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Experimental verification of state space model and thermal performance analysis for active solar walls

Guoqing Yu *, Pengcheng Zhao, Dong Chen, Yihong Jin

School of Environment and Architecture, University of Shanghai for Science and Technology, Shanghai 200093, China

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ABSTRACT

Building-integrated solar thermal system is a new tendency in the building sector. An active solar wall is studied in this paper, which integrates flat plate solar thermal collector and building wall. The performance of an active solar wall is predicted by the state space model and measured by experimental testing respectively. The calculated results by state space model agree well with the measured data from experimental testing, which indicates that state space model is valid. Thermal analysis for a particular solar wall is conducted in clear and cloudy days either in summer or winter respectively by state space model under Shanghai meteorological conditions and compared with the separate wall. The results indicate that: (1) Integration has a little effect on the useful heat gains by solar collector. In clear summer days, the useful heat gains are less than the separate solar collector by about 2–3%; In clear winter days, the useful heat gain is greater than the separate solar collector by about 5–8%; (2) Integration has great effect on the heat flow through walls. In clear summer, heat flow into the room through solar wall is significantly reduced by 55–63% than the separate wall. It is favorable to reduce cooling load. In winter, heat loss through solar wall is heavily reduced by about 80–88% than the separate wall. It is favorable to reduce the space heating load in winter.

1. Introduction

It has been known that buildings are consuming one third of the total energy supply in developed countries and one-fourth in developing countries (Zhang et al., 2015). Among the solutions to the energy problem, the utilization of solar energy is one of the most encouraging ecological avenues. Solar thermal is the most mature technology among all currently available solar technologies, many forms of solar collectors and solar systems have been studied and applied in buildings. Building-Integrated Solar Thermal (BIST) System is a new tendency in the building sector. BIST configurations offer multiple advantages compared to Building-Added (BA) installations due to higher aesthetic value by replacing the traditional building elements. Ursula Eicker, Ece Demir and Daniel Gürlich studied strategies for cost efficient refurbishment and solar energy integration in European Case Study buildings, which shows building integrated renewables can provide some or most of the building energy demand with a strong dependency on climatic conditions (Eicker et al., 2015). In early years, collector-storage wall is a typical form of integration of solar collector and building and mainly used for space heating in winter. It is usually termed as passive solar system since there is no pump or fan (Duffie and Beckman, 2013), and many studies were conducted on this passive form and its variants (Quesada et al., 2012).

Compared to passive form of solar utilization, 'Active Solar Thermal Façade' (ASTF) is a new building integrated solar thermal product, which allows integration of a solar thermal collecting device into a building envelope element (e.g. wall, window, shading, or roof), thus creating both the shielding and solar energy collecting functions for the façade (Zhang et al., 2015). An ASTF not only improves the thermal insulation of a building but also collects a certain amount of heat from the solar radiation striking onto its surface, which can be delivered to some space for heating, ventilation, or cooling purposes. Due to the prevailing prefabrication of building construction, the industrialized production of precast slabs and precast facade modules becomes more and more popular, which provides an opportunity for massive production of the ASTF modules. Buker and Riffat reviewed building integrated solar thermal collectors in recent ten years (Buker et al., 2015).

When a solar collector is integrated with building, the boundary conditions of heat transfer both for the solar collector and the building envelope are changed. Zhang et al. thoroughly reviewed the work that has been done on Active Solar Thermal Facades (ASTFs) and they found that further efforts should be taken to

* Corresponding author.
E-mail address: yuguoqinghvac@163.com (G. Yu).

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Nomenclature

C	specific heat of nodes, J/(kg·°C)
ρ	density, kg/m^3
R	thermal resistance, (m^2·°C)/W
λ	thermal conductivity, W/(m·°C)
Δy	thickness, m
V	water capacity in the solar collector, m^3
G	water flow rate of solar collector, kg/s
S	total solar radiation absorbed by the absorber plate of the collector, W/m^2
τ	time variable, s
T	nodal temperature, °C
h	heat transfer coefficient
C	coefficients matrix indicating the heat storage capacity with respect to unit temperature change of each node, C_{ii} is the coefficient in front of T_i, C_{ij} is zero when $i \neq j$
A_0	coefficients matrix representing heat flow due to the temperature difference between adjacent temperature nodes
B_0	coefficients matrix representing the effect of thermal disturbance on each node
u	input matrix, it is vector that consists of time-dependent thermal disturbance
T	vector including temperature of each node, state variable
$\dot{T}$	vector including temperature change rate of each node with respect to time
v	wind velocity, m/s
RMSD	root mean square deviation
MBD	mean bias

Subscripts

c	glass cover
p	absorber plate
f	fluid
in	insulation
wall	building wall
a	ambient
s	sky
r	radiative heat transfer
room	room
wind	wind
fi	inlet water

study on the dynamic performance of a whole ASTF system, hence thermal models for ASTF should be put forward, and simulations or experimental testing should be conducted to know the effects of integration on solar colleting efficiency and heat flow (Zhang et al., 2015).

As for the thermal analysis of ASTFs, the studies are fairly few. Lamnatou et al. (2015) comprehensively reviewed the modeling and simulation of building-Integrated solar thermal systems. They found that most of the studies of energetic simulations are about BIPV and skin façades and there are few studies about building integrated solar thermal systems (solar collector, solar chimney, Trombe wall, etc.). There is an urgent requirement of energetic and thermal simulations particularly for active building integrated solar thermal systems that can provide space/water heating for the building.

Matuska and Sourek (2006) developed a physical model of a façade collector and they coupled it to the building by means of TRNSYS. The TRNSYS model comprises a multizone model and a solar system model and the connection between solar collector and façade is realized by inputs and outputs between models. The model for the façade collector does not include the façade hence the interactions between façade and collector can't be reflected directly in the model. Hassan and Beliveau (2008) designed a roof-integrated solar collector and 3D finite element models were developed to evaluate the thermal performance of the collector. Juanicó (2008) provided a new design of roof-integrated water solar collector for domestic heating and cooling. It takes advantage of new synergies between collector and roof. Its main concept is based on the use of water redistribution for changing the roof configuration. Motte et al. (2013) used the finite difference method and circuit analogy method to analyze the thermal performance of a new rain gutters integrated with solar collector. Maurer et al. (2013) investigated the heating and cooling performance of a high-rise building incorporating façade-integrated transparent solar thermal collectors.

Yu et al. (2015) present a state space model for thermal analysis of integrated structure of flat plate solar collector and building envelope, the state space model is verified by FLUENT simulation, some thermal analysis for a particular building integrated solar structure was conducted. Compared to transfer function method, state space method can provide details of internal nodes and it is easy to deal with multi inputs and multi outputs. Compared to finite difference or finite element method, state space method takes much less computation time and has better stability.

Based on the work of Yu et al. (2015), experiments were conducted for wall-based ASTF, i.e. active solar wall and the results of measurement were compared with those of simulations by state space model in this present paper. The comparisons show the state space model is capable of long-term (several months or years) thermal analysis for building integrated solar structure. The state space method has good computation stability and the length of time step of 10 min and 1 h has little effect on the computation accuracy. Then the thermal performance of active solar wall during clear days and cloudy days in winter and summer is studied in details by state space method, and compares with the separate solar collector or the separate wall. The thermal analysis reveals the effects of integration both on solar collectors and building envelopes during various conditions. Integration of solar collectors and building envelopes is favorable to reduce space heating and cooling load.

2. The state space model for solar walls

2.1. The configuration of solar walls

The typical structure of the active solar wall is shown in Fig. 1. It is the integration of a flat plate solar thermal collector and building wall, which includes glass cover, absorber plate, tubes, back insulation and building wall (we'll call it solar wall later in this paper). The heat collected by absorber plate is delivered to other place for heating by the fluid in the tubes. Compared with separate solar collector or wall, the design of solar wall is intended to improve the thermal insulation of a building while producing heat.

2.2. Discretion of solar walls

The state space method is the basis of modern control theory. States are macro features of transient systems. The variables char-