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An integrated approach to evaluate the performance of solar water heater in the urban environment

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ABSTRACT

Solar water heater (SWH) is increasingly used in the urban area where the collectors are liable to be shaded by nearby buildings, however, the effect of nearby buildings on the behavior of SWH has not yet been understood well. This paper presents an integrated approach to quantitatively evaluate the performance of SWH in the obstructed scenes of arbitrary geometric complexity by coupling the radiation model in the urban resource flow tool CitySim with the SWH model developed in TRNSYS. A case study is conducted to illustrate the effect of the obstructions on daily and annual thermal performance and annual primary energy consumption of SWH. The results from the case study reveal that the SWH with typical configurations in the obstructed context may consume more primary energy than conventional water heater does, however this is not the case for the SWH in the unobstructed context. Fortunately, using the proposed approach can effectively avoid this problem. Thus, the proposed approach is useful for making better use of SWH in the urban context to maximize energy saving.

1. Introduction

The use of solar water heaters (SWH) is encouraged to produce domestic hot water, because SWH can substantially reduce primary energy consumption compared with conventional water heaters [1]. In China, a series of incentive policies were issued by central and local government [2,3] to advocate the application of SWH in the urban area. Meanwhile, with the China's rapid progression of urbanization, high-rise residential buildings have become the dominant type of residential buildings in China's cities [4]. Unlike low-rise residential buildings of that collectors are generally installed on the roof, the roof of high-rise residential buildings do not have enough space to accommodate as many collectors as required for meeting all residents' hot water demands. Therefore, the facade of high-rise buildings is considered as a useful area to install collectors [4]. However, in the urban environment, solar collectors are inevitably shaded by adjacent buildings and building itself if collectors are installed on the façade, which leads to reduce the irradiance received by solar collectors. Even for roof-installed collectors, they may be shaded by higher adjacent buildings. Under these circumstances, it is not clear yet that to what extend the performance of the SWH is affected by obstructions, and whether SWH can still save primary energy compared to conventional water heaters.

To the best of our knowledge, only a few studies [4,5] referred to the application of SWH in the urban context. However the effect of obstructions on the performance of SWH was not evaluated yet quantitatively. In addition, the existing tools and software for simulating SWH, such as TRNSYS [6] and those listed in Ref. [7], do not also explicitly take the effect of obstructions into account. At present, the common guideline adopted for planning SWH in the obstructed context is that the position where solar collectors may be installed should get no less than 4 h of sunshine duration [8,9]. However, this guideline is just empirical and cannot provide any quantitative information about the performance of SWH.

To ensure that SWH is used appropriately in the urban context, this paper presents an integrated approach for quantitatively evaluating the performance of SWH with the consideration of the effect of nearby obstructions in detail. In this approach, first the irradiance on the collector in the obstructed context is obtained using the radiation model in CitySim [10], and then the performances of SWH system is analyzed using the SWH model developed in TRNSYS [6] with the results from CitySim as boundary conditions. In addition, to automate coupling CitySim with TRNSYS, an integrated program is created using C++ programming language. A case study was carried out to illustrate the advantages of the proposed approach and the effect of the obstructions on the performance of SWH.

2. Methodology

The proposed approach is composed of two main modules. One module is to calculate the solar irradiance on the collector under

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Nomenclature

a_0, a_1, a_2	coefficients of collector efficiency equation
A_c	collector gross area (m^2)
E_{SWH}	embodied energy of SWH per square meter of collector (kWh/m^2)
d_r	distance ratio
ΔH	height difference between the bottom of collector and the top edge of obstructing building (m)
ΔT	temperature difference adopted in the collector test (°C)
f	solar fraction
G_b	beam irradiance (W/m^2)
G_{bn}	normal beam irradiance (W/m^2)
G_d	diffuse irradiance (W/m^2)
G_g	ground reflected irradiance (W/m^2)
G_r	reflected irradiance from adjacent obstructed surfaces (W/m^2)
G_s	sky diffuse irradiance (W/m^2)
G_T	total irradiance (W/m^2)
h	height above the ground of the bottom of collector (m)
H	height of the building (m)
K_b	incidence angle modifier for beam irradiance
K_d	incidence angle modifier for diffuse irradiance
K_g	incidence angle modifier for ground reflected irradiance
K_θ	incidence angle modifier
N	life span of SWH (year)
P	primary energy conversion factor
PESP	primary energy saving potential (kWh)
Q_0	annual energy consumption using conventional water heater (kWh)
Q_A	annual energy consumption by SWH (kWh)
Q_{aux}	annual energy consumption by auxiliary heater (kWh)
Q_{pump}	annual energy consumption by circulating pump (kWh)
R	radiance (W/m^2 Sr)
S	horizontal distance between obstructing and obstructed building (m)
W	width of obstructing building (m)
w_r	width radio
α	view factor of sky patch for the considered plane
Φ	solid angle (Sr)
η	thermal efficiency of collector
θ	incident angle between sky patch and the considered plane (rad)
θ_s	incident angle between the sun and the considered plane (rad)
ψ	view factor of the considered plane for the sun

the obstructed circumstance, called as radiation calculation module. The other is to dynamically simulate the performance of the SWH, called as SWH simulation module. In this section, these two modules are introduced, respectively. In addition, the method of integrating these two modules is presented.

2.1.1. Radiation calculation module

This module uses a radiation model, known as simplified radiosity algorithm (SRA) [11], as the solver. The SRA model has some advantages for calculating the irradiance distribution in the urban context. The advantages include that (1) the SRA model takes into account the anisotropy of sky diffuse irradiance and real geometry of obstructions to sun and sky as well as reflections from adjacent dominant obstruction; and (2) it can give similarly accurate results at a computation cost of at least five orders of magnitude lower compared with RADIANCE does [12]. The principle of the SRA model is introduced in brief below.

Total irradiance G_T, in W/m^2, on a given plane is calculated as,

$$G_T = G_b + G_s + G_g + G_r \tag{1}$$

where G_b, G_s, G_g, and G_r denote, respectively, beam irradiance, sky diffuse irradiance, ground reflected irradiance, and reflected irradiance from adjacent obstruction.

The SRA model calculates diffuse and reflected irradiance, respectively, based on a general solution as given in Eq. (2).

$$G_{s(g,r)} = \sum_{i=1}^{p} (R \cdot \Phi \cdot \alpha \cdot \cos\theta)_i \tag{2}$$

where R, in W/m^2 Sr, is radiance of the particular discrete sky patch that subtends a solid angle Φ (Sr). For G_s, the radiance is anisotropic and calculated using Perez model [13], whereas for G_g and G_r, the radiance is isotropic due to assuming all surfaces to be Lambertian. α is the proportion of the patch that can be seen by the considered plane. θ is the incident angle between the patch and the considered plane. p is the number of patches considered, note that this number for G_r is double the one for G_s and G_g.

The beam irradiance G_b is calculated by $G_b = G_{bn} \cdot \psi \cos\theta_s$ based on the normal beam irradiance G_{bn} which is incident at an angle θ_s to the considered plane of which some fraction ψ is visible from the sun. Thanks to advanced computer rendering adopted in the SRA, the view factors (α and ψ) can be solved efficiently and take real geometry of obstructions into account. For detailed descriptions of the SRA, one may refer to the original references [11,12].

The SRA model has been integrated into an urban resource flow tool CitySim [10], which is used directly in this paper. To run CitySim, an XML file is needed, which contains a geometric description of 3D form of buildings and collectors. In addition, the XML file also has a pointer to the local climate file.

In the proposed approach, the outputs of CitySim are saved into an intermediate file including G_T, G_s, G_g and G_r for each collector for each hour in a year, which are used as boundary conditions by the SWH model.

2.1.2. SWH simulation module

This module contains a SWH model developed using the TRNSYS transient system simulation program, which has been extensively used [14–16] and widely accepted by the scientific community [15] in the field of solar thermal simulation. A common domestic SWH, as shown in Fig. 1, is mainly composed of solar collector, storage tank, auxiliary heating device, circulating pump, controller, and tempering valve. Here solar collector component is described in detail below as it is the most important component in the SWH model. In addition, some differences between common simulation and the simulation under the obstructed circumstance are presented.

Solar collectors can be divided into two types, i.e. evacuated tube collector and flat plate collector. For evacuated tube collector and flat plate collector, Type 71 and Type 1 in standard component library of TRNSYS are used, respectively. The thermal efficiency of both types of collector can be represented by the general equation below [17],

$$\eta = a_0 K_\theta - a_1 \frac{\Delta T}{G_T} - a_2 \frac{\Delta T^2}{G_T} \tag{3}$$