoming outdoor air and water added to the air stream via evaporation. The addition of evaporative devices to wind towers has been proven to significantly improve the cooling performance of the advanced forms of wind towers [8,12–15]. To date, these types of PDEC towers have been integrated into the built environment in a number of buildings, but the technology has not seen widespread implementation.

A more reliable method that helps designers understand the down-draft evaporative cooling process and its potential energy implication on buildings is needed. PDEC towers have been reported to achieve considerable energy savings and improved indoor environmental quality [8,13–17]. On the other hand, some

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http://dx.doi.org/10.1016/j.apenergy.2016.06.055
0306-2619/

Nomenclature

A_t	PDEC tower cross-sectional area in m^2
A_{wc}	area of the wind catcher in m^2
D	water droplet size in μm
g	moist content of air in liter
H	effective tower height from the bottom to the water spray at the top in m
L	depth of tower cross-section in m
$\dot{m}_a$	air mass flow rate in kg/s
Q	outlet air volume flow rate in m^3/h
RH	outlet relative humidity of PDEC flow in %
T_{db}	outdoor air dry bulb temperature in °C
T_e	outlet air temperature in °C
T_{wb}	outdoor air wet bulb temperature in °C
V_a	volume of air in liter
V_e	outlet air velocity at the bottom of PDEC tower in m/s
V_i	inlet air velocity at the top of PDEC tower in m/s
V_o	outdoor wind speed in m/s
V_w	volume of water in liter
W	width of tower cross-section in m
WF	water flow rate in l/h
WS	outdoor wind speed in m/s
ρ_a	density of air in kg/m^3
ρ_w	density of water in kg/m^3

Subscripts

db	dry bulb
e	tower exit
i	tower inlet
o	outdoor
t	tower
wb	wet bulb
wc	wind catcher

researchers have reported that, due to their climatic dependency, PDEC towers struggle to maintain a comfortable indoor environment in comparison to conventional mechanical cooling systems [9,11,13,18,19]. Additionally, previous studies focused mostly on the quantification of energy savings even though PDEC towers affect extensively the indoor thermal environment and indoor air quality. In fact, a number of approaches have been used to explain both the down-draft evaporative cooling process and the resulting indoor environments that they create such as post occupancy surveys, field experiments, building simulation, and computational fluid dynamics (CFD) analysis [1,4,5,8–10,12,17,18,20–38]. While such efforts have improved their performance to some extent, PDEC towers are still not commonly used as a low-energy solution in the cooling of buildings. Thus, to promote both the better and more frequent utilization of this technology, it is critical to provide a better understanding of the main physical phenomenon, the simultaneous heat and mass transfer, and the various benefits of these systems.

The accurate prediction of the air outlet conditions received from PDEC towers is critical. A number of parameters have been identified to significantly impact the conditions of air at the PDEC system outlet [2,8,11,12,20,31]. Most existing models assume that the performance is a function of the wet-bulb depression [8,16]. In other words, they assume that PDEC towers operate using a fixed wet-bulb depression effectiveness despite the fact that outdoor air conditions almost always vary. In fact, it is very difficult to maintain a constant performance without significant advancement in performance control. A few models include more parameters such as tower height, wind speed, and water flow rate and some studies have carried out parametric studies using these models to investigate the influence of other factors [8,15,16,18,31]. While a number of factors considerably affect the performance of PDEC towers [4–11,20,24–26], the effect of various parameters has not been well understood. Thus, it is very important to thoroughly examine how individual variables impact the performance and to seek what other factors have a strong impact to the performance.

An accurate mathematical model can play a key role in the advancement of PDEC tower systems since it can be used to predict the energy performance of system. Moreover, a mathematical model can then be readily implemented within the structure of a building energy simulation program, which will further assist designers in determining whether such a system is feasibly for a particular combination of building and climate [9,15,19,23]. A few models, such as Givoni's [8] empirical model, have been used for years since they enable predicting the humidity level of PDEC systems. However, the predictions of such models are unlikely to be accurate when conditions such as the outdoor air temperature, the water flow rate, and the physical tower dimensions are different from those used in the experiments. The performance of PDEC towers should be examined in all situations where they could be used. To that end, mathematical models are needed that accurately predict the outlet conditions of PDEC systems based on the true inlet conditions and can be integrated into simulation program so that the actual impact of a PDEC tower can easily be investigated with acceptable accuracy.

This study investigates the significance of individual parameters on the performance of a PDEC tower with a spray system. It also aims to develop mathematical models so that the performance of the system can be readily estimated by implementing the developed mathematical equations in a building energy simulation program. To achieve this, a parametric analysis is performed under a wide range of conditions using a FLUENT model that was validated against experimental data set by the authors [9]. Details of the computational schemes of the FLUENT model can be found in [9,10]. The statistical analysis includes all of the main parameters that were identified as significantly affecting the system performance. Finally, it formulates mathematical equations that accurately predict the temperature, the humidity, and the velocity of the air leaving the spray PDEC tower system.

2. Literature review

2.1. Analytical models

Early studies conducted a number of experiments and developed analytical models. Givoni [8] established empirical models to predict outlet air temperature, volume flow rate, and velocity from the results of experiments as follows:

$$T_e = T_{db} - (T_{db} - T_{wb})[1 - \exp(-0.8H)(1 - \exp(-0.15WF)] \tag{1}$$

$$Q = 0.125WF \cdot H^{0.5} \tag{2}$$

$$V_e = 0.7H^{0.5} + 0.47(WS - 1) \tag{3}$$

Yajima and Givoni [39] experimented with a PDEC system in a mockup model in Yokohama, Japan on a summer day. The PDEC tower was directly connected to a duct that discharged PDEC air-flows to outdoor. The height and the square cross-section of the system were 3 m and 0.6 m, respectively. The supply water flow rate was 7–14 l/min. They then formulated two regression equations for predicting outlet air temperature as a function of the wet-bulb depression

$$T_e = 0.8304(T_{db} - T_{wb}) - 0.346 \tag{4}$$

and outlet air velocity as a function of water flow rate and outdoor air velocity as

$$V_e = (0.464WF + 0.2731) - 0.0351V_o \tag{5}$$

Givoni [40] summarized the results of an experiment in a test cell in California, USA in the following study. A tower height of 2 m and a water flow rate of 14 l/min were used. The study described a possibility of sea water usage to overcome a limitation of a PDEC system since water resources in a hot dry climate is typically limited, where a PDEC tower system is suitable to operate. Almost no difference in the performance between a system injecting fresh water and sea water was found. It also found that a higher tower up to 3 m and a greater water flow rate resulted in a greater temperature reduction. Two empirical equations from the results of the experiment were then formulated. Outlet air temperature was expressed as a function of the wet-bulb depression and water flow rate as

$$T_e = T_{db} - [0.9(T_{db} - T_{wb}) \times (1 - \exp(-0.15WF)] \tag{6}$$

Supply air volume flow rate was expressed as it varies with water flow rate and a tower height in meter squared as the following relationship

$$Q = 42WF \cdot H^{0.5} \tag{7}$$

These models neglected influences of air mass flow rates that vary with the sizes of a wind catcher and a tower cross-section though it accounted for influences of wind speed. Water droplet sizes, which is one of the most important parameters, were also excluded. These models can be applicable to a narrow range of climatic conditions and a small tower, which were used for the experiments.

Robinson et al. [19] introduced a simple approximation in the efficiency of the wet-bulb depression, due to lack of solutions to solve main physical phenomena of the down-draft evaporative cooling process. The study assumed that a PDEC system always achieved 70% of the wet-bulb depression as follows

$$T_d = T_{db} - 0.7(T_{db} - T_{wb}) \tag{8}$$

It then reversely determined the water demand to achieve the fixed efficiency of the wet-bulb depression as

$$V_w = \rho_a V_a (g' - g)\rho_w^{-1} \times 10^3 \tag{9}$$

Bahadori et al. [17] proposed a thermal network analysis to evaluate the cooling performance of wind towers. The study assessed two new designs in conjunction with a traditional wind tower that has no evaporative devices. The thermal network analysis applied surface heat balances from energy equations in order to calculate inside and outside surface temperatures. The flow field was determined by a pressure balance. It divided the computational domain into 1 m-height sections and assumed an adiabatic cooling process throughout each section.

Soutullo et al. [37] established a thermal model to optimize the energy performance of a larger scale fan-assisted evaporative wind tower, which the height and diameter of the tower were 18 m and 25 m, respectively. The model assumed three thermal zones throughout the effective height of a tower of a PDEC system, and an adiabatic cooling process between zones was assumed. It employed generic mass and energy balances and the mass and energy balances were applied to each zone. It estimated a mass transfer coefficient to calculate water flow rates.

2.2. Related works

Analytical models have been implemented in a whole building energy simulation program in order to utilize comprehensive capabilities of such programs. This approach enabled users to investigate the energy performance of a PDEC system, a carbon reduction capability, and potentials for being used with other cooling strategies. The analytical models above that Robinson et al. [19] introduced were coupled with Esp-r program though the operation of a PDEC system at constant performance is in fact extremely difficult without significant advancements of the system, due to its strong climatic dependency. The authors of this study [18] implemented Givoni's empirical models (Eqs. (1)–(3)) in EngeryPlus program since the prediction of water consumption was possible as the models included two key parameters, such as a water flow rate and an air velocity, other than the efficiency of the wet-bulb depression. However, due to inherent limitations of Givoni' model as explained above, the results of the simulations may not be able to handle a wide range of climatic conditions, tower configurations, and system operating conditions. The thermal model that Soutullo et al. [37] developed was also integrated with TRNSYS program and the predictions of the model in the wet-bulb depression was compared with the measured data from the experiment.

A CFD analysis is another approach that has been increasingly used to understand the main physical phenomenon of the down-draft evaporative cooling process, i.e., simultaneous heat and mass transfer. As part of an EU project, Cook et al. [12] utilized a commercial CFD code CFX to model the direct evaporative cooling process. While treating continuous phase and disperse phase as well as their coupling, the study reversely predicted water demand to achieve a constant temperature drop. However, the study assumed a symmetric computational domain and the validation process was not described. Saffari and Hosseinnia [33] used an open CFD package to model a wind tower with a wetted column that Bahadori [17] proposed. This CFD model was validated against the Bahadori's analytical model. The study evaluated a number of parameters and confirmed that the magnitude of a temperature reduction varied with an ambient air velocity, a water droplet size, and a water temperature. Soutullo et al. [37] also evaluated a fluid flow using a CFD package FLUENT. The study investigated influences of a wind catcher, a tower height, and a bottom opening. It suggested that one bottom opening enhances the efficiency of a wind tower significantly. The authors of this study [9,10] also developed a FLUENT model that was validated against a series of data collected from an EU project. The study explicitly demonstrated the down-draft evaporative cooling process and performed a parametric analysis under a dry and a humid condition. It highlighted the importance of a detailed design process as the cooling performance of a PDEC system strongly dependent on a number of parameters. Kalantar [42] developed a numerical model to study a wind tower by using the FLUENT code. The model solved a set of equations to explain the down-draft evaporative cooling process. It was validated with a data set from [25] that all parameters used for the experiment were not fully descriptive. While this model properly treated both continuous and disperse phases and their coupling, the validation process, which is critical, needed to be further explained. Calautit et al. [38] used a CFD technique to compare cooling performances between a PDEC tower and a heat pipe assisted wind tower. The study used the same geometry as [42] and the results of both a PDEC tower and a wind tower with heat pipes were compared.

A few studies evaluated the importance of individual variables, especially a water droplet size while many studies highlighted that it is a key parameter that significantly affects the performance of a PDEC tower. Pearlmutter et al. [25] studied different tower configurations to see the influences of water droplet sizes and supply volume flow rates. A prototype analysis with a one-third scale tower, which was a height of 3 m and a cross-sectional area of 1 m^2. A field test was followed with a full scale round tower that had the height of 10 m and the diameter of 3.75 m. The results of the study confirmed that a finer water droplet led a greater temperature reduction and cooling capacity. It also discovered that the mixed droplet case performed best as coarse droplets increased natural down-draft flow. Belarbi et al. [21] proposed a cellular approach to determine a time for the completion of evaporation in a PDEC application. The cellular approach assumed a uniform distribution over the water spray region. On the other hand, this approach determined initial conditions based on the input of bubble size, which is extremely difficult to define. The authors of this study [9,10] also evaluated the cooling capacity of a PDEC system with the variation of water droplet sizes ranged from 50 μm to 300 μm. The differences in a temperature reduction and a relative humidity variation reached 7.49 °C and 41.65% in a dry condition (RH 20%), and 6.12 °C and 26.52% in a humid condition (RH 40%), respectively.

3. Results

3.1. Parametric analysis

3.1.1. Overview

The authors [9,10] greatly enhanced the prediction of the cooling performance of a spray PDEC tower system. As discussed in the literature section above, CFD models found in the literature [12,33,37,38,42] have not been explicitly validated. They also oversighted the effects of main parameters, especially a water droplet size while much of the studies, discussed in the previous literature section, described that it is a critical factor that strongly affects the cooling performance of a PDEC tower. All these studies disregarded a droplet size or its distribution. To that end, it can be said that they partially explain the down-draft evaporative cooling process. On the other hand, the CFD model that the authors developed [9,10] fully demonstrated the validation process, including a specific droplet size. The computational domain of the CFD model was set to be from the top of a water spray system to the top of bottom openings, so that the model can be universally used to predict the outlet air conditions of a PDEC system. In addition, the model also adequately accounted for turbulence at the inlet, wall-bounded flows, and 2-way coupling of continuous phase and disperse phase. As a result, the accuracy of the process model significantly improved.

A parametric analysis was performed to understand the physical phenomena that occur within the effective area of a spray PDEC tower system as well as the impact of various factors on the cooling performance of the system. Some parameters, such as the wind speed, the tower height, the water flow rate, and the droplet size are known to be ones which significantly affect the performance of these systems. Almost all PDEC systems that currently used as cooling applications have been designed based upon the performance estimated by analytical models discussed in the literature section that include only the wet-bulb depression. The demerits of these models are that they were developed under very limited conditions such as a particular climate region, a specific tower configuration, and a water supply condition. As a result, it is expected that the predicted conditions of the air leaving PDEC towers may be inaccurate when climatic conditions and tower configurations differ from the conditions used for experiments. Therefore, the influence of all main parameters must be further investigated under a broader range of climates, physical tower sizes, and operating settings in order to improve the accuracy of the existing models.

It is also important to identify parameters that have not been treated in the literature. The size of the water droplet is known to be a critical factor, and it is generally speculated that finer droplets achieve a better performance [15,17,20,27]. However, the literature does not thoroughly address how droplet sizes affect the supply air of a spray PDEC tower system or what droplet sizes would be the most effective in terms of energy efficiency. Building applications of a spray PDEC tower system are typically designed to achieve the maximum wet-bulb depression, resulting in a high humidity level. Likewise, many questions arise when physical configurations vary such as the tower height, the cross-sectional area, and the wind catcher area. Answers regarding these parameters are needed since these would resolve critical questions regarding the potential implementation of this particular system. To address this issue, a parametric analysis was designed to investigate the significance of each parameter on the performance of spray PDEC tower systems. The main parameters include not only the ones which have been identified by the existing literature in a limited way, but also unknown factors such as the droplet size and the air mass flow rate in the wind catcher and tower cross-sectional area.

3.1.2. Air mass flow rate

The mass flow rate of the incoming outdoor air is not conclusively treated in the literature. One study investigated what type of wind catchers introduces more outdoor air [28]. Some studies have dealt with the influence of wind speed with no consideration of the physical size of a PDEC tower [7,8,25]. However, the combination of these variables determines the air mass flow rate that a spray PDEC system needs to condition. Thus, studies do not currently exist that properly estimate the air mass flow rate corresponding to the physical size of a wind catcher and a cross-sectional area of PDEC tower. To date, the air conditions at the outlet of PDEC towers have been estimated to be constant regardless of the size of the PDEC tower. That is, a constant wet-bulb depression was assumed despite the fact that either the actual mass flow rate over the wind catcher or tower cross-section vary. It becomes clear that the predictions by the existing models and methods are inaccurate when any of the components that determine air mass flow rate differ from those used in the previous studies.

Table 1 illustrates eight different combinations of both the wind catcher and the PDEC tower cross-sectional area to see how the performance varies along with the variation of air mass flow rates. The FLUENT models that the authors developed were used to predict the conditions of PDEC flows at the outlet, such as temperature, relative humidity, and velocity in each combination. The variations of wind catcher size and PDEC tower cross-sectional area were then modeled for wind speeds ranging from 1 m/s to 6 m/s using an interval of 1.0 m/s [9]. All other conditions for this series of tests remained the same. They included an outdoor temperature of 35 °C, a relative humidity of 20%, a wet bulb temperature of 18.87 °C, a tower height of 7.15 m, a droplet size of 30 μm, and a water flow rate of 50 l/h. The resulting air conditions for each combination at different wind speeds are listed in Table 2.

As expected, the performance of the PDEC tower system varied significantly with the variation of the air mass flow rate at the same tower cross-sectional area. The output data presented in Table 2 clearly shows that the lower air mass flow rate, the greater temperature drops when the tower cross section is the same. The PDEC tower configurations that resulted in a lower inlet air velocity (V_i) achieved greater temperature drops than higher air velocities. A larger temperature drop was also achieved as the outdoor wind speed decreased since it resulted in a lower air mass flow rate. Similarly, it is also seen that a smaller wind catcher with a

Table 1
Combinations of the sizes of the wind catcher and the PDEC tower.

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

Table 2
Outlet air conditions under 8 PDEC tower configurations.

Configuration	V_i (m/s)	V_o (m/s)	$\dot{m}$ (kg/s)	T_e (°C)	RH_e (%)	V_e (m/s)
1	6	6	110.02	33.22	24.05	4.77
2	4.5	6	82.51	32.63	25.63	3.57
3	3	6	55.01	31.46	29.0	2.36
4	1.5	6	27.50	27.99	39.4	1.16
5	6	6	61.88	32.63	25.63	4.58
6	3	6	30.94	30.3	32.64	2.27
7	3	6	13.75	27.99	41.33	2.11
8	1.5	6	6.88	21.25	76.55	1.03
1	5	5	91.68	32.87	25.0	3.96
2	3.75	5	68.76	32.16	26.95	2.96
3	2.5	5	45.84	30.76	31.2	1.97
4	1.25	5	22.92	26.65	47.4	0.97
5	5	5	51.57	32.16	26.96	3.8
6	2.5	5	25.79	29.38	36.05	1.89
7	2.5	5	11.46	26.62	47.54	1.75
8	1.25	5	5.73	18.87	Saturated	0.97
1	4	4	73.34	32.34	26.4	3.16
2	3	4	55.01	31.46	29.03	2.35
3	2	4	36.67	29.75	34.8	1.55
4	1	4	18.34	24.65	57.6	0.76
5	4	4	41.26	31.46	29.04	3.04
6	2	4	20.63	28.0	41.4	1.55
7	2	4	9.17	24.6	57.75	1.39
8	1	4	4.58	18.87	Saturated	0.68
1	3	3	55.01	31.45	29.0	2.37
2	2.25	3	41.26	30.3	32.7	1.77
3	1.5	3	27.50	28.0	41.3	1.16
4	0.75	3	13.75	21.35	79.14	0.57
5	3	3	30.94	30.3	32.77	2.27
6	1.5	3	15.47	25.74	50.28	1.11
7	1.5	3	6.88	21.25	79.84	1.03
8	0.75	3	3.44	18.87	Saturated	0.5
1	2	2	36.67	29.73	34.78	1.55
2	1.5	2	27.50	28.0	41.3	1.17
3	1	2	18.34	24.65	57.75	0.76
4	0.5	2	9.17	18.87	Saturated	0.38
5	2	2	20.63	28.0	41.42	1.49
6	1	2	10.31	21.3	79.4	0.73
7	1	2	4.58	18.87	Saturated	0.67
8	0.5	2	2.29	18.87	Saturated	0.32
1	1	1	18.34	24.64	57.73	0.77
2	0.75	1	13.75	21.35	79	0.57
3	0.5	1	9.17	18.87	Saturated	0.38
4	0.25	1	4.58	18.87	Saturated	0.18
5	1	1	10.31	21.3	79.47	0.73
6	0.5	1	5.16	18.87	Saturated	0.35
7	0.5	1	2.29	18.87	Saturated	0.32
8	0.25	1	1.15	18.87	Saturated	0.18

corresponding lower air mass flow rate at the same wind speed resulted in greater temperature drops and relative humidity increases at the same cross-sectional area of the tower. Differences in temperature and relative humidity in tower configurations 1 through 4, which have four different sizes of wind catcher at the same tower cross-sectional area of 4 m × 4 m, increased as ambient air speed decreased. These tendencies also appeared in the other combinations.

It can also be seen that the outlet conditions of PDEC systems are driven mainly by an inlet air velocity over the tower cross-sectional area. The outlet air conditions were determined by the magnitude of the air mass flow rate at the same tower cross section. However, a lower air mass flow rate does not necessarily result in a greater temperature drop when the tower cross-sections differ. For instance, the configuration 2 has a greater tower cross section, which leads to a greater mass flow rate at the same wind speed. The air mass flow rate of the configuration 5 that has a smaller tower cross-section is lower. Both configuration 2 and 5 show very similar results in temperature and relative humidity. The same tendency also appears in the configuration 4 and 7. This is because these cases have the same Reynolds number, resulting in the same turbulence parameters, i.e., turbulent intensity and length scale. It can be said that the down-draft evaporative cooling process is directly affected by the magnitude of turbulence.

The ratio of the wind catcher area to the tower cross-sectional area also seems to play an important role, determining the velocity of the incoming air stream over the cross-sectional area of the tower. In several cases, the outlet conditions of the system are saturated. Saturation conditions generally occurred in the cases where both the air mass flow rate was below 10 kg/s and the corresponding inlet air velocity was below 1 m/s. This trend is also seen in cases that have a lower ratio of wind catcher area to tower cross-sectional area, causing saturation at relatively higher wind speeds. For instance, the ratio of wind catcher area to the tower cross-section is 0.25 in both the configurations 4 and 8. Saturation appears at an outdoor wind speed of 5 m/s, which has a corresponding inlet air velocity of 1.25 m/s, in the configuration 8 while appeared at a relatively higher inlet wind speed of 2 m/s in the configuration 4. These results suggest that the ratio be maintained at a certain value such as greater than 0.5 in order to minimize saturation conditions at the outlet of a PDEC system, especially at lower outdoor wind speeds. This ratio can also be used to achieve a greater temperature drop in climates that outdoor wind speed is relatively higher.

A very strong linear relationship between the inlet and outlet air velocity is found. One definite trend in the results is that the outlet air velocity is directly related to the inlet air velocity in all configurations. The coupling of both fluids, i.e., water and air, during the down-draft evaporative cooling process reduces the velocity of the air stream. However, the coefficient of determination, i.e., the R^2 value, of the linear relationship in all cases was 0.997. This strong linear relationship indicates that the momentum of the air stream significantly affect the resulting air velocity in conjunction with 2-way coupling of the fluids, rather than the diffusivity of the air streams through different tower cross-sections considered in this study. This is likely due to a formation of a high-speed air stream along the wall that the incoming air stream bounds.

3.1.3. Tower height

The height of PDEC tower has also been identified as an important design parameter which affects the performance of the system significantly [6,7,11,13,25]. While some studies show that the relationship between the PDEC tower height and the performance is not linear, it is true that it has a significant impact on the performance [18,25]. Thus, given that the tower height is important to both the performance and cost of the system its exact influence on performance is not fully understood. This study considers a number of tower height scenarios to better understand the rela-

Table 3
Conditions of variables for the analysis of tower height.

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

tionship between tower height and performance. These scenarios include different climates, tower cross-sections, and wind speeds. Tower sizes are also categorized into smaller towers and larger towers. The height varied from 3 m to 14 m with an interval of 1 m while the other parameters remained constant within a specific scenario. Table 3 illustrates the parameter settings imposed in the analysis for this subsection.

As demonstrated in Table 4, different trends in the outlet air conditions appear. One of the trends found in the results is that a greater variation of outlet air conditions appears in the lower tower height range below 5 m. The greatest difference in temperature, relative humidity, and velocity at the outlet is predicted as the tower height increases from 3 m to 5 m. It is clear that the evaporative cooling process cannot be fully completed due to the relatively greater momentum of the incoming air at the top and the circulation of humidified backflows within the PDEC tower [9]. Another trend is that the variation of the outlet air conditions decreased significantly as tower height reached 8 m in the bigger tower cases (case 3 and 4) while smaller tower cases (case 1 and 2) show a consistent temperature drop as tower height increases. Another trend related to the outlet velocity is that it decreases as tower height increases, lessening the supply air flow rate due to a longer evaporation time. These trends indicate that an effective tower height for larger towers would be approximately 2 times greater than the width of the tower cross-section when it is aligned with the wind direction, and a higher tower would promote evaporative cooling process longer in smaller towers.

The sensible cooling capacity of the PDEC tower system varies substantially in the different cases. A simple comparison of the sensible cooling capacity was studied, assuming an indoor setpoint temperature of 25 °C. The height achieving the greatest temperature drop was chosen in each case. The tower sensible cooling capacities in cases 1 and 3 were calculated to be −61.8 kW and −127 kW. The system was predicted to supply warmer air under the given conditions, causing a significant increase in the cooling load. Conversely, in the case 2 and 4, the system provided cooling of 40.37 kW and 29.75 kW, respectively. It can be concluded that the inappropriate design of PDEC towers could cause an adverse effect on the interior environment of a building if not properly controlled and managed.

Table 4
Outlet air conditions with variation of tower height in the four different cases.

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

3.1.4. Shape of tower cross-section

Various shapes can be used for a PDEC tower cross-section. While most towers are square, some PDEC towers have a rectangular, hexahedral, or octagonal cross-section [3,29]. Since different shapes are possible, it is necessary to study whether the shape of tower cross-section affects the cooling performance. While the prediction of the overall air distribution with a 3-D computational model may be more accurate, a 2-D model would also result in reasonably accurate predictions, since it can properly model the turbulence at the inlet and the wall-bounded flows over the computational domain. A rectangular cross-section was chosen since it is the most popular shapes.

Necessary parameters for the FLUENT model were adjusted to model rectangular-shaped towers. Since the majority of the aspect ratios in the literature appears to be either 4:3 or 3:2, an aspect ratio of 3:2 is chosen for this study. The turbulent parameters, i.e., turbulent intensity, turbulent kinetic energy, and turbulent dissipation rate, are calculated by using generic equations determining turbulence according to the chosen 3:2 aspect ratio [9,41]. The following outdoor condition is used for this analysis: an ambient air temperature of 35 °C, a relative humidity of 20%, and a wind speed of 4 m/s. A tower height, droplet size, and water flow rate are assumed to be 7.15 m, 30 μm, and 50 l/h, respectively. The configurations of the wind catcher and the tower cross-section are listed in Table 5. The wind catcher was assumed to be placed on the surface along the length of rectangular tower; as a result, air flowed along the width as shown in Fig. 1. The width of the tower is defined to be parallel to the wind direction, which is perpendicular to the inlet surface of the wind catcher.

The results showed that the temperature predicted at the exit of the towers is dependent on the tower width, which is parallel to the direction of the incoming air. Table 6 illustrates the outlet conditions of PDEC flows in the four different tower configurations. In addition, a narrower width tower (Rectangular 2) achieve a greater temperature drop. That is, the outlet temperatures were lower in the narrower width tower and greater in the wider width tower (Rectangular 1). In contrast, the air velocities of the wider width tower were greater and those of the narrower width tower were lower. A bigger difference in the outlet temperatures between the three, i.e., square, rectangular 1, and rectangular 2, was observed in the cases that a PDEC tower treated an air mass flow rate less than approximately 20 kg/s, which is case B, C, and D. The narrower width tower (Rectangular 2) achieved the best overall performance.

Another finding is that the width of the tower cross-section determines the characteristics of the resulting fluid flow. In this

Table 5
PDEC tower configurations for the analysis of the shape of the PDEC tower cross-section.

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

[a] Note that dimensions are listed as width by depth.

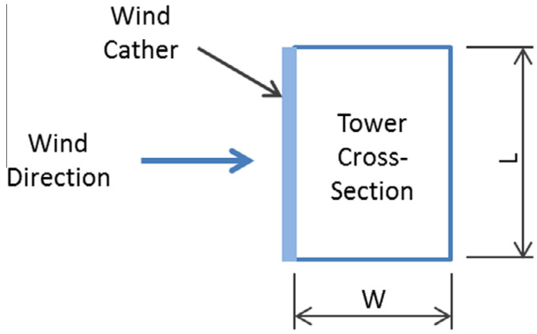

Fig. 1. Schematic of the tower aspect ratio on the plan view of the tower cross-section.

series of runs, the turbulent quantities are calculated depending upon the shape of the cross-sectional area. While the Reynolds number of both shapes Rectangular 1 and 2 were the same since the hydraulic diameter, which is a function of the area and perimeter of the cross-section, the inlet air velocity, and the viscosity are identical, the characteristics of the resulting fluid flow, such as wall-bounded flows and backflows, differ in the two rectangular cross-sections. However, the resulting flow was similar in the square tower and the rectangular tower where the width of rectangular tower was equal to the length of one size of the square shape. For example, the resulting flow for the tower with a 3 m-width by a 5 m-depth is very similar to that of the square tower with the 3 m-long sides. Thus, it can be said that rectangular towers could be considered as a square tower that has the same length as the width of rectangular one when the aspect ratio is not significantly different from the one 3:2 used in this analysis.

3.1.5. Droplet size

Water droplets size is known to be a critical factor that significantly affects the cooling performance of spray PDEC tower systems. It is generally known that the finer water droplets are the better the cooling performance is. While many studies recognize the importance of the size of the water droplets [11,12,25], relatively few investigate how their size affects performance. It is thus very important to see how significant the impact is. Simulations using the FLUENT model were run under four different outdoor conditions. The following input conditions were used to create a variety of cases: an outdoor air temperatures of 30 °C and 35 °C, a relative humidity of 20% and 40%, a tower height of 7.15 m, a wind catcher size of 4 m × 2 m, a tower cross-section of 4 m × 4 m, and a velocity of 2 m/s. As a result of these assumptions, the inlet air velocity and the air mass flow rate were the same in all cases for this portion of the study.

Significant differences appeared in the outlet air conditions as the droplet size varied as shown in Tables 7 and 8. The maximum difference in the outlet temperature between the smaller droplet and the biggest droplet of 500 μm is 8.49 °C in the drier case (RH 20%). Sizable differences in the relative humidity are also found, and the maximum relative humidity difference between the smaller and greatest was 53.83% for the humid condition (RH 40%). It is true that the outlet air conditions may vary with changes in the other parameters such as the water flow rate and the wind speed. However, it also seems clear that the water droplet size has a very strong influence on the outlet air conditions although the level of significance under different situations could vary.

The effect of momentum transfer of water droplets to the air stream was likely negligible. Some studies indicated that bigger droplets may create airflow toward the bottom as they transfer momentum to the air stream [22,25]. Yet, the results of this study showed that outlet air velocities were fairly constant with almost no variation, ranging from 0.76 m/s to 0.79 m/s. Since the impact of momentum transfer with the variation of water droplet size is unknown, it is hard to say that an increase of the outlet velocity of 0.01–0.02 m/s is significant. It could perhaps be helpful for PDEC systems to provide more air volumetric flow when larger droplets are injected at a greater water flow rate. It is reasonable to say that momentum transfer is insignificant under the given conditions.

A certain range of water droplets would be universally feasible. It can be seen from the data that smaller droplet generally achieve larger temperature drops and increased relative humidity. One tendency in the data is that the performance of the system begins to drop off when the droplet size increases beyond approximately 100 μm. It should also be noted that using finer droplets below 30 μm may be inefficient. It is likely that air stream affects the evaporative cooling process, which leads to a longer evaporation time. In addition, it is very difficult to produce such very fine droplets. To do so, the water spray system must maintain a higher pressure and more sensitive control, demanding higher power consumption and operating costs. Provision of a specific size of water droplets to respond to variable outdoor conditions over time is another challenge. Thus, it is recommended that the droplet size

Table 6
Outlet air conditions predicted under different tower configurations and inlet air conditions.

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

Table 7
Outlet air conditions resulting from the variation of water droplet sizes at an ambient air temperature of 35 °C.

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

Table 8
Outlet air conditions resulting from the variation of water droplet sizes at an ambient air temperature of 30 °C.

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

should be between 30 μm and 100 μm in order to minimize the use of water and to produce consistent, energy-efficient performance.

3.1.6. Water flow rate

This parameter is utilized as a key variable for achieving better performance under almost all situations. A definite tendency regarding the operation of a spray PDEC tower system in the literature is that a large amount of water use with a finer water drop will achieve the greatest temperature drop. Another important fact regarding this parameter is that it determines the level of humidity of the outlet air. In addition, many studies have pointed out that a large amount of water usage is one of the main disadvantages of this particular system. To date, reliable methods for minimizing water usage and analyzing the effects of the high humidity outlets from PDEC systems on the thermal comfort of occupants have not been reported in the literature. Therefore, it is particularly important to closely look at how the water flow rate impacts the performance and how the water flow rate can be used more effectively to water use.

A series of runs to investigate the performance of PDEC tower with spray system in a hot-dry condition under three different conditions is shown in Table 9. A tendency present in the results was that the air mass flow rate plays a critical role. The outlet from the PDEC system is saturated at the water flow rate of 70 l/h in case 2 where the air mass flow rate was the lowest. As expected, the differences between each interval grew bigger as the air mass flow rate decreased. Another interesting finding is that with each increase in water flow rate of 5 l/h, the outlet air temperature can drop by as much as 1.17 °C and the relative humidity could increase by as much as 3.46%. As noted in many studies, the water flow rate strongly affects performance. In addition, its significance varies with the air mass flow under the same outdoor air conditions (see Table 10).

To further investigate the effect of water flow rate, another series of runs under different conditions is necessary. Table 11 lists the conditions imposed on these additional simulations. These new conditions include a greater interval for the water flow rate, different tower configurations, and a lower air mass flow rate. A noticeable tendency found in the results is that the magnitude of the temperature drop is heavily dependent on the magnitude of the air mass flow rate. Another interesting finding is that a greater water flow rate may result in a decrease in the overall volume flow rate at the outlet of a narrower tower. It seems that wall-bounded flows were formed over the bottom due to a greater momentum of the air stream. In fact, it was difficult to segregate the impact of the water flow rate from the impact of other variables on since almost all conditions considered were different. However, the results indicated that an adjustment of water flow rate can significantly affect the performance, and the magnitude of the impact will vary with the magnitude of the air mass flow rate within the PDEC tower (see Table 12).

A careful design process is needed to avoid inefficient water use. Inefficient water use would result from situations where more water mass flow is used than is required to obtain saturated conditions at the exit. A general tendency in the literature is that more water is used than the amount needed to achieve the maximum wet-bulb depression. This is perhaps one of the main causes of excessive water use. Thus, eight different scenarios are analyzed to determine the required water for rate to achieve saturation conditions at the PDEC tower outlet. These eight scenarios are illustrated in Table 13.

The water demand leading to saturation varies from as low as 50 l/h in the case 1 and 6 to as high as 200 l/h in the case 5. Medium sized towers at a high outdoor wind speed, namely cases 2, 3, and 5, required a greater water flow rate reaching as high as 200 l/h. In addition, saturation occurred generally at a lower water flow rate in a smaller tower. As one can see from the results, the outlet air conditions are determined not by a single strong parameter but by a combination of multiple factors. Therefore, the design of water flow rate must be coordinated in conjunction with other parameters to maximize the temperature drop at the lowest water use.

3.2. Regression analysis

3.2.1. Overview

An accurate prediction is critical to analyze the overall impact of a spray PDEC tower system. It is a challenge to predict the performance accurately due to the complexity of the down-draft

Table 9
Conditions of variables for the analysis of water flow rate.

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

Table 10
Air conditions at the tower exit under the three different scenarios described in Table 9.

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

Table 11
Combinations of various conditions for the analysis of water flow rate.

Case	A_{wc} (m)	A_t (m)	T_{db} (°C)	T_{wb} (°C)	RH_o (%)	V_i (m/s)	V_o (m/s)	$\dot{m}$ (kg/s)	D (μm)	H (m)
1	3.0 × 2.0	3.0 × 3.0	33.0	20.1	30	1.4	2.8	9.82	75	7.5
2	3.0 × 1.5	3.0 × 3.0	38.0	19.19	20	1.8	3.0	13.0	90	8.0
3	1.5 × 1.5	1.5 × 1.5	42.0	21.89	16	2.0	2.0	5.04	20	5.0
4	1.5 × 1.5	1.5 × 1.5	32.0	19.59	30	2.5	2.5	6.51	70	5.0

Table 12
Air conditions predicted for four different combinations.

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

evaporative cooling process. These systems are widely designed by using models relying on the wet-bulb depression with no significant consideration of the other parameters. It should be noted that those models can hardly account for the effects of other parameters that also have a strong dependency as discussed in the previous section. As a result, the predictions of those models are inherently inaccurate. The results presented in the previous section showed that the performance has a strong dependency on all parameters, and thus a model should thus account for the influences of all parameters including the air mass flow rate, the water droplet size, and the water flow rate.

More importantly, the capability of these systems for improving the indoor environmental quality (IEQ) should be proven. One of the key benefits of the spray PDEC tower system is that it improves not only indoor thermal comfort but also indoor air quality by delivering a large amount of fresh outdoor air. Models should predict all the necessary air conditions such as air mass flow rate, temperature, and relative humidity in order to see how the PDEC system improves IEQ. To date, almost all mathematical models only predict the outlet air temperature, assuming a certain efficiency of the wet-bulb depression while a few models predict humidity level at the outlet of the PDEC system [8,18]. One of the best approaches to determining IEQ would be to use a whole building energy simulation program that enables the modeling of all physical phenomena that take place in a building and its surrounding. However, this can be done only when reliable mathematical models are available that can be implemented into such program. Mathematical models are particularly needed to analyze how the humid supply air from the system impact IEQ in a space served by the system.

Statistical analysis is widely used to explain the relationship between dependent variables and independent variables and formulate mathematical equations. The parametric analysis presented in the previous section shows that all of the critical parameters noted above are strongly interdependent. Furthermore, the significance of each parameter needs to be investigated in more detail so that some solution to control the performance by

Table 13
Water demand required to reach saturation in eight different situations.

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

adjusting individual variables may be found. One challenge is finding a relationship between multiple independent variables and a dependent variable, especially when each relationship between a single independent variable and dependent variable is substantially different. A regression analysis may explain such relationships between the main parameters and a dependent variable to a reasonable level of accuracy.

3.2.2. Methods and sampling

The sampling should cover almost all possible conditions under which a spray PDEC tower system can operate. The applicability of the system in climates other than hot-dry climate needs to be proven even though it is true that the system performs best in this particular climate. Six climates were chosen since the system has a strong dependency on climatic conditions. Table 14 lists the maximum and minimum limits of temperature and relative humidity for each climate. Since all of the system parameters are interdependent, they are also included in this study. The statistical analysis included a wide range of sampling conditions such as climates, tower configurations, and water conditions in order to look at how the system performs in as many situations as possible. Fig. 2 illustrates all of the variables sampled for the regression analysis.

Two dependent variables, temperature and air velocity, were taken. The sensible cooling capacity of the system is determined by the generic heat transfer equation when two variables are known such as the air mass flow rate and the temperature difference. The humidity level of the air should also be known so that the latent cooling load and thermal comfort can be determined. To predict the overall influence of the system, those conditions, i.e., temperature, relative humidity, and velocity, are to be known. Among these variables, the relative humidity can be found from the air temperature, assuming an adiabatic cooling process. Two different regression equations that predict two dependent variables, i.e., outlet air temperature and velocity, will be formulated.

Sample cases are performed in all climatic regions for each main variable. Each FLUENT simulation produced a single sample. A series of runs was undertaken for the combinations of six climates and a main parameter while the other main variables remained at a representative value obtained from the parametric analysis. For instance, when droplet size was chosen, the other four variables such as water flow rate, wind speed, tower height, and tower configuration remained at a constant value until 15 FLUENT simulations for 15 droplet sizes from 20 μm to 200 μm in six different climates were completed. The total sample numbers of this combination were thus 90, and the total number of samples collected in this sampling process for the five combinations was 426. The 412 samples collected during the parametric analysis were also included in the regression analysis for a total of 838 different data points.

Table 14
Climatic classification used for the regression analysis.

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

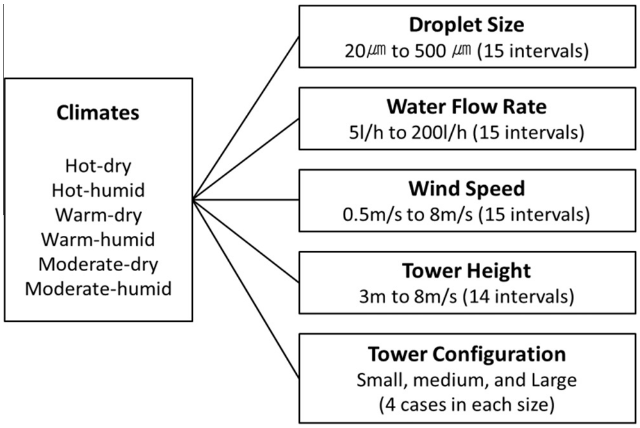

Fig. 2. Diagram of preliminary sampling method.

The general purpose statistical software Minitab 16 was used for the regression analysis. The determination of independent variables was made by correlations between each dependent variable, i.e., temperature and velocity, and all of the independent variables. The relationships between each dependent variable and the independent variables were then analyzed. This correlation analysis suggests that all of the main parameters were correlated with temperature and five parameters were correlated with velocity. Two regression equations for temperature and velocity were formulated in this process. Once the preliminary sampling process was complete, a calibration process followed to determine whether or not additional samples were needed.

A forward selection method was used during the calibration process to minimize the computational effort since the creation of a sample required significant computational effort and time. Each regression equation predicted the outlet condition, i.e., either temperature or velocity, under those situations considered in the parametric analysis. The predictions by the regression equations were then compared with the predictions by the FLUENT model. Samples were collected for certain intervals that showed larger differences between the FLUENT model and the mathematical model. This calibration process continued until no significant variations were found in the coefficient of determination value, R^2, as well as the significance probability of the regression coefficient, P-value.

3.2.3. Regression analysis

All variables considered in the parametric analysis were included in the multiple regression analysis for temperature since they were found to correlate with temperature. The total number of samples collected during the preliminary sampling process was 838. An additional 809 samples were added during the calibration process. As a result, the number of samples collected in the analysis using the FLUENT model was 1647 in all, and the following linear regression equations were obtained. The standard deviation and coefficient of determination R^2 were 2.732 and 0.771, respectively. The equation to explain the variability in temperature is:

$$T_e = -13.6 + 1.35V_i + 0.386V_o + 0.0958\dot{m}_a - 0.07WF - 0.022D - 0.0865H + 0.686T_{db} + 0.709T_{wb} \quad (10)$$

It is noted that the linear regression equation in the practical ranges where more extreme conditions were excluded showed a better statistical relation. The linear regression equation for temperature above explained that 77.1% of the population was known to have a relation to temperature. The variability of the population in some extreme situations was found to be relatively greater than under normal conditions. Those extreme situations included hot-humid conditions such as temperature over 38 °C and relative humidity greater than 50%; high or low velocity at the tower inlet such as velocities greater than 4 m/s or less than 0.75 m/s; and larger droplet sizes greater than 200 μm. These conditions are generally not encountered in a spray PDEC tower system. A stronger relationship was found in the analysis when the samples were limited to the more typical conditions, resulting in an R^2 of 82.3% and a standard deviation of 1.956.

A number of variables were excluded in the regression analysis to predict outlet air velocity since a weak correlation was found between the outlet air velocity and the variables (water droplet, wet-bulb temperature, and dry-bulb temperature). An excellent linear relationship in the preliminary samples was found between the outlet air velocity and the remaining five independent variables. All variables showed fairly strong correlations with velocity, so that the preliminary 838 samples were determined to be enough to explain the relationship. The value of the coefficient determination and a standard deviation found in this analysis were 0.997 and 0.052, respectively. The linear equation for the outlet air velocity is:

$$V_e = 0.107 + 0.706V_i + 0.21V_o + 0.00413\dot{m}_a - 0.00016WF - 0.024H \quad (11)$$

4. Conclusion

Given the fact that a spray PDEC tower system can achieve significant energy savings and improve indoor environmental quality, it has not been successfully integrated into the built environment beyond a few rare cases. One of the main reasons for this is that the physical cooling process has not been well understood. Another reason is that there has been a lack of methods for analyzing the real impact of this particular system. To remedy these gaps, a parametric analysis to see the significance of individual parameters and a regression analysis to formulate mathematical models have been conducted. The study uncovered important findings that have never been clearly explained in the literature. First, it shows that the performance strongly depends on the magnitude of air mass flow rates that significantly vary with the configurations of a spray PDEC tower. No study in the literature properly handles the variation of air mass flow rates within the effective tower area where the down-draft evaporative cooling process occurs. Second, it embodies the significance of water droplet sizes with the variations of different conditions, beyond the notions that a finer droplet results in a greater temperature drop. Third, it allows an accurate estimate of all design parameters. Particularly, an accurate prediction of a water demand for the completion of the down-draft evaporative cooling process over the effective tower area will significantly reduce water use that is one of key drawbacks of a spray PDEC tower system. The main findings from the results of the study are as follows.

Practical design guidelines for main parameters can be suggested. Due to the strong climatic dependency, the capacity of the system is insufficient to meet the entire cooling demand of a space. One of the solutions to overcome this limitation is to find the way that the system can maintain the best performance that is responsive to a local climate. To that end, the following design guidelines of the system are found to be effective to enhance the energy and water efficiency of the system.

- A reasonable range of the inlet air velocity over the cross-sectional area of a spray PDEC tower system is between 0.75 m/s and 1.5 m/s. The mass of incoming air determined by the air velocity would be the one that the system can effectively handle to achieve a better performance. The mass flow rate of the air flowing through the system could be modulated, or the cross-section of a PDEC tower set to be larger than the area of a wind catcher.
- The effective tower height that a spray PDEC tower system completes the down-draft evaporative cooling process would be as low as double and as high as triple the width of the tower cross-sectional area. It may be higher when the tower cross-section is smaller. A higher PDEC tower than this recommendation does not always guarantee a better cooling performance.
- The performance of a spray PDEC tower system with a rectangular cross-section would be dependent on the width of the tower cross-section parallel to the direction of incoming air flow. However, this may vary if the aspect ratio is significantly different from 3:2 used in this study.
- The range of water droplet size used in a spray PDEC tower system that can produce a constant capacity at the lowest temperature would be between 30 μm and 100 μm. A fixed water droplet size in that range would be useful to maintain a constant pressure throughout the water piping system. The control of the cooling performance would be much easier if this parameter is fixed.
- The water flow rate resulting in the greatest temperature drop will be much less than the rate typically used in the literature. It needs to vary with outdoor conditions to achieve the desired humidity and temperature drop without wasting water. This finding is very useful to minimize excessive water use.

In addition to the design guidelines, another important conclusion of the study is that a comprehensive design process is required to draw the best performance from the system based on local climatic conditions. The parametric analysis suggests that both incoming outdoor air flow and water flow rates are effective to achieve a greater temperature drop while the other parameters also have a significant impact. In addition, the variability of temperature drop as the water droplet size ranged from 10 μm to 500 μm is significant. However, the significance of its impact on the performance of a spray PDEC tower system varies substantially when any of the other parameters change. Furthermore, the configuration of the system also causes a significant variation in the outlet air conditions. The ratio of the tower width to the tower height as well as of the wind catcher dimension to the tower cross-sectional area is found to lead to sizable variations in the outlet air conditions. All of the parameters discussed in this study affect each other. Therefore, these parameters must be customized to the local climatic conditions.

Mathematical models formulated in this study are expected to play an important role. One of the key barriers to the integration of this system is the lack of methods that can accurately estimate its impact. Much of previous works relied on either overly simplified methods or assumptions that the system may not achieve without any significant advancements in the technology. They also do not include the influence of important parameters such as the air mass flow rate and the water droplet size. The mathematical models formulated in this study include all of the critical parameters, so that the outlet air conditions can be accurately predicted. Another important aspect of these mathematical models is that they can be utilized in many ways. The actual impacts of a spray PDEC tower system can be comprehensively analyzed under numerous situations when these models are implemented into a whole-building simulation program.

This study verified the influence of known factors and also presented findings that may help to advance the performance of a spray PDEC tower system. However, many efforts are still needed to advance the performance of the system in order for it to be an alternative to conventional mechanical air-conditioning systems. The mathematical models should be implemented into a reliable building energy simulation program so that all the benefits and the limitations of the system can be thoroughly examined. Any problems with the current form of the system should also be identified, so that resolutions that address these issues can be presented.

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