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Thermal modelling and experimental validation of a semi-transparent water wall system for Sydney climate

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ABSTRACT

A transient heat balance model (THBM) based on energy conservation is developed for predicting the thermal performance of a semi-transparent water wall system. In order to validate the THBM against field measurements, real climate conditions in Sydney, Australia are adopted and the time variations of both internal and external convective and radiative heat transfer coefficients are calculated using empirical correlations from the literature. An alternative concrete wall model is also developed for further validation of the THBM. Good agreements between the THBM simulation and field data are achieved for both the water wall and concrete wall systems. The validated THBM is then adopted in a sensitivity analysis in order to assess the thermal performance of the semi-transparent water wall system under different configurations. It is found that the daily maximum water and air temperatures decrease significantly with the decrease of the transmissivity of the semi-transparent panels, whereas an increase of the attenuation coefficient of solar radiation in water has an insignificant impact on the water and air temperatures. The present results also indicated that increasing the thickness of the water column can reduce the fluctuations of the water temperature and the diurnal peak air temperature. From the practical application point of view, reducing the transmissivity of the external panel provides the most effective way to mitigate over-heating in the semi-transparent water wall system.

1. Introduction

Energy consumption by residential and commercial buildings accounts for nearly one quarter of the total worldwide consumption of delivered energy (Energy Information Administration, 2013), and it is predicted that the building energy consumption will increase by approximately 1.6% per year from 2010 to 2040. Therefore, saving energy in buildings is critical for the combat against global energy crisis and climate change. For this purpose, a number of passive solar technologies have been developed for buildings. Among the various passive solar strategies, water wall is an excellent solution which can maintain thermal comfort in buildings while reducing energy consumption. The water wall system has unique advantages over other passive strategies as it allows part of the solar radiation to enter the buildings, and thus reduce the need for lighting during the daytime. The semi-transparent nature of the water wall system also gives the system aesthetic advantages over opaque walls. In addition, the cost of the water wall system is significantly lower than that of thermal storage walls using phase change materials (PCMs).

Extensive analyses have been reported in the literature on the thermal performance of water walls. Sodha et al. (1981) compared the thermal performance of a Trombe wall with a water wall plus concrete, a water wall plus insulation panels and a simple water column by calculating the heat transfer through these walls in an air-conditioned room using a heat balance model (HBM). The HBM is based on the energy conservation concept to establish energy balance associated with conductive, convective and radiative heat transfer in order to obtain surface and fluid (i.e. water and air) temperatures. Their results illustrated that a water wall plus concrete system was more desirable than the other configurations for the winter climate in New Delhi, and the more water contained in the water wall plus concrete system, the better performance was achieved. Sodha et al. (1992) also compared the effects of two types of thermal storage materials (i.e. water and concrete) on the thermal performance of a non-air-conditioned room using the HBM. It was found that the concrete storage was less effective than the water storage in reducing the swing of the room air temperature for the same storage mass because of the lower heat capacity of the concrete.

Nayak (1987) conducted a comparison of the thermal performance of two types of south-facing water walls including a water wall with concrete and a transwall (a semi-transparent water wall

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Nomenclature

ACH	air changes per hour
C	specific heat capacity, J/kg K
D	model depth, m
g	acceleration due to gravity, m/s^2
G	solar irradiance, W/m^2
h	heat transfer coefficient, W/m^2 K
H	model height, m
Pr	Prandtl number, ν/κ
q	heat flux, W/m^2
Ra	Rayleigh number, $g\beta\Delta TH^3/\nu\kappa$
t	time, s
T, T_0, T_{sky}	temperature, ambient temperature and sky temperature, K
V	volume of the room, m^3
W	model width, m
x	horizontal coordinate, m
Greek letters	
α	absorptivity
β	coefficient of thermal expansion, 1/K
δ	thickness
ΔT	temperature difference, K
ε	emissivity
η	attenuation coefficient of solar radiation in water, 1/m
κ	thermal diffusivity, m^2/s
λ	thermal conductivity, W/m K
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ	Stefan–Boltzmann constant, 5.669×10^{-8} W/m^2 K^4
τ	transmissivity
Subscripts	
a	air
c	convective
d	diurnal cycle (day)
f	fluid
i	insulation
j	node points
max, min	maximum and minimum values
p	Perspex
r	radiative
s	solid
w	water
Superscripts	
max, min	maximum and minimum values
n	time-step

which allows part of the sunlight to penetrate from outside into the room via the water wall) for a heated space using the HBM. The results showed that the transwall was more effective than the concrete water wall in meeting the daytime heating load. However, a concrete water wall was better from the viewpoints of reducing temperature swings and the overall day-and-night performance because it caused a significant phase shift. Tiwari (1991) also carried out a comparison of the performance of a transwall, a water wall and an isothermal mass for heating in a non-air-conditioned passive solar house for the harsh cold climate of Srinagar, India. A transient analysis based on the HBM was carried out and steady state conditions were achieved after 3 days. They found that the performance of the transwall was better than the isothermal mass and the water wall in terms of both improving night room air temperature and minimising temperature fluctuation.

Experimental studies of water wall have attracted much less attention than analytical investigations. Among the existing experimental studies, Govind et al. (1987) investigated the effect of thermal energy storage (TES) in a winter greenhouse. A greenhouse with a floor area of 15.4-m^2 and a water drum capacity of 3.02-m^3 was constructed for the purpose of growing early summer vegetables. The results indicated that the thermal energy storage by water offered a much higher air temperature than the ambient and minimised the fluctuations of the air temperature in the greenhouse, and a good agreement was obtained between a theoretical model based on the HBM and the experimental measurements. Gupta and Tiwari (2002) developed a transient analysis model based on the HBM to investigate the TES effect of a water mass in a passive greenhouse. They concluded that the temperature fluctuation inside the room decreased with an increase of the water mass and was large in winter and small in summer. An experiment was carried out to validate their model and a fair agreement between the predicted and experimental results was reported. Robinson et al. (2013) designed a full-scale passive solar system utilising heat pipes to transfer latent heat to a storage water tank inside a classroom at the University of Louisville during the spring heating season of 2010. Their field measurements indicated that the thermal storage water tank was heated to a sufficiently high temperature to supply heat to the classroom even during the coldest days of the season. During a long period (4 consecutive days) of low solar isolation, the average hourly heat delivery to the classroom remained positive and was always above 16.6 W/m^2. A computer model based on the HBM was developed and a fair agreement between the predicted and experimental results was reported.

It is seen from the above reviewed literature that the HBM has dominated the water wall research for over three decades. The existing HBMs adopted for water wall research suffer from two major deficiencies. Firstly, the convective heat transfer coefficients embodied in the HBMs have been assumed constant in all the models. However, it is understood that the convective heat transfer coefficient depends on the flow and thermal conditions, which may change with time in real-life applications. Therefore, it is necessary to account for the time variation of the convective heat transfer coefficients in the HBMs. And secondly, the radiation exchange between internal surfaces is commonly neglected in the HBMs although some models have considered the radiation emitted by external surfaces (e.g. Sodha et al., 1981; Kaushik and Kaul, 1989). The study of Wu and Lei (2015) has showed that the internal surface-to-surface radiation exchange has a significant impact on the flow structure in a cavity, and thus the internal radiation exchange should be accounted for in the HBM. The purpose of this investigation is to develop a transient heat balance model (THBM), accounting for time variations of both internal and external convective heat transfer coefficients and the internal surface-to-surface radiation exchange, for describing the thermal behaviour of a water wall system. Although the THBM is not completely new to the building science community and has been successfully applied to building research previously (e.g. Li et al., 2015; Mottard and Fissore, 2007), its application to water wall research has never been reported. In this study, a reduced-scale prototype experiment under real climate conditions in Sydney, Australia has been conducted for validating the model.