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Experimental and theoretical analysis on thermal performance of solar thermal curtain wall in building envelope

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ABSTRACT

The need for energy efficient building design has stimulated the integrating buildings with energy systems. In this paper, a novel solar thermal curtain wall (STCW), which is the solar collector installed as a building envelope or integrated to normal facades, is developed. A stand-alone house with the STCW was constructed and thermal performance of the STCW was tested and theoretically analyzed. The results showed that the STCW combined energy production for hot water supply with other functional features of architectural, structural and aesthetic as a new kind of building component. In typical summer day and winter day, the efficiency of the STCW system were 56.8% and 41.0%, respectively. The heat transfer coefficient of the STCW varied monthly, with the maximum value recorded being 1.99 $W\,m^{-2}\,K^{-1}$ in August and the minimum value recorded being 0.86 $W\,m^{-2}\,K^{-1}$ in January. A sensitivity analysis was made to investigate variations on the heat transmission load of the solar curtain wall. The results show that the transmission heating load can be reduced by about 39% when the insulation is increased from 25 mm to 50 mm. A comparison between the solar collector integrated with traditional wall and solar curtain wall only was made. Integrated solar collector to wall provides more damping of load fluctuation and smaller peak load, compared with traditional walls, the heating load of façade-integrated walls are less and the walls even contribute heating for the building. Though the cooling load was increased, the comprehensive performance for the façade-integrate walls are superior to the traditional walls.

1. Introduction

Buildings in major cities worldwide are in huge requirement of air conditioning and hot water. Thus renewable energy is popular in buildings to enhance the building energy efficiency and building-integrated solar thermal system has experienced a great development. The integration of photovoltaic and solar thermal collectors into the walls or roofing structure of a building could provide greater opportunity for the use of renewable solar energy technologies. A substantial amount of research has been done on building integrated solar water heating system [1–7]. The roof and the wall are distinctively used as integrative thermal building elements, which means that the roof and the wall performed the functions of a building envelope, as well as a component to collect solar energy. Due to its advantages such as clean and low operation cost, solar hot water system contributes a lot to make buildings energy efficient. However, many studies have addressed on the performance of the solar system [8,9] and building-integrated PV walls [10–13].

Actually, the heat gain through the solar curtain wall may affect the indoor climate environment which has influence on the energy consumption of air conditioning or heating. Study of the thermal performance of the solar thermal curtain wall (STCW) is useful for the wall to reduce indoor cooling loads under the premise of high efficiency of energy generation. There are only a few studies [10–12,14] done on the thermal performance of the solar curtain collector as building envelope. These studies report that solar thermal collectors show good performance in reducing the space load. Tomas et al. [1] investigated the façade-integrated solar thermal collectors for water heating and found that façade solar collector should have an area increased by approximately 30% to achieve the usual 60% solar fraction compared with conventional roof solar collectors with a 45° slope and building behavior is not strongly affected by façade collectors when sufficient insulation layers are presented. Motte [15] presented a new concept of solar collector integrated into a rainwater gutter and investigated on the thermal

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Nomenclature

A	area (m^2)
C	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
h_c	convection coefficient ($W\,m^{-2}\,K^{-1}$)
h_{c-a}	convection coefficient between cover and ambient
$h_{r,c-a}$	radiation heat transfer coefficient between cover and ambient
h_{c-p}	convection coefficient between cover and plate
$h_{r,c-p}$	radiation heat transfer coefficient between cover and plate
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
Gr	Grashof number
Pr	Prandtl number
Nu	Nusselt number
g	gravitational acceleration ($m\,s^{-2}$)
I	solar irradiation flux ($W\,m^{-2}$)
t	temperature (K)
v	wind velocity ($m\,s^{-1}$)
q	heat flux ($W\,m^{-2}$)
R	thermal resistance ($m^2\,K\,W^{-1}$)
W	width (m)
W_o	distance between the tubes (m)
D_o	outside diameter (m)
D_i	inside diameter (m)
L	height of the solar collector (m)
H	height of the room (m)

Greek symbols

τ	time (s); transmittance
ρ	density ($kg\,m^{-3}$)
δ	thickness (m)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
α	absorption rate
ε	emissivity
Δ	difference

Subscripts

a	ambient air
c	glass cover
p	absorber plate
w	wall
ins	insulation material
f	fluid
e	emittance
s	sky
col	solar collector
i	indoor room

performance of the system. Maria et al. [3] addressed a survey to more than 170 European architects and gave out an integration criteria, design guidelines and a methodology to design future solar thermal collectors system suited to building integration. Ji et al. [16] studied the annual performance of façade-integrated hybrid photovoltaic/thermal collector system used in residential buildings of Hong Kong and got the results that the performance of the system was better than the conventional solar collector and space heat gain was reduced compared with traditional concrete wall. Hongxing Yang et al. [10] compared the PV walls and massive walls and found that the photovoltaic integration in building walls reduced the corresponding cooling load components by 33–50%.

The main objective of this research is to study the heat transfer coefficient and the transmission load of the solar thermal curtain wall and compare it with traditional walls. A solar thermal curtain wall incorporated with a house was constructed and tests were carried out to study the thermal performance of the system and the solar curtain wall. In order to evaluate the integrative energy performance of the STCW, a simulation model based on heat transfer theory was built. This paper first presents a brief review of the experimental results and validation of the simulation model and a year round performance of STCW.

2. Description of the solar thermal curtain wall

2.1. Construction of the STCW

The solar thermal curtain wall (STCW) system is a solar thermal system with collectors installed as a building envelope or an integrating curtain collector to normal facades. The STCW combines energy production with other functional features of architectural, structural and aesthetic as a new kind of building component. Solar components integrated in the building envelope can provide an important contribution to the utilization of renewable energy as the equipment performs the function of an envelope while it simultaneously collects solar energy for heating purposes. The STCW system can reduce the air conditioning load when it performs the function as envelope, for the external walls and roof are the interface between its interior and outdoor environment and the solar curtain wall performed as the insulation which is the most cost-effective way of controlling the outside elements to make homes more comfortable. The SCTW can also supply hot water for bathrooms, kitchens, swimming pools and the like while it makes the high-rise building available for solar using and avoids the roof ownership controversial problem as the curtain collectors are used as envelope or integrated to facade. Besides, the curtain wall collector module can be manufactured as a construction element (facade cladding, roof covering etc.) and the material and color can be designed considering the building which eases the integration work.

A stand-alone house with the solar collector integrated as envelope was constructed for investigating the thermal performance of solar thermal curtain wall. Fig. 1 shows the experimental set-up. As the building envelope, the solar curtain wall can also be used for domestic hot water production. Experiments were done on the south wall of the studied-house, from which the three collector modules in vertical are connected in series, forming two pairs in a parallel circuit, such that the collectors for each column can have the same inlet water temperature from the water tank.

The solar thermal curtain wall module which is actually a flat-plate collector is composed of a layer of highly transparent glass sheet, a layer of highly absorptive plate, pipes and insulations. The plate is basically a tube-in-sheet-type plate. Fig. 2 shows the layers of the solar thermal curtain wall module. The structure parameters of the module is shown in Table 1.

Fig. 1. The appearance of the solar curtain wall system.