Energy and Buildings 126 (2016) 14–27

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Numerical analysis on the cooling performance of a ventilated Trombe wall combined with venetian blinds in an office building

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ARTICLE INFO

Article history:
Received 3 December 2015
Received in revised form 26 April 2016
Accepted 6 May 2016
Available online 10 May 2016

Keywords:
Numerical model
Trombe wall
Venetian blinds
Split-type air conditioner
Cooling load reduction
Office building

ABSTRACT

Using a Trombe wall with venetian blinds (VBTW) as a cooling system in an office building with split-type air conditioner and simultaneously considering the requirements of outdoor air supply are few investigated. A dynamic model on the VBTW was presented and validated by the experiment in this paper. The influence of three parameters in combination with two set-point temperatures 24 °C and 26 °C on the cooling load were investigated: blind tilt angles from the horizontal (15°, 45°, 60°, 75°), air gap width (5 cm, 10 cm, 15 cm and 20 cm), core layer materials (red brick 1760, red brick 1120, concrete block 1440 and concrete 2210) together with different thickness. The results indicated that by increasing the air gap width, the cooling load was increased a little. However, variations of the blind tilt angle have a significant effect on the cooling load. Bigger blind tilt angle (closing) yielded lower heat flux across the VBTW. Finally, the use of low instead of high density materials in the core may reduce the cooling load. The heat-transfer rate through the wall depended on the compared thermal conductivity and their thermal capacity. The afore-mentioned findings are helpful for the energy saving design of the solar utilization.

1. Introduction

Today's buildings are dominated by the 'active' environmental control system for heating, ventilation and air conditioning often resulting in an increase in conventional energy use and CO_2 emission. Therefore, we need to actively seek renewable energy technology to relieve building energy consumption [1]. Among the renewable sources, solar energy plays the most import role due to its infinity and cleanness. Trombe wall is a sustainable architectural technology of the solar energy utilization for space heating and ventilation [2,3]. A conventional Trombe wall is a system that makes use of indirect solar gain [4]. It is normally comprised of a massive wall painted black, an exterior glazing cover and a ventilated air gap in between [5]. Two adjustable dampers at the massive wall and adjustable vent of the glazing cover are designed for winter heating and summer cooling. The blackened massive wall absorbs and stores the solar energy transmitted through the glazing. Heat exchange of Trombe wall with the indoor environment is partly by conduction through the wall and partly by ventilation through the vents due to buoyancy effect [6].

The Trombe wall is mainly used in cold and mild climates for passive solar heating. It can reduce a building's energy consumption for residential heating by up to 30% [7]. There have been numerous studies on the Trombe wall for passive solar heating: Khalifa and Abbas et al. [8] numerically study the effect of storage wall material and thickness on room temperature. Similar studies are conducted by [9–11]. In this direction, Agrawal and Tiwari have proposed an optimal thickness of 30–40 cm for a concrete Trombe wall [12]. Chen et al. [13] conducted an experiment of Trombe wall with shading device and found that the use of shading can reduce about 20%–40% heat loss in the air gap on a winter night. Several studies on the Trombe wall for passive cooling focused on reducing the drawback of the Trombe wall in summer for hot climates: Ghrab-Morcos et al. [14] described that overhangs in Trombe wall were of valuable aid to against overheating. Ji et al. [15] proposed that appending a shading curtain in summer were adopted for PV-Trombe wall. Similarly, Soussi et al. [16] pointed out that the building with properly shielded Trombe wall can reduce the annual cooling requirements. Gan et al. [17,18] carried out the numerical simulation of a Trombe wall for summer cooling and investigated the effect of the wall height and insulation. Stazi et al. [19] adopted some strategies to enhance the efficiency of Trombe walls in summer time. Rabani et al. [20,21] presented an experimental study of a new designed Trombe wall in combination with solar chimney and water spraying system. The results demonstrated that the new

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http://dx.doi.org/10.1016/j.enbuild.2016.05.016
0378-7788/

Nomenclature

A	Area (m^2)
c	Specific heat capacity (J/(kg K))
d	Air gap hydraulic diameter (m)
D	Air gap width (m)
E	Daily cooling load (KJ/m^2)
F	View factor
g	Gravitational acceleration (m/s^2)
H	Height of the VBTW (m)
h	Heat transfer coefficient (W/m^2 K)
I	Vertical solar radiation ($W\ m^{-2}$)
m	Mass (kg)
Nu	Nusslet number
Pr	Prandtl number
P	Permeability
q	Heat flux across the wall (W/m^2)
Re	Reynolds number
si	Blind tilt angle (°)
T	temperature (°C)
t	Time (s)
V	Air velocity (m/s)
$\dot{V}_{bz}$	Ventilation rates (m^3/h)

Greek symbols

α	Absorptivity
β	Heat expansion coefficient (K^{-1})
λ	Thermal conductivity (W/(m °C)
ε	Emissivity
τ	Transmittance
ρ	Density (Kg/m^3)
ϕ	Absorbed solar energy (W)
η	Cooling load reduction

Subscripts

a	Air in the air duct
b	Venetian blinds
c	Convection heat transfer
f	Fan
g	Glazing cover
r	Radiation heat transfer
w	Trombe wall with venetian blinds
nw	Normal south wall
in	Air inlet
out	Air outlet

designed Trombe wall can decrease indoor temperature by about 8 °C in hot season.

In recent studies, a novel Trombe wall combined with venetian blinds (VBTW) was proposed by the present authors [22,23]. The amount of absorbed solar radiation can be controlled by adjusting the angle of venetian blinds to achieve a relatively stable and comfortable indoor condition. The present authors emphasized the winter performance of the VBTW and found that the VBTW was more effective when used in office buildings [23]. At hot summer and cold winter area in China, office buildings are normally equipped with split-type air conditioners. In summer, outdoor air supply to the office building is by fortuitous ventilation through cracks and openings in the building fabric. However, as a result of wide-spread draught proofing of doors, windows, etc., office buildings have become less well ventilated [24]. Therefore, well-designed natural or mechanical ventilation system are required to provide comfortable and healthy conditions for its occupants. Trombe wall with venetian blinds (VBTW) is treated as an ingenious design for addressing ventilation issues due to its simple geometry and non-additional air channel cost. Meanwhile, the loss of heat through ventilation can be used to cool building envelope. Therefore, the VBTW can reduce air conditioner energy consumption without sacrificing the indoor air quality. Few investigations have been reported on the summer performance of the VBTW when applied in an office building with air conditioner, which was still unclear up to now. The principal purpose of this paper was to investigate the cooling load reduction of the VBTW compared with the normal south wall. To this end, this study was structured in two parts. The first part outlined the model of the VBTW summer mode, and went on to describe the validation process using the experimental results. The second part of this paper presented a parametric study when using the VBTW on an office building of 20 m^2. It is noteworthy that some part of the model is too simplified to match the testing results well. Thus, the present paper only investigated the cooling load and few parameters effects and didn't refer to some issues, such as the VBTW's cost efficiency, the payback time, VBTW's maintenance and the effect of fan position.

2. Experimental setup

2.1. Description of the experimental platform

In our previous study [23], the experimental cells have been built in Hefei, China. Its average elevation is 26.8 m, latitude 31°52′N, and longitude 117 17′E. Hefei enjoys the subtropical humid monsoon climate with four distinct seasons (winter, spring, summer, and autumn). The climate is characterized by relatively hot summer and cold winter. The cooling days are between June and September.

The experiment cells consist of two rooms (right: test room, left: reference room) with interior dimensions of width 3800 mm/depth 3900 mm/height 2600 mm (see Fig. 1). Each room has been installed a split-type air conditioner and is oriented due south. All the building envelopes are insulated except the south wall. The two ventilated VBTWs have been applied on the south wall of the test room to maximize capture of sun rays, as shown in Fig. 2. To validate the summer model of the VBTW, we conducted the experiments on the afore-mentioned test room (left room in Fig. 1). The whole south wall comprises the VBTW part and the normal south wall part (see Figs. 1 and 2). In addition, the glazing and the outer surface of normal south wall are in a same plane. The ventilated VBTW, as shown in Fig. 3, was composed of a glazing cover, a massive wall behind venetian blinds, and a ventilated air gap in between. The proposed venetian blinds were characterized by selective absorption: one side of venetian blinds was covered with high absorptivity coating (blue titanium, 0. 9) and the other side was covered high reflectivity coating (aluminum film, 0.15). The side with high absorptivity coating is overturned outward in winter. In contrary, in hot season the other side with high reflectivity coating face the sun to prevent overheating effect. The venetian blinds can be placed in the out surface of the glazing or in the air gap. However, locating the venetian blinds in air gap can prolong its using life and improve the aesthetic appealing look of the system. Moreover, the buoyancy effect can be enhanced to reduce the energy consumption of the fan. Therefore, in our study the venetian blinds was installed in the air gap. In addition, the outer glazing can be opened for the maintenance of the system. There are two air vents for winter heating and two air vents for summer cooling. For summer cooling, the lower vent at the massive wall and the vent at the glazing cover are opened. The solar heated air in the air gap draws room air from the lower vent at the massive wall and the heated air is then flows out to the ambient through the vent at the glazing cover. The driving force which controls the airflow rate is generated by the buoyancy effect and a fan. The normal south wall as well as massive wall has three layers: