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Performance evaluation of building integrated solar thermal shading system: Active solar energy usage

Li Li [a], Ming Qu [a,*], Steve Peng [a,b]

[a] School of Civil Engineering, Purdue University, 550 Stadium Mall Dr. CIVL G243, West Lafayette, IN, United States
[b] California State University, East Bay, United States

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ABSTRACT

This paper presents an evaluation of the building integrated solar thermal shading (BISTS) system on solar energy usage. A medium office building in Los Angeles defined by the U.S. Department of Energy (DOE) was used in the case study. The BISTS louvers mounted on the south, east, and west façades of the building were used to harvest solar energy to supply domestic hot water (DHW), space heating and/or cooling. The solar thermal system was modeled and simulated in TRNSYS. Solar fraction and solar useful efficiency were calculated, and a recommended operation strategy was proposed. The results indicated that: 1) potentially, the annual domestic hot water load can be fully supplied by the BISTS system. To achieve a recommended solar fraction 75%, either 10 m^2 collector on the south façade or 33 m^2 collector on the east and west façades are required; 2) 20.2% of cooling load or 64.6% of heating load can be met by the remaining collectors. The BISTS on the south façade is primarily recommended to provide space heating and/or cooling; 3) combined heating and cooling enables the system to take more advantage of solar energy for energy savings from auxiliary heating.

1. Introduction

Currently, solar technology has been used in a variety of applications, such as solar water heating, solar space heating and cooling, solar refrigeration, solar desalination, solar thermal power, and solar furnaces [1]. The integration of solar systems to the building envelope has attracted increasing attentions as it provides a new solution to reduce fossil fuel consumption and greenhouse gas emissions by taking advantage of renewable energy [2]. There are several ways to implement a solar system to a building. Some solar systems are separated elements that are added to the building after construction, some solar systems replace the building elements thereby serving multiple functions. The integrated solar thermal collectors are commonly located on roofs [3,4], façades [5,6], gutters [7–9], and shadings [10]. Building integrated solar thermal shading (BISTS) system is a new type of solar thermal application that potentially replaces traditional building exterior shading devices with small-sized solar thermal collectors for thermal heat generation, solar heat gain reduction, and glare control.

Buildings are responsible for 41% of the country's primary energy use in the United States. Of all the energy consumed by buildings, space heating, space cooling, water heating, and lighting account for over 60% [11]. The BISTS system can not only absorb solar energy for space heating, space cooling, and water heating, but also influence the interior daylight condition and visual comfort. However, the studies about the BISTS systems have not been widely reported [12]. Palmero-Marrero et al. [10] evaluated the potential of an integrated solar louver collector system for water heating in EES, which is a general equation-solving program that can numerically solve thousands of coupled non-linear algebraic and differential equations [13]. Different collector configurations were analyzed. Up to 83% of annual solar fraction was obtained for Lisbon and 95% for Tenerife. The building energy requirements and temperature behaviors were also calculated [14]. However, this analysis considered only the south-oriented horizontal louvers and it was based on a single-zone building.

Although the study about the BISTS system is limited, many other building solar systems have been evaluated. Some research focused on the life cycle analysis [7,8], and some other investigated the thermal and/or energetic behavior of the solar systems. Both experimental and modeling methods have been used in previous studies. For a yearly performance prediction, practical test is time

* Corresponding author.
E-mail address: mqu@purdue.edu (M. Qu).

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consuming, expensive and difficult to be adopted because it may take long periods of time to obtain test results [15]. Many modeling programs, such as TRNSYS, WATSUN, Polysun, and F-Chart are used for the performance prediction of solar energy systems with their acceptable accuracy [16]. Oishi et al. [15] used TRNSYS to model and evaluate the performance of three types of representative solar DHW systems in Japan. Simulation results of water temperature behavior were compared with the practical indoor/outdoor testing data and revealed that the errors were less than 6%. Matuska et al. [6] compared the thermal behavior of façade-integrated collectors with standard roof-located collectors for water heating in a block of flats with TRNSYS simulation. The study reported that façade solar collectors should have an area increased by approximately 30% to achieve the usual 60% solar fraction, which is defined as the percentage of heat load that is met by solar energy [10], compared with conventional roof solar collectors with a 45° slope. This is because façade-integrated solar system has limitation to adjust the slope angle, resulting in reduction in irradiation reception.

Most building solar systems were employed for domestic hot water usage. Compared to space heating and cooling, DHW load is small and constant all year round and the system is not very complex to integrate. Kalogirou [17] conducted a feasibility study for the use of solar parabolic trough collectors for hot water production in Cyprus for both domestic and hotel applications. The systems were optimized using the F-Chart program and compared to similar systems using flat plate collectors. Monthly and annual solar fractions were computed and the results showed that for large scale water production, the parabolic trough collectors were more efficient than the flat plate ones. Some solar systems supply both DHW and space heating. Hassan et al. [4] studied a roof-integrated solar collector on a typical two or three story building in Blacksburg. 3D finite element models were developed in ABAQUS software to evaluate the thermal performance. The results concluded that the energy collected is sufficient to satisfy about 85% of the building space heating and hot water requirements. Recently, the application of solar absorption chiller or solar adsorption chiller makes it possible to use solar energy to provide space cooling. And the solar cooling systems have been applied to different building types, including offices, schools, hospitals, and hotels [18]. Florides et al. [19] modeled a lithium bromide – water absorption solar cooling system in TRNSYS for a typical house in Cyprus. A system optimization in terms of energy gain and life cycle savings was carried out to select the optimum tank size, collector type, collector slope and area, thermostat setting of the auxiliary boiler. Hang et al. [20] presented an optimization of solar cooling system considering the solar fraction and budgets limits. The central composite design approach was used to reduce the number of experimental trials and the simulations were carried out in TRNSYS. A case study based on a small-sized office building in West Lafayette was conducted to verify the simulation results.

Although solar thermal systems have potential to provide free energy for DHW, space heating, and space cooling, few research combined these three applications in one study to evaluate. In addition, since it is not easy to integrate solar collectors as shading devices in terms of esthetic and structural consideration, limited scientific results are available for helping decision making of BISTS design and operation. Motivated by the above reasons, this paper presents a case study to predict the performance of the BISTS system on solar energy usage, as the second paper of BISTS system evaluation.

2. Research approach and evaluation indicators

A case study was carried out to evaluate the solar energy usage of the BISTS system based on an application to a medium office reference building from the U.S. Department of Energy (DOE) located in Los Angeles, CA [27]. The BISTS were placed on the south, east, and west windows to provide DHW, space heating and/or cooling of the building in the study. As the DHW load is relatively constant, the BISTS system is primarily employed to provide domestic hot water. The rest BISTS collectors are either used for space heating, cooling, or both. Various system configurations and different operation strategies were investigated and analyzed by using building and energy system simulation in TRNSYS, which is a transient systems simulation program with a modular structure developed at the University of Wisconsin by the solar energy laboratory [34]. TRNSYS platform has been validated by many studies to provide accurate results with less than 10% error between the simulation results and the measured data [21].

The east BISTS are considered to work in the morning before 12 p.m. of solar time and the west BISTS are considered to work from 12 p.m. of solar time to the end of the afternoon since the west-facing collectors are blocked by the building itself from receiving solar radiation in the morning and likewise for the east-facing collectors in the afternoon. The BISTS were installed symmetrically on the east and west façades, therefore this study assumes that either the eastern or western BISTS operates during a day. In this way, we do not need to consider the variation of solar heat flux from the morning to the afternoon. For the south collectors, they have solar accessibility during daytime.

Solar Fraction and Solar Useful Efficiency were used as the indicators of system performance. Solar Fraction (F_{solar}) is the ratio of the energy contributed by solar source to the total load requirement. It can be calculated as equation (1).

$$F_{solar} = \frac{Q_{useful}}{Q_{load}} = 1 - \frac{Q_{aux}}{Q_{load}} \tag{1}$$

where,

Q_{load}: total thermal load [kJ];
Q_{useful}: thermal energy from the solar source [kJ];
Q_{aux}: thermal energy from the auxiliary heater [kJ].

Solar energy gained from the collectors sometimes cannot be fully used due to heat loss and mismatch with load demands. Solar Useful Efficiency (η_{solar}) is hence employed to determine the percentage of the collected solar energy that has been effectively used. It is calculated as the ratio of the useful solar energy and the total solar energy gain from the collectors, as shown in equation (2).

$$\eta_{solar} = \frac{Q_{useful}}{Q_{gain}} \tag{2}$$

where,

Q_{useful}: thermal energy from the solar source [kJ];
Q_{gain}: total solar energy gain from solar panels [kJ].

3. Collector information

The prototype panel of the studied BISTS collector is 210 mm wide and 51.5 mm thick, and the length can be customized. The main housing is made of 2 mm polycarbonate. And the top and bottom surfaces are oval curved. The panel core is 10 mm thick for fluid flow through. The lower portion has 25 mm polyurethane foam insulation, with heat conductivity of 0.03 W/(m × K). The upper portion has 10 mm air layer. The cross section of a BISTS prototype and the installation layouts are schematically shown in