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Determination of optimum tilt angle and orientation for solar collectors based on effective solar heat collection

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HIGHLIGHTS

- Propose an effective solar heat collection concept to rule out ineffective solar radiation.
- Apply the optimization model to a solar collector installed in Lhasa.
- There is about 5° deviation in the optimum orientation between two methods.
- It is not necessary to adjust the solar collector every month in the studied region.
- Give correction factors based on total effective solar heat collection.

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ABSTRACT

Determination of optimum tilt angle and orientation of solar collectors by maximizing the total solar radiation may overestimate the energy production benefits, because a considerable amount of solar radiation is ineffective for practical solar collectors. In this paper, the concept of effective solar heat collection is proposed to rule out the ineffective solar radiation that could not be converted to available energy. Accordingly, an optimized mathematical model is developed and used to determine the optimum tilt angle and orientation of solar collectors installed in Lhasa during the heating season. Compared with the total solar radiation based optimum results, there is a deviation of 5° in the optimum orientations based on the effective solar heat collection. The case study shows that it is not advisable to adjust the optimum tilt angle on a monthly basis because there is no significance change in total solar energy gains in comparison with the case of no such adjustment during the heating season. In addition, the correction factors to achieving the maximum effective solar heat collection are given at different tilt angles and orientations to guide installation of solar collectors in practical engineering applications.

1. Introduction

As an eco-friendly and nearly inexhaustible energy resource, solar energy is undoubtedly an encouraging solution to energy shortage and a means of achieving sustainable development. Solar photovoltaic and solar thermal systems have been widely utilized at large extent in energy supply for buildings in recent years [1–6]. Solar collector is the core component of solar thermal utilization in buildings. To maximize the amount of energy captured by solar collectors, the sun-tracking system is often used as an attractive technology for solar collectors or panels [7–12]. Nevertheless, sun-tracking systems have disadvantages such as high cost, energy intensive and unsuitable for small solar collectors or panels [13].

In addition to the novel configuration design [14,15], for solar collectors without a sun-tracking system, their tilt angles with respect to the horizontal plane and orientations significantly affect the solar

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Nomenclature

$[(T_i - T_a)/H_T]_t$	normalization temperature difference, (°C·m^2)/W
$[(T_i - T_a)/H_T]_c$	critical normalization temperature difference, (°C·m^2)/W
F_R	collector heat removal factor
τ	transmittance of the cover system at a given angle
α_a	angular absorptance of the collector
$(\tau\alpha_a)_n$	transmittance-absorptance product at normal incidence
U_L	collector overall heat loss coefficient, W/(°C·m^2)
T_i	collector inlet temperature, °C
T_a	outdoor ambient temperature, °C
H_T	solar radiation density received per collector area, W/m^2
H_{Tt}	total solar radiation density on a tilted surface, W/m^2
H_{Bt}	direct-beam solar radiation density on a tilted surface, W/m^2
H_{Dt}	diffuse solar radiation density on a tilted surface, W/m^2
H_{Gt}	ground reflected radiation density on a tilted surface, W/m^2
H_B	beam radiation normal to a horizontal surface, W/m^2
R_B	geometric factor
HD	diffuse radiation on a horizontal surface, W/m^2
ρg	ground reflectivity coefficient
$Q_u(h, \beta, \gamma)$	transient effective solar heat collection, kJ
$\eta_T^+(h)$	transient efficiency of the collector at time h, %
A	collector daylighting area, m^2
$H_T(h, \beta, \gamma)$	solar radiation on the solar collector mounted at tilt angle β and orientation γ at time h, W/m^2
$Q_u(\beta, \gamma)$	total effective solar heat collection during the heating season, kJ
η	collector efficiency, %
δ	solar declination angle, °
n	day of year
ω	solar hour angle, °
α	solar altitude angle, °
φ	geographic latitude, °
θ_z	zenith angle, °
θ	solar incidence angle, °
β	solar surface tilt angle, °
γ	surface azimuth angle, °
$\beta_{optimum}$	optimum tilt angle, °
$\gamma_{optimum}$	optimum surface azimuth angle, °

radiation received by the collector surface. The simulation results of Despotovic et al. [16] show that, in comparison with solar photovoltaic panels fixed at current roofs' angles in Belgrade, the annual energy gain obtained by paneling at yearly, seasonal and monthly optimum tilt angles is increased by factor of 5.98%, 13.55% and 15.42%, respectively. Skeiker [17] found that, an annual energy gain can be increased by about 30% when the solar collectors' tilt angle changes from fixed value to an optimum value. For south-facing solar photovoltaic panels in Tabass of Iran, in comparison to the case without adjustment, the extra annual energy by adjusting the photovoltaic surfaces at monthly, seasonal, semi-yearly and yearly optimum tilt angle can account for 23.15%, 21.55%, 21.23% and 13.76%, respectively [18]. Therefore, in engineering applications, solar collectors are usually mounted on the roof of a building at an optimum tilt angle and orientation for maximum solar energy gain.

Over the years, considerable efforts have been made to determine the optimum tilt angle and orientation by maximizing the total solar radiation on the collector surface for a particular day or a specific period at different locations. Tang and Wu [19] proposed a simple mathematical procedure to estimate the optimum tilt angle of a solar collector based on monthly horizontal radiation. Khahro et al. [20] established a diffuse solar radiation model to obtain the optimum tilt angle for a prospective location in southern region of Sindh, Pakistan, and recommended adjustment every half year. Stanciu et al. [21] applied three typical models to evaluate the solar radiation density and calculate the optimum tilt angle for flat plate collectors at different geographical latitudes. Moghadam et al. [22] studied two different building arrangements to investigate the effect of shadow of adjacent taller constructions on receiving solar energy. To consider the impact of changes in the weather, Armstrong et al. [23] proposed a new method to optimize solar energy extraction for climates susceptible to frequently overcast skies and validated for all other weather types. Smith et al. [24] developed a method combining zone, water vapor, aerosol and other cloud parameters related radiative transfer model with a tilt procedure to determine the optimal tilt angle in all-sky conditions.

The optimum results of most studies [19–28] were obtained by maximizing extraterrestrial solar radiation, direct solar radiation and total incident solar radiation on the collector surface. However, when the heat convection loss on the collector surface is even higher than the captured solar radiation, the collector surface could not convert all the captured solar radiation to available energy. As a result, traditional optimization methods may overestimate the benefits of energy conversion because unavailable solar radiation has not been ruled out. Therefore, the interest of this study lies in presenting a new calculation method for optimum tilt angle and orientation by considering the ineffective solar radiation. Firstly, the concept of effective solar heat collection is proposed. Based on this, an optimization model is established and the optimum tilt angle and orientation of the solar collectors installed in Lhasa are calculated. In addition, the correction factors based on total effective solar heat collection is presented in this paper as well to provide useful information for the installation of solar collectors in Lhasa.

2. Methodology

2.1. Concept of effective solar heat collection

Our previous study [29] shows that, the heat collection efficiency of the solar heating systems is not only affected by the radiation intensity, but also related to the outdoor dry-bulb temperature. Lower outdoor temperature is not conducive to the solar heating systems to obtain solar radiation energy. When the outdoor temperature is low and while solar radiation intensity is weak, the thermal loss due to convection heat transfer on the collector surface is higher than the solar radiation received on the collector surface. As a result, the running collectors can even dissipate heat to surrounding environment. At this point, the solar collectors cannot capture the net solar energy and should stop running. As shown in Fig. 1, at lower temperatures during sunrise and sunset, solar radiation reaching the collector surface cannot be used to heat water in the collector and generate available energy. Thus the effective solar heat collection period is about 2 h less than the sunshine duration, especially in cloudy and snowy conditions.

According to the formula for solar thermal collector efficiency [30]:

$$\eta = F_R(\tau\alpha_a)_n - F_R U_L (T_i - T_a)/H_T \tag{1}$$

where η is the collector efficiency; F_R is the collector heat removal factor; τ is the transmittance of the cover system at a given angle; α_a is the angular absorptance of the collector; $(\tau\alpha_a)_n$ is the transmittance-absorptance product at normal incidence; U_L is the collector overall heat loss coefficient, [W/(°C·m^2)]; T_i is the collector inlet temperature, [°C]; T_a is the outdoor ambient temperature, [°C]; H_T is the solar radiation density received per collector area, [W/m^2].

The ratio between the (T_i-T_a) and H_T is defined as the normalization temperature difference, denoted by $[(T_i - T_a)/H_T]_t$. The critical