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Experimental study on the building evaporative cooling by using the Climatic Wind Tunnel

Lei Zhang[a,*], Yanshan Feng[a], Qinglin Meng[a], Yu Zhang[b]

[a] *Building Energy and Environment Laboratory, School of Architecture, Guangzhou Municipal Key Laboratory of Landscape Architecture, State Key Lab of Subtropical Building Science, South China University of Technology, Wushan Road, Tianhe District, Guangzhou, 510641, P.R.China*
[b] *School of Chemistry and Chemical Engineering, South China University of Technology, Wushan Road, Tianhe District, Guangzhou, 510641, P.R.China*

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ABSTRACT

Building evaporative cooling is an effective energy saving technology. With the aim to provide a reliable experimental method for the building evaporative cooling research, the dynamic evaporating and heat transfer process of two samples were studied by using the Climatic Wind Tunnel (CWT). The results of this study indicate the following: (1) The thermal resistance of the wet sample was two times that of the dry sample, which significantly improved the thermal insulation capacity of the wet sample. (2) The Penman–Monteith (P–M) model in Pedology was introduced to analyze the evaporation amount which was caused by the comprehensive effect of radiation term and aerodynamic term. The results displayed that the evaporation amount caused by radiation term accounted for 80.4% of the total evaporation amount. (3) The hourly evaporation data were used to calculate the heat balance equation on the facing layer of the wet sample. The calculation results demonstrated that the evaporating process can consume approximately 70% of the maximum incident solar radiation heat.

1. Introduction

After entering into the 21st century, along with the rapid development of China's construction industry, the building energy consumption has also increased significantly. According to statistics, from 1996 to 2008, the total building energy consumption in China increased from 259 million tons of coal equivalent to 655 million tons of coal equivalent, which is an increase by a factor of 1.5. In particular, the building energy consumption in 2008 accounted for approximately 23% of the total energy consumption of China, and this proportion continues to grow [1]. Reference to the energy consumption structure of developed countries, in the future, the energy consumption of buildings in China will account for approximately 40% of the total energy consumption of the entire community [2–4].

The significant increase of building energy consumption in China is closely related to the rapid urbanization and improvement of people's living standard. China is undergoing a rapid process of urbanization, and many new buildings are constructed every year to meet the needs of housing and production, which consumes much energy. According to the data released by the National Bureau of Statistics, the construction area completed every year in China has increased dramatically, from 170 million m^2 in 1985 to 3.59 billion m^2 in 2012 [5], which is an increase factor of almost 22.

Additionally, along with the development of China's economy and the improvement of residential lives, the residential demand for indoor thermal comfort continues to increase, and the energy consumption of buildings will also continue to grow rapidly. According to the data released by the National Bureau of Statistics, the average air-conditioning capacity per 100 households for urban residents in China increased from 0.34 in 1990 to 126.81 in 2012 [5], which is an increase by a factor of approximately 373.

Hot weather with abundant rainfall and high temperatures essentially characterizes the entire southern region of China. This high-temperature, high-humidity weather affects the comfort of outdoor activities and increases the operation time of air-conditioning equipment in buildings; however, from the perspective of climate resource theory, humid climates contain all of the meteorological elements for evaporative cooling. If used correctly, evaporative cooling can also reduce the building energy consumption.

Wanphen et al. [6] selected four materials (pebbles, silica sand, volcanic ash, and siliceous shale) to study. The authors tested the moisture and thermal performance of these four materials under simple boundary conditions. Then, in a wind tunnel that could simulate solar radiation, temperature, and humidity, the researchers cyclically obtained evaporation, surface temperature, and heat flow

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* Corresponding author. Tel.: +86 13642691580; fax: +86 2087110164.
E-mail address: arzhang@scut.edu.cn (L. Zhang).

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Nomenclature

A_s	surface area (m^2)
c_p	specific heat of dry air at constant pressure (MJ/(kg °C))
E	evaporation amount per unit area (kg/m^2 h)
e_a	actual vapor pressure (kPa)
E_o	evaporation rate (mm/h)
e_s	saturation vapor pressure (kPa)
G	surface heat flux (MJ/m^2)
$h_{c,ext}$	total surface convective heat transfer coefficient (W/m^2 K)
$h_{c,for}$	forced surface convective heat transfer coefficient (W/m^2 K)
$h_{c,nat}$	natural surface convective heat transfer coefficient (W/m^2 K)
L	evaporation latent heat (kJ/kg)
n	data amount during the calculation period
P	pressure (kPa)
P_s	surface perimeter (m)
$q_{c,d}$	convective heat transfer on the exterior surface of the dry facing layer (W/m^2)
$q_{c,w}$	convective heat transfer on the exterior surface of the wet facing layer (W/m^2)
$q_{d,d}$	thermal conduction flux flowing through the dry facing layer (W/m^2)
$q_{d,w}$	thermal conduction flux flowing through the wet facing layer (W/m^2)
$q_{e,w}$	evaporation heat transfer on the facing layer of the wet sample, W/m^2
q_i	heat flux on the interior surface of sample (W/m^2)
$q_{l,d}$	net long-wave radiation heat transfer on the exterior surface of the dry facing layer (W/m^2)
$q_{l,w}$	net long-wave radiation heat transfer on the exterior surface of the wet facing layer (W/m^2)
$q_{r,d}$	net short-wave radiation on the exterior surface of the dry facing layer (W/m^2)
$q_{r,w}$	net short-wave radiation on the exterior surface of the wet facing layer (W/m^2)
R	thermal resistance of the waterproof layer and base layer (m^2 K/W)
R_f	surface roughness coefficient
R_L	long-wave radiation (W/m^2)
R_n	surface net radiation (MJ/m^2)
T	all-day average air temperature or hourly air temperature (°C)
T_s	thermodynamic temperature on the exterior surface of the facing layer (K)
t_a	air temperature (°C)
t_s	surface temperature (°C)
v	all-day average wind speed or hourly wind speed (m/s)
u_R	uncertainty of R value (m^2 K/W)
u_{θ_e}	uncertainty of exterior surface temperature (°C)
u_{θ_i}	uncertainty of interior surface temperature (°C)
u_{q_i}	uncertainty of heat flux on the interior surface (W/m^2)
V_f	air flow velocity above the surface (m/s)
β	ratio between the molecular weight of water and air
γ	psychrometer constant (kPa/°C)
Δ	slope of saturation vapor pressure curve (kPa/°C)
θ_e	exterior surface temperature (°C)
θ_i	interior surface temperature (°C)
ε	emissivity
ϕ	angle between the surface and horizontal plane, 0° for the horizontal plane, and 90° for the vertical plane
σ	Stephen–Boltzmann constant

data of these four materials. The test results indicate that porous material can effectively reduce the surface temperature, where the degree of reduction in the surface temperature is closely related to the moisture content of the material, absorption coefficient of solar radiation, wind speed, and evaporation. Oliveira et al. [7] performed studies on passive cooling techniques in 14 cities in Brazil and selected four wall structures as the objects of study: highly reflective walls, wet surface walls, composite walls with high reflection and a wet surface, and insulation walls. The researchers established the heat balance equation of the wall, which comprehensively considered thermal conduction, convection, radiation, and evaporation. By solving this equation, the heat gain and heat loss for the air in the room were obtained, and these four wall types were compared with normal walls. The results of their studies indicate that for typical Brazilian houses, the passive design has an extremely significant effect on reducing the cooling capacity demand of rooms. He et al. [8–10] placed a ceramic tube in the water and studied the evaporation cooling process after the ceramic tube absorbed water. The authors used the evaporation efficiency of the ceramic tube to calculate the evaporation, which was derived using the functional relationship between the volumetric water content and evaporation efficiency through experimental measurements; additionally, the evaporation was calculated to determine the evaporation exchange heat by measuring the volumetric water content of the ceramic tube. Pires et al. [11] suggested that the water-storage medium is the important factor that affects the evaporative cooling effect. To obtain the ideal water-storage medium required in their subsequent study, the researchers studied the evaporative cooling capacity of six types of building materials and five types of textile fabrics in a small wind tunnel with a fixed wind speed and temperature. The experimental results showed that among the construction materials, the performance of the ceramic hollow brick was the best; among the textile fabrics, the performances of the fabric samples with cavities were the best. The authors eventually determined that polyester fabric with honeycomb cavities should be used as the sample for the following evaporative cooling study.

Outdoor field measurements can accurately describe the building evaporating process in actual outdoor weather conditions; however, outdoor measurements are considerably restricted by natural conditions and experimental results are difficult to reproduce. An experimental study conducted in a laboratory can obtain continuous, stable experimental data, and experimental results can be reproduced. Therefore, the laboratory experimental study is more reliable when researching the dynamic evaporating process of construction materials. In order to make the measurement results in laboratory closer to that in actual outdoor environment, all elements of the weather should be simulated and controlled to create an experimental environment that is similar to actual outdoor environment.

In this paper, a CWT was used to reproduce the typical environment of a summer day in the Guangzhou area. In the CWT, the dynamic evaporating and heat transfer process of two samples were studied. The results presented in this paper can improve the experimental method of building evaporative cooling research and supplement basic data that can be used for the engineering application of evaporative cooling techniques in buildings.