IMPLEMENTATION OF ANALYTICAL MODELS FOR PASSIVE DOWN-DRAFT EVAPORATIVE COOLING (PDEC) TOWER WITH SPRAY SYSTEMS

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ABSTRACT

In order to address the lack of reliable methods that can analyze the overall effects of PDEC tower with a spray system, analytical models that predict supply air conditions of the system were implemented into a whole building energy simulation program EnergyPlus. This paper describes the simulation algorithm of the new module to predict the performance of the system. Case studies were performed to verify the capability of the module. The results of the case studies showed that the module adequately predicted the supply air conditions, and it was also capable of estimating energy performance and indoor thermal environment when the system served as a primary cooling system.

INTRODUCTION

A passive downdraft evaporative cooling (PDEC) tower is a component that is designed to capture the wind at the top of a tower and cool the outdoor air using water evaporation (Kang and Strand, 2013.) Wind towers are the simplest type of a PDEC tower system and have been used in hot and dry climates since ancient Egypt (Ford et al., 2010; Givoni, 1994.) Applications of an advanced form of wind towers have been developed to improve the performance by installing evaporative devices such as wetted pads or water sprays (Baradhori, 1985; Ford et. al., 2010; Givoni, 1994; Thompson et. al., 1994.) While no standardized name of this type of system available, they are often referred to as a PDEC tower with pad or spray, depending upon the type of evaporative devices. Past studies have investigated these advanced types of PDEC tower systems and showed that they accomplish better cooling performance than a wind tower, leading to sizable cooling energy saving (Givoni, 1994; Ford et al., 2010.)

A number of methods have been developed in order to predict the performance of the system and estimate its contribution to building energy performance. The majority of early studies focused on experiments due to the complexity of downdraft evaporative cooling process (Baradhori, 1985; Thompson et. al., 1994; Givoni, 1994; Ford et al., 2010.) Some analytical models have been developed, and computational techniques were also introduced to explain the main phenomenon, i.e., simultaneous heat and mass transfer. However, these methods lack accuracy in the prediction of the supply air conditions of the system; as a result, there have been significant gaps between the actual performance and the predicted by those methods. Since the performance of the system is heavily dependent on climatic conditions that constantly vary with time, accurate prediction of the performance is very difficult. In addition to the climatic dependency, various influences of the system are to be explicitly examined when it cools a thermal zone. Thus, it is particularly important to develop reliable methods that not only significantly enhance the accuracy of the predictions, but also enable investigating the overall impact of the system on building energy efficiency.

This study intends to develop a new simulation module that implements analytical models predicting the conditions of the supply air of the PDEC tower with a spray system. It describes the modeling algorithm of the module as well as its implementation in a whole building energy simulation program, EnergyPlus. The module fully coupled with the program predicts the supply air condition from the system; as a result, energy performance of a building is predictable when the system is used as a primary cooling application. It then performs a case study to verify the capability of the module, presenting comparisons in energy performance and indoor thermal environment between a baseline building and a PDEC integrated building.

MODEL IMPLEMENTATION

Overview

An analytical model is needed to improve the prediction of the performance of PDEC tower with a spray system. Existing analytical models heavily rely on the wet-bulb depression (WBD), which is the difference between dry-bulb temperature and wet-bulb temperature of outdoor air (Ford et al., 2010; Givoni, 1994). They also assume that the system always achieved a constant WBD at a fixed water flow rate while outdoor weather conditions vary with time. In addition, much of the models were developed within limited conditions: a climate, a physical tower configuration, and a fixed water flow rate, which gives rise to inaccuracy of the predictions when any of those conditions differs from those employed for developing the models.

To remedy these gaps, the authors developed an analytical model (Kang 2011.) The authors developed a computational model using a commercial CFD code, FLUENT, and the FLUENT model was validated against an experimental data set (Kang and Strand 2013.) In this study, they performed a series of computational analysis with the FLUENT model under a variety of conditions. They studied not only those have been believed that the system can appropriately condition incoming outdoor air to desirable conditions, but also a wide range of other conditions. The main parameters included wind speed, outdoor dry-bulb temperature, outdoor relative humidity, air mass flow rate, water flow rate, droplet size, and tower height. As a result of a regression analysis, an analytical model that predicts the supply air temperature and the supply air velocity of the system was formulated. Details of computational modeling of the FLUENT model, its validation, and the method of the regression analysis can be found in the authors' previous studies (Kang 2011; Kang and Strand 2013.)

One of the significant contributions of the analytical model is that it includes effects of not only known factors such as wet-bulb depression, tower height, water flow rate, and wind speed, but also factors that have not been well treated in the literature such as air mass flow rate flowing through a PDEC tower and water flow rate. As the analytical model includes such key factors that greatly affect the performance of the system, it accounts for the variation of air mass flow rate varying with time and tower configuration, effects of water droplet size, a wider range of outdoor weather conditions, and physical tower configuration. Thus, the predictions of the supply air conditions of the system is accurate.

The whole building energy simulation program, EnergyPlus was chosen because it is capable of modeling physical phenomena taking place in buildings and their surroundings. The PDEC tower with a spray system was treated as a natural airflow since the system is a stand-alone component that deals with incoming outdoor air without the aid of the air distribution system. The program assumes that all natural airflows are immediately mixed with the air in the thermal zone that the system serves. Thus, the cooling load in the zone at each time step is determined after all natural airflows such as the supply air flows from the system, infiltration and ventilation were mixed with the air in the zone.

Simulation algorithm

The modeling algorithm of the new module starts by checking if outdoor weather conditions, such as temperature, relative humidity, and wind speed, are appropriate for the PDEC tower with spray system to provide cooling and that cooling is in fact needed by the zone. It also looks whether the indoor air temperature is within the limit defined by the user input in order to avoid overcooling the zone.

Once it verifies that the system can and should operate, it then determines the humidity ratio of outdoor air in order to estimate the enthalpy and the density of outdoor air by using the following EnergyPlus built-in functions that are based on equations found in the ASHRAE Handbook of Fundamentals (ASHRAE 2013):

$$\omega_i = PsyWFnTdbTwbPb(T_{db}T_{wb}, P) \quad (1)$$

$$h_i = PsyHFnTdbW(T_{db,}\omega_i) \quad (2)$$

$$\rho_i = PsyRhoAirFnPbTdbW\left(T_{db,}\omega_i, P\right) \quad (3)$$

The outdoor air mass flow rate can then be calculated as:

$$\dot{m}_a = \rho_i A_{wc} V_o \quad (4)$$

From the continuity equation regarding mass conservation, inlet velocity over the tower cross-section at the top of the PDEC tower, where both fluids, i.e., water and air, begin to contact, is:

$$V_t = \frac{A_{wc}}{A_t} V_o \quad (5)$$

The temperature of the supply air can be directly calculated by the analytical model formulated by a linear relationship between the temperature and main variables as follows:

$$T_e = -13.6 + 1.35V_t + 0.386V_o + 0.0958\dot{m}_a$$
$$-0.071WF + 0.0222D - 0.0865H$$
$$+0.686T_{db} + 0.709T_{wb} \quad (6)$$

The velocity of the supply air can also be directly calculated by the analytical model that include a linear relationship between the velocity and variables such as air mass flow rate, outdoor wind speed, inlet air velocity, water flow rate, and tower height as follows:

$$V_e = 0.107 + 0.706V_t + 0.0217V_o + 0.00413\dot{m}_a$$
$$-0.000167WF + 0.0245H \quad (7)$$

Once the supply air temperature and velocity are determined by the analytical model, the program can estimate other thermal properties of the supply air. The enthalpy of the supply air is then assumed to be the same as that of the outdoor air since the evaporative cooling is an adiabatic cooling process. As both the supply air temperature and enthalpy are known, the humidity ratio of the supply air can be estimated from the following EnergyPlus built-in function:

$$\omega_e = PsyWFnTdbH(T_e, h_i) \quad (8)$$

The program determines the relative humidity and density of the supply air from the following

EnergyPlus built-in functions when the temperature and humidity ratio are known:

$$RH_e = PsyRhFnTdbWPb(T_{e,}\omega_e, P) \quad (9)$$

$$\rho_e = PsyRhoAirFnPbTdbW(T_{e,}\omega_e, P) \quad (10)$$

The supply air mass flow rate and velocity over the surface of the outlets are then estimated by the conservation of mass:

$$V_{out} = \frac{A_t}{A_e} V_e \quad (11)$$

$$\dot{m}_e = \rho_e A_e V_{out} \quad (12)$$

The module also provides an input that specifies losses of the supply air flow and the supply water flow during the downdraft evaporative cooling process. The input can also be used to account for the efficiency of capturing outdoor air by a wind catcher since the analytical model does not deal with the direction of the wind, which vary substantially with time. The supply air flow rate that is delivered to a thermal zone where the system serves is thus:

$$Q_e = \frac{\dot{m}_e}{\rho_e}(1 - F_a) \quad (13)$$

The evaporation rate is then calculated by the following material balance equation:

$$\dot{m}_a \omega_1 = \dot{m}_a \omega_2 + \dot{m}_w \quad (14)$$

Therefore, the evaporation rate is expressed as:

$$Q_w = \frac{\dot{m}_e(\omega_e - \omega_i)}{\rho_w} \quad (15)$$

The total water consumption that the system injects within the PDEC tower incluindg losses specified by the user is then:

$$Q_T = Q_w(1 + F_w) \quad (16)$$

The water pump is the only energy device that consumes electricity. The electric power consumption of the system is simply calculated by the product of the rated pump power in watts and the part load ratio as:

$$P = P_{rated} L \quad (17)$$

MODEL VERIFICATION

Simulation overview

A case study was designed to see whether the implementation of the analytical model ensures a comprehensive analysis of the performance of the PDEC tower with a spray system and its capability of saving cooling energy. A primary school reference building that the U.S. Department of Energy (DOE) developed was chosen (Torcellini et al., 2011.) The characteristics of the US DOE primary school reference building model are listed in Table 1.

The city of Yuma, AZ, USA was selected because the system is particularly suitable to its weather conditions, which is classified as a hot-dry climate (ASHRAE, 2010.) One typical summer day was selected to see if the simulation program could estimate the appropriate system performance in a representative space where the system cools. The peak dry-bulb temperature of the selected day was 42.4 °C, and the maximum wet-bulb depression that is the difference between dry- and wet-bulb temperature was approximately 19.6 °C. The daily variation of the outdoor air conditions such as temperatures and wind speed of the city is listed in Table 2.

A number of inputs were needed to define the parameters that affect the performance of the system. Many parameters are associated with the downdraft evaporative cooling process. Some are known to significantly affect the performance. They include water flow rate, tower height, and outdoor climatic conditions. In addition to these parameters, the analytical model includes other important parameters such as the size of water droplet, and tower physical configuration to calculate air flow rate of the air stream flowing through PDEC towers as shown in equations (6) and (7). An input field in regard to loss factors was also established in order to account for the capturing efficiency of the wind catcher and losses of both air and water flows. The addition of these important parameters ensures the accuracy of the predictions of the module. Table 3 lists the inputs used in the simulations. As a result, the simulation program was allowed to thoroughly assess the energy performance of the reference building when the system was used as a cooling application.

Results

- Supply air conditions

The temperature variation of the supply air was very similar to that of outdoor wet-bulb temperature as shown in Figure 1. That is, the system accomplished the maximum WBD or nearly maximum over the occupied hours at the conditions listed in Table 3. This result indicates that the water flow rate of 200 l/h could accomplish the maximum temperature drop in the city. On the other hand, the supply air temperature during afternoon hours was greater than the indoor setpoint temperature of 24 ºC as the outdoor wet-bulb temperature increased, which was close to or a little greater than the indoor setpoint temperature.

The warmer supply air flow may increase the cooling demand of the zone since only when the indoor air temperature was lower than the supply air temperature can the system provide cooling. This was experienced when a higher cooling load is typically expected as the consequence of increased solar radiation on the west side of the building where the classroom located. In addition, the supply air mass flow rate increased as outdoor wind speed increased. Increasing water flow rate is expected to lower the supply air temperature during these afternoon hours since the supply air temperature was higher than the outdoor wet-bulb temperature and the water flow rate was constant. However, supplying a large amount of humid air to the zone will most likely increase the indoor humidity level significantly though the climate was hot-dry in this region.

The relative humidity of the supply air was above 85% during all occupied hours. Increasing humidity of the air is one of the main benefits of the system since the system is particularly suitable to the hot-dry climate. However, the indoor humidity level may fall into the outside of the indoor comfort range, depending upon local climatic conditions and the operating conditions of the system such as indoor relative humidity, water flow rate, and supply air flow rate. To that end, the relative humidity of the supply air should be maintained at a certain level so that the system does not give rise to an uncomfortable indoor thermal environment. The variation of indoor relative humidity due to humid supply air from the system will be discussed in the following subsection.

- Energy Performance

Sizeable reductions in cooling energy and carbon production for this example are shown in table 4. The PDEC tower with a spray system showed a reduction in cooling electricity of roughly 96% in comparison to that of the primary cooling systems used in the base case building model. This was because of the fact that the water pump is the only component that consumes energy. The electricity consumption to operate the building energy systems including air distribution system also reduced substantially as the PDEC system operates without the aid of fans. The electricity consumption by fans in the base model was approximately 10% of the total cooling energy consumption. These energy savings in turn reduce carbon emission which is directly associated with the operation of building energy systems.

As expected, a significant increase in water consumption also resulted from the use of this alternative energy system. The system injected water through a water spray system at the top of the PDEC tower. It is typical of such systems that it supplies a large amount of water at a constant rate in order to achieve as much temperature drop as possible. This inherently causes a larger water consumption than the amount of water that the system in fact needs. As can be seen in Figure 2, the indoor air temperature was much lower than the setpoint temperature of 24°C, overcooling the classroom by 3 PM. The results of the simulation show a significant potential in minimizing water use if the system modulate water injection as much as it meets the cooling load.

- Indoor Thermal Environment

There is a significant difference in the indoor thermal environment between the two cases studied as shown in Figure 2. In the PDEC case, the variations of both the indoor mean air temperature and relative humidity were significant. The indoor setpoint temperature of 24 ºC in the classroom was met only once, and the zone overcooled more than half of the day. In addition, the indoor relative humidity varied by almost 20% during the occupied hours while indoor humidity level maintained below 60% except for a few hours in the morning. This is in contrast to the conventional forced air system in the base case, which maintain a relatively constant indoor air temperature and humidity throughout the occupied hours.

Figure 3 shows the variation of Fanger's Predicted Mean Vote (PMV) index that indicates satisfaction with the thermal environment. The PMV index between +0.5 and -0.5 are generally considered as occupants in a space feel comfortable. The PMV index in the PDEC case showed that occupants feel slightly cold much of the occupied hours as the system overcooled the classroom. The variety of the PMV index during the occupied hours was also significant in comparison with the base case.

It is very important to note that the results of the simulation indicate that the space where the system serves can hardly maintain occupants' thermal comfort as the capacity of the system vary greatly due to the variation of outdoor air conditions. This is one critical drawback of the PDEC tower with a spray system: its performance is solely dependent on the local climate. The supply air conditions of the system should be within a range that can maintain a comfortable indoor environment.

CONCLUSION

A simulation module developed by implementing an analytical model that predicts the performance of a PDEC tower with spray system into a whole building energy simulation program. The addition of the module allows the program to explore not only how the energy performance of the building varies, but also how they affect the indoor thermal environment when the system served as a cooling application. The program was then used to compare the energy performance between the base and PDEC system integrated cases in the US DOE primary school reference building.

The results of the case study suggested the necessity of performance control since the current operating condition may cause adverse effects to the indoor thermal environment and excessive water consumption. The system should respond to the variation of indoor cooling demand much more like a conventional air-conditioning system. This will be the subject of future investigations.

NOMENCLATURE

ω_i = humidity ratio of outdoor air [kg/kg-dry-air]
h_i = enthalpy of outdoor air [J/kg]
ρ_i = density of outdoor air [kg/m^3]

ω_e = humidity ratio of PDEC flow [kg/kg-dry-air]
RH_e = relative humidity of PDEC flow [%]
ρ_e = density of outlet air [kg/m^3]
A_e = outlet opening area [m^2]
A_{wc} = wind catcher area [m^2]
A_t = tower cross-sectional area [m^2]
V_o = ambient wind speed [m/s]
T_e = outlet air temperature [°C]
WF = water flow rate [kg/s]
D = water droplet size [μm]
H = effective tower height [m]
T_{db} = outdoor dry-bulb temperature [°C]
T_{wb} = outdoor wet-bulb temperature [°C]
V_e = air velocity [m/s]
V_{out} = outlet air velocity over outlet surface [m/s]
$\dot{m}_e$ = outlet air mass flow rate [kg/s]
F_a = fraction of air loss
F_w = fraction of water loss
Q_e = outlet air volumetric flow rate [m^3/s]
Q_e = outlet air volumetric flow rate [m^3/s]
Q_w = evaporation rate [m^3/s]
Q_T = total water consumption rate [m^3/s]
P = pump power consumption [W]
P_{rat} = rated pump power [W]
V_t = inlet air velocity over tower [m/s]
$\dot{m}_w$ = water mass flow rate [kg/m^3]
$\dot{m}_a$ = incoming air mass flow rate [kg/m^3]
ω_1 = humidity ratio of inlet air [kg/kg-dry-air]
ω_2 = humidity ratio of outlet air [kg/kg-dry-air]

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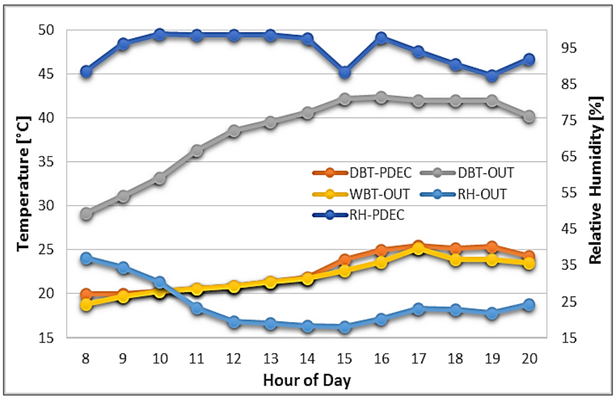

Figure 1 Conditions of the supply air leaving PDEC tower with a spray system

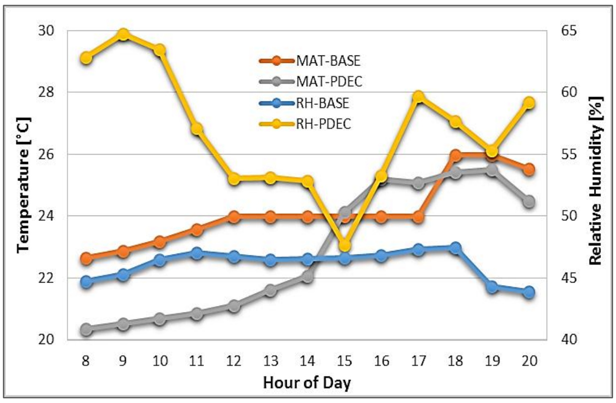

Figure 2 Conditions of indoor air in a classroom

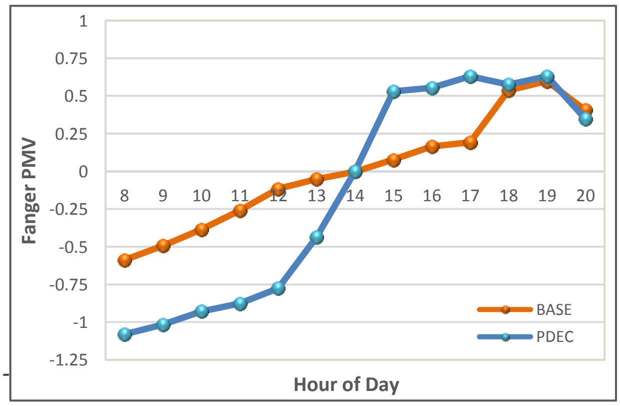

Figure 3 Fanger's PMV variation in a classroom

Table 1
Characteristics of reference primary school building

Type	Single story E-shaped primary school
Area (m^2)	6871
Number of Zones	25
HVAC	Single duct VAV system with reheat PSZ-AC units for subsidiary facilities
Setpoint Temp (°C)	24 (7AM-6PM) and 27 (6PM-7AM)
Design Condition	ASHRAE Standard 90.1-2004 ASHRAE Standard 62-1999
Schedules	Vary with space type
Pupils	650
Glazing Fraction	0.35
Ventilation (m^3/s)	0.175 (classroom)
Infiltration (ACH)	0.49 (classroom)

Table 3
Representative simulation input parameters

INPUTS	VALUE
Water flow rate [l/h]	200
Effective tower height [m]	5
Water flow loss fraction	0.05
Air flow loss fraction	0.05
Wind catcher area [m^2]	6.25
Tower cross-section area [m^2]	16
Water droplet size [µm]	30
Pump rated power [W]	150
Minimum indoor temperature [ºC]	20
Maximum relative humidity [%]	40
Minimum ambient temperature [ºC]	28

Table 2
Daily variation of outdoor air condition during occupied hours in Yuma, AZ, USA

TIME	8	9	10	11	12	13	14	15	16	17	18	19	20
DBT (°C)	29.2	31.2	33.2	36.3	38.6	39.6	40.6	42.2	42.4	42.0	42.0	42.0	40.3
WBT (°C)	18.8	19.7	20.3	20.6	20.9	21.4	21.8	22.6	23.6	25.2	23.9	23.9	23.5
WIND SPEED (m/s)	2.1	1.5	1.9	3.0	3.6	3.6	3.6	4.2	4.4	4.1	4.4	4.6	4.9

Table 4
Reductions of energy consumption and carbon emission in PDEC integrated case

METERS	BASE	PDEC TOWER	REDUCTION [%]
Cooling:Electricity [MJ]	7100.8	258.72	96.4
Electricity:Facility [MJ]	13529.4	5774.7	57.3
Fans:Electricity [MJ]	683.8	6	99.1
Cooling:MainsWater [m^3]	1.5	223.5	-
CO2:Facility [kg]	2716.5	1174.6	56.8