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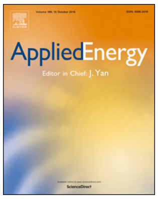

Performance control of a spray passive down-draft evaporative cooling system

Daeho Kang[a,*], Richard K. Strand[b]

[a] Department of Environmental Control Technology, New York City College of Technology, The City University of New York, 172 Pearl Street, Brooklyn, NY 11201, USA
[b] Illinois School of Architecture, University of Illinois at Urbana-Champaign, 611 Lorado Taft Drive, Champaign, IL 61820, USA

HIGHLIGHTS

- The study proposes the practical control strategies for spray PDEC cooling system.
- The results confirm that water flow control mitigates much of the inborn problems.
- The system is found to be suitable for a small-scale space.
- The system can be used in a wider range of climates with an advanced control.
- The system is most beneficial when used as a secondary cooling system.

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ABSTRACT

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

1. Introduction

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

Wind towers have been used as a means of comfort cooling for decades [6–9]. Adoption of evaporative cooling devices such as water sprays and wetted pads significantly improve the cooling performance and different forms of wind towers with evaporative devices have been developed [6,10–13]. A spray PDEC system has been used for cooling open spaces or large scale spaces since a direct evaporative cooling system deals with a large volume of air and discharges the conditioned air at a low velocity [6,12,14–17]. As the enhancement of energy efficiency has been one of the key areas in building sectors that consume

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[*] Corresponding author.
E-mail address: dkang@citytech.cuny.edu (D. Kang).

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Nomenclature

A	areas of tower cross-section or tower outlets in m^2
A_i	area of surface i in m^2
C_p	zone air specific heat in J/kg K
$C_z\frac{dT_z}{dt}$	energy stored in zone air in J/h
D	water droplet size in µm
DBT	outdoor air dry bulb temperature in °C
H	effective height of a tower of a spray PDEC system in m
HD	hot dry climate
h_i	convective heat transfer coefficient of surface i in W/m^2 K
h_m	inside moisture transfer coefficient in kg/m^2 s
$Kg_{mass_{sched\ load}}$	internal latent loads in kg_{air}/s
$\dot{m}$	air mass flow rate in kg/h
$\dot{m}_i$	air mass flow rate of the air in thermal zone i in kg/h
$\dot{m}_a$	air mass flow rate of the outdoor air in kg/h
OA	outdoor air
$RCMD$	recommended values for indoor relative humidity and PMV
$\dot{Q}$	evaporation rate in m^3/s
$\dot{Q}_i$	the convective internal load from internal heat source i in watts
$\dot{Q}_w$	water evaporation rate in kg/h
T	dry bulb temperature of air in °C
T_{db}	outdoor air dry bulb temperature in °C
T_s	supply air temperature at the outlet of a spray PDEC system in °C
V	air velocity in m/s
V_i	air velocity at the top of PDEC tower in m/s
V_o	wind speed in m/s
WBT	outdoor air wet bulb temperature in °C
WF	water flow rate in liter/min
WM	warm moderate climate
W	humidity ratio of air in kg_{water}/kg_{air}
W_z^t	humidity ratio at time t in the thermal zone in kg_{water}/kg_{air}
X	temperature difference between the supply air and wet bulb temperature in °C

Greek

ρ_{air}	density of air in kg/m^3
ω	humidity ratio of the air in kg_{water}/kg_{air}
ω_i	humidity ratio of the inflows in kg_{water}/kg_{air}

Subscript

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

energy most, a spray PDEC system has been adopted in the cooling of buildings in order to utilize the benefits of the direct evaporative cooling [5,6,12,18–22]. To date, many studies focused on this particular system and advanced the performance of the system [1,5,6,12,23–25].

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

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

2. Literature review

Bajwa, Aksugur, and Al-Otaibi investigated the potential of a pad PDEC system as a means of comfort cooling in the Kingdom of Saudi Arabia [22]. It was perhaps the first study to monitor thermal comfort in a building that a PDEC system served. The 2.2 m long square tower mounted operable louvers on the supply outlets. Measurements were undertaken for nine days between July and September in 1987. The pad PDEC system operated once in the morning from 5 to 10 and once afternoon from 3 to 6. Outdoor air temperature remained above 40 °C during the occupied hours in July 1987 and the supply air temperature ranged from 26 °C to 32 °C. The calculated Fanger's Predicted Mean Vote (PMV) values without evaporative cooling were ranged from +1 to +2, which indicates slightly warm to warm. The PMVs varied between ± 1 except a few hours of the experimental period in September. The study suggested on-off control along with outdoor relative humidity and wind direction.

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

Brian Ford et al. monitored Torrent Research Center building in