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Experimental investigation of the thermal isolation and evaporative cooling effects of an exposed shallow-water-reserved roof under the sub-tropical climatic condition

Wansheng Yang[a,c], Zhangyuan Wang[a], Xudong Zhao[b,a,*]

[a] School of Civil and Transportation Engineering, Guangdong University of Technology, Guangzhou 510006, Guangdong, PR China
[b] School of Engineering, University of Hull, Hull HU6 7RX, UK
[c] State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou 510640, PR China

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ABSTRACT

The aim of the paper is to experimentally investigate the thermal isolation and water evaporation effects of an exposed, shallow-water-reserved roof incorporating an impounding reservoir. This involved a brief theoretical analysis of the heat and mass transfer process associated with the water-reserved roof and most importantly, the dedicated measurement to the selected building roof in Guangzhou (China), located at a typical sub-tropical climatic region. As a result, temperature variations of different roof layers during the day and night time were recorded and the thermal isolation effect of the water-reserved roof against the building internal space was assessed. Furthermore, the water level within the impounding reservoir was measured at the regular time interval and variations of the instant and average water evaporation rate and associated latent heat intake during the day and night time were calculated. The impacts of the solar radiation, ambient air temperature, relative humidity and flow speed towards the evaporative cooling effect of the water-reserved roof were individually analyzed and a general correlation between the water evaporation rate and these impacting factors was subsequently developed. It was found that the water-reserved roof has the functions of heat storing, temperature attenuation, and peak temperature appearance time lagging, leading to the reduced roof heat transfer by around 55%. The temperature of the roof surface with the impounding reservoir was around 6.8 °C (in average) lower than that of the traditional exposed roof surface; while the water temperature difference between the surface and base level of the impounding reservoir was around 0.9 °C (in average). The maximum roof temperature appearance time for the reservoir-incorporated roof could be lagged by up to 100 min compared to the traditional exposed roof. The water body temperature at night was 3.5 °C lower than that in day-time, indicating that the roof could obtain the enhanced heat dissipation effect during the night time operation. Evaporation of the water within the impounding reservoir occurred during both day and night time; this helped reduce the temperature of the water-reserved roof surface and associated heat transfer rate through the roof, thus leading to the reduced energy consumption in the building's air conditioning and ventilation systems. Average water evaporation rates during day and night time were 0.378 kg/(h m^2) and 0.137 kg/(h m^2), respectively. Higher solar radiation, higher ambient air temperature, lower ambient air relative humidity, and higher air speed helped increase the evaporation rate of the water across the surface of the impounding reservoir. To give a brief, the research helps understand the heat and mass transfer mechanisms associated with the exposed shallow-water-reserved roof and thus contribute to design a better thermal-performed roof structure and energy efficient buildings under the sub-tropical climatic conditions.

1. Introduction

The exposed shallow-water-reserved roof has several identifiable advantages, e.g., heat storing, temperature attenuation, peak temperature appearance time lagging, as well as water evaporation resulted cooling. Compared to the commonly used surface

* Corresponding author at: University of Hull, School of Engineering, Cottingham Road, Hull HU67RX, UK. Tel.: +44 0 1482 466684; fax: +44 0 1482 466664.
E-mail address: xudong.zhao@Hull.ac.uk (X. Zhao).

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Nomenclature

C	the blackbody radiation coefficient, 5.67 (W/(m^2 K))
H	height of water (m)
h_c	the convection heat transfer coefficient (W/(m^2 K))
h_{out}	convection heat transfer coefficient between water surface and ambient air (W/(m^2 K))
M_{evap}	rate of evaporation (kg/(m^2 s))
P_a	divisional vapour pressure of air (Pa)
$q_{conv,a-w}$	heat flux by convection to the water surface from ambient air (W/m^2)
q_{evap}	heat flux by evaporation from the water surface to the ambient air (W/m^2)
q_{solar}	solar radiation (W/m^2)
R_w	thermal resistance of the water layer ((K m^2)/W)
$t_{a,indoor}$	indoor air temperature (°C (or K))
t_{in}	surface temperature of inside roof (°C (or K))
t_s	water surface temperature (°C (or K))
$t_{w,base}$	water base temperature (°C (or K))
α	the solar radiation absorption coefficient of water surface
ΔT	temperature difference between the air temperature and the water base (°C)
v	wind speed of water surface (m/s)
σ	the Stephen Boltzmann constant, 5.67×10^{-8} (W/(m^2 K^4))
ϕ	the angular coefficient between water and sky
c_{pw}	specific heat of water (J/(kg K))
E	water evaporation rate (kg/(m^2 h))
h_{in}	convection heat transfer coefficient between the interior roof surface and ambient air (W/(m^2 K))
h_r	the long wave radiation heat transfer coefficient (W/(m^2 K))
m_w	mass of water (kg)
P_w	saturated vapour pressure of water surface (Pa)
$q_{cond,w-r}$	heat flux by conduction heat transferred to the roof from water (W/m^2)
$q_{rad,w-sky}$	long wave heat flux between the water and atmospheric (W/m^2)
R_{roof}	thermal resistance of the roof construction ((K m^2)/W)
t_a	air temperature (°C (or K))
T_e	the long wave radiation temperature, (K)
$t_{roof,surface}$	the outsider surface temperature of roof construction, (°C)
t_w	water body temperature, (°C (or K))
T_{ws}	water surface temperature, (K)
γ	latent heat of vaporization of water, (2.45×10^6 J/kg)
ε	the Reflectance coefficient of water
λ_w	thermal conductivity of water (W/(m K))
τ	time (s)
φ	air relative humidity (%)

Subscripts

base	water base
max	maximum
s	solar
av	average
d	daytime
n	night
t	total

reflective and insulated roofs that can reduce the temperature of the roof surface and the heat flow into the indoor space, the shallow-water-reserved roof has several additional advantages: (1) evaporation induced cooling that can further enhance the cooling effect against the roof; (2) rain-water reservation that enables collection of the frequent rainfalls for various uses in buildings (e.g. flush, washing, cleaning etc); This characteristic makes it most applicable to the sub-tropic climatic region (e.g. Guangzhou) where rainfall is a common weather phenomenon; (3) higher thermal mass (4200 kJ/t K for water .vs. 840 kJ/t K for concrete) that makes it a better/lighter insulator than the traditional concrete.

Many researchers have taken a series of investigations into the evaporative cooling and thermal insulation effects of the water-reserved roof. In China, the very earlier work on this subject was undertaken by Zhao (1959a,b), focusing on investigation of the evaporative cooling effect of the water-straining roof under the natural ventilated condition in Xi'an, which is located at a dry and hot climatic region. As the follow-on work, the China Construction Research Institute (ATPB, 2004) studied the thermal properties of the water-reserved roof in 1977. Sooner after, Chen (ATPB, 2004) experimentally investigated the reflectivity of the water surface of the roof-based impounding reservoir. Meng, Zhang, and Zhang (2006) measured the variation of the temperature of evaporating water in a glass roof with water pouring, which was delivered with the recycled rainwater using a solar powered circulation pump. Furthermore, a number of researchers investigated the dynamic heat transfer performance of the roof-based impounding reservoir (Dong, 1991; Ding, 1998; Liu, Yu, Tang, & Zhang, 1998). In terms of the practical application, the barns are the places where the water-reserved roofs were used most and studies into the barn roofs' thermal insulation performance were undertaken (Fan, Cao, & He, 2007; Le, 2006; Xiong, 2004; Yan, 2005; Wang, 2006) by several researchers. The method applied was to measure the temperatures of the roofs' exterior and interior surface and ambient air. However, no studies have yet been made into the mechanism of thermal insulation of this type of roof.

From worldwide point of view, Florides, Tassou, Kalogirou, and Wrobel (2002) and Ghiabaklou (2003) studied the method of providing thermal insulation to the vertical envelopes, e.g. walls, windows or glasses, using the evaporation effect of the water curtains provided by the waterfall devices, which is especially suitable for the use in dry climatic regions. Similarly, Nahar, Sharma, and Purohit (2003) developed a thermal insulation method for the roof, which placed a floating thermal insulation layer onto the roof-based impounding reservoir. In summer, the impounding reservoir prevented solar radiations from striking the underneath layers of the roof in day-time; and acted to cool down the roof structure by evaporating the water at night. In winter, the water layer absorbed solar radiation thus keeping warmth of the roof structure in day-time, and minimized temperature drop of the roof in night. Ghosal, Tiwari, and Srivastava, (2003) conducted the thermal insulation and water evaporation experiments for a greenhouse with a roof covered by water pouring jute grass. The roof could obtain good cooling effect by evaporating the water under activation of solar radiations. Furthermore, Tang carried out the theoretic study of the evaporative cooling effect of the roof-based impounding reservoir with a floating substance (Tang & Etzion, 2005; Tang & Etzion, 2004a; Tang & Etzion, 2004b), thus generating a dedicated simulation model. Kharruf and Adil (2008) developed a specific model appropriate to the Middle East climatic conditions. The dual functions of such a roof are (1) enabling thermal insulation by treating the water storage layer as a barrier to the solar radiations; and (2) implementing a mechanical ventilation measure between the water layer and the solid roof layers to enable evaporation of water, thus enabling cooling the roof structure, as well as whole building space.