An Optimized Model for Solar ThermalCollectors Based onConcept of Effective Heat Collection

Yuexia Lv\textsuperscript{a,b}, Pengfei Si\textsuperscript{c,*}, Xichen Liu\textsuperscript{c}, Xiangyang Rong\textsuperscript{c}, Ya Feng\textsuperscript{c}, Jinyue Yan\textsuperscript{d,e}

\textsuperscript{a}School of Mechanical & Automotive Engineering, Qilu University of Technology, Daxue Rd No.3501, Jinan 250353, China
\textsuperscript{b}(Ningbo) RK Solar Energy Tech. Ltd., Zhongguan WestRoad No.777, Ningbo 315201, China
\textsuperscript{c}China Southwest Architecture Design and Research Institute Corp., Ltd., Tianfu Avenue No.866, Chengdu 610041, China
\textsuperscript{d}School of Business, Society and Energy, Mälardalen University, Västerås SE-72123, Sweden
\textsuperscript{e}School of Chemical Science and Engineering, Royal Institute of Technology, Stockholm SE-10044, Sweden

Abstract

The performance of solar collector highly relies on its tilt angle with respect to horizontal plane and orientation (surface azimuth angle) of the collector. The effective heat collection concept was proposed and an optimized mathematical model was further developed to determine the optimum tilt angle and orientation for the solar collector. The developed model was applied in a case study of the Lhasa district, in comparison with the results obtained in accordance with conventional optimization results. The research results showed that, there is about 5° deviation between the optimum results obtained according to effective heat collecting capacity and the optimum results obtained according to maximum total solar radiation falling on the solar collector.

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1. Introduction

As an effective, renewable, safe and eco-friendly energy resource, efficient utilization of solar energy has undoubtedly been regarded as an encouraging solution to global energy shortage and a means to achieve sustainable development for human beings. Due to rapid development of solar energy technologies and continuous decreased cost of solar energy equipment, percentage of renewable energy by solar thermal and photovoltaic are increasing as the energy supply for buildings. The surface azimuth

* Corresponding author. Tel.: +86-28-6255-1510; fax: +86-28-6255-1510
E-mail address: 175987342@qq.com
angle and tilt angle of a solar collector with respect to horizontal surface highly affect the solar radiation reaching the collector surface.

In recent years, a number of studies have been carried out to investigate the optimum tilt angle and orientation of solar surface for different building applications, and several models have been developed to determine the optimum tilt angle and amount of solar radiation on an inclined surface [1-3]. Despotovic et al. [4] determined the yearly, biannual, seasonal, monthly, fortnightly and daily optimum tilt angles of solar collectors for Belgrade, by searching for the values for which the solar radiation on the collector surface is the maximum for a particular day or a specific period. Gunerhan et al. [5] recommended that the solar collector should be mounted at the monthly average tilt angle and the slope should be adjusted once a month to increase the utilization efficiency of solar collectors in Izmir. Khorasanizadeh et al. [6] established a diffuse solar radiation model to determine the optimum tilt angle of south-facing solar surfaces in Tabass of Iran, and calculate the fixed monthly, seasonal, semi-yearly and yearly adjustments.

Nevertheless, in most models, the optimum results were obtained by achieving the maximum irradiation on the collector surface, without considering the influences of atmospheric temperature and working medium temperature on the collector performance. In practical applications, the atmospheric temperature, average temperature, fluid average temperature, fluid inlet and outlet temperature and other parameters are dynamically changing, which may result in a certain deviation from the optimum results obtained without taking above variables into account.

Therefore, it is the corresponding interest of this paper to propose the effective heat collection concept and further develop an optimization model to evaluate the collector performance in a better reasonable manner.

2. Methodology

In this section, a concept of available/effective heat collection has been proposed, based on which an optimized mathematical model has been further developed.

2.1. Concept of effective heat collection

Available/effective heat obtained by the collector within a certain period is the energy difference between the captured solar energy and the energy lost to ambient environment, in which absorbed solar energy is the solar energy reaching the collector surface subtracted by thermal loss due to collector radiation. Figure 1 is the energy balance schematic drawing of a solar collector.

The concept of effective heat collection is illustrated using example located in Lhasa. As shown in Figure 2, the heat collecting capacity of the collector installed varies against time. Minus zone indicates
that the system should be stopped in order not to lose heat to the ambient. The following equation is applicable for most collectors:

$$\eta = \frac{Q_u}{AI_F} = F_g (\tau a)_n - F_g U_L (T_i - T_a) / I_F$$  

(1)

Where $\eta$ is the efficiency of the solar collector; $Q_u$ is the output energy from the collector, W; $A$ is the solar collector area, m$^2$; $I_F$ is the solar irradiance received per collector area, W/m$^2$; $F_g$ is the collector efficiency factor; $(\tau a)_n$ is the effective transmittance-absorptance product at normal incidence; $U_L$ is the overall heat loss coefficient, W/(°C·m$^2$); $T_i$ is the mean fluid temperature through solar field, °C; $T_a$ is the ambient air temperature, °C.

![Fig. 2. Heat collecting capacity of the collector in Lhasa](image)

When solar collector efficiency $\eta=0$, $[(T_i-T_a)/IT]c$ is defined as critical normalization temperature at which the absorbed solar energy equals to heat loss. In case of $[(T_i-T_a)/IT]t \approx [(T_i-T_a)/IT]c$, $\eta>0$, the collector could obtain effective heat when the solar radiation energy absorbed by the collector is higher than the collector energy lost to ambient environment. Conversely, the collector would dissipate heat to the ambient environment. Therefore, the effective heat collection of solar collector system can be defined as the energy difference between the absorbed solar irradiance and the collector energy radiated to ambient environment when the normalization temperature at time $t$ is lower than the critical normalization temperature.

### 2.2. Calculation of solar radiation on tilted surface

To optimize the solar collector installation, the solar radiation reaching the horizontal surface is generally converted to the solar radiation on the tilted surface.

#### 2.2.1 Basic parameters

The declination angle $\delta$ can be expressed by:

$$\delta = 23.45 \sin \left( \frac{284 + n}{365} \right)$$  

(2)

Where $n$ is the day number in a year.

Hour angle $w$ is the sun change within a day, which varies by 15°per hour, negative in the morning and positive in the afternoon. Sunrise and sunset hour angles are the maximum, while the high noon hour angle is zero.

Altitude angle is the minimum line-surface angle between the solar ray and local horizon, which can be calculated by:

$$\sin a_n = \sin \Phi \sin \delta + \cos \Phi \cos \delta \cos \omega$$

(3)

Where $\Phi$ is the geographic latitude.

Surface orientation angle $\gamma_t$ equals to zero for tilted surface facing the due south.

#### 2.2.2 Calculation model
The tilt angle with respect to horizontal plane is $S$, and the angle of incidence of the direct solar radiation on the tilted surface $\theta$ can be estimated by the following equation:

$$\cos \theta = \sin \delta \sin \Phi \cos S - \sin \delta \cos \Phi \sin S \cos \gamma_f + \cos \delta \cos \Phi \cos S \cos \omega$$

$$+ \cos \delta \sin \Phi \sin S \cos \gamma_f \cos \omega + \cos \delta \sin \Phi \sin S \sin \gamma_f \sin \omega$$

(4)

The direct solar irradiance on the tilted surface $I_{D,\theta}$ is:

$$I_{D,\theta} = I_s \cos \theta$$

(5)

Where $I_s$ is the direct solar irradiance on the surface vertical with solar ray, W/m$^2$.

The solar scattered radiation on the tilted surface $I_{d,\theta}$ can be expressed by:

$$I_{d,\theta} = I_{d,\theta}(1 + \cos S)/2$$

(6)

Where $I_{d,\theta}$ is the solar scattered radiation on horizontal plane, W/m$^2$.

Ground reflection radiation can be calculated by the following formula:

$$I_{p,\theta} = \rho_s (I_{D,\theta} + I_{d,\theta}) (1 - \cos S)/2$$

(7)

Where $\rho_s$ is the ground reflection ratio, taking average value of 0.2; $I_{D,\theta}$ is the direct irradiance on horizontal plane, W/m$^2$.

$$I_{D,\theta} = I_s \sin a$$

(8)

Total irradiance on the tilt surface $I_{\theta}$ is expressed by:

$$I_{\theta} = I_{D,\theta} + I_{d,\theta} + I_{p,\theta}$$

(9)

Hourly solar irradiance per unit on the tilt surface $H_h$ is expressed by:

$$H_h = I_{\theta} \times 10^{-6}$$

(10)

2.3. Optimization mathematic model

Conventional optimum tilt angle and optimum orientation of solar collector are obtained based on calculation of the maximum solar irradiance. However, as previously discussed in Section 2.1, the collector radiates to ambient environment when $\theta < 0$. In this case, the solar collection system will stop working and the solar irradiance reaching collector surface could not be converted to available heating energy. Therefore, the present study determines the optimum tilt angle and optimum orientation by calculating the maximum effective heat collector at variable tilt angles and orientations.

Effective heat collection in heating season can be described as:

$$Q_e(\alpha, \gamma) = \sum_{I}^{3600} n_e \cdot A \cdot I_{I}(\alpha, \gamma) / 1000$$

(11)

Where $Q_e(\alpha, \gamma)$ is the effective heat collection in heating season, kJ; $A$ is the collector daylighting area, m$^2$; $I_I(\alpha, \gamma)$ is the hourly solar irradiance of tilted surface in heating season, W/m$^2$; $\alpha$ and $\gamma$ are collector tilt angle and orientation, respectively, °; $\eta_e$ is the instant efficiency of collector, %, and the superscript + indicates positive value in the accumulation.

So the optimization objective function is:

$$\text{MAX}[Q_e(\alpha, \gamma)] = \text{MAX} \left[ \sum_{I}^{3600} n_e \cdot A \cdot I_{I}(\alpha, \gamma) / 1000 \right]$$

(12)

3. Case study

Lhasa is a city severely shortage in fossil energy, as well as the city with the highest power consumption ratio in China urban energy consumption. Annually accumulated solar radiation in Lhasa is up to 7.2GJ/m$^2$, ranking first in cities of China. Therefore, solar energy has been considered as a promising option to reduce the demands in fossil fuel and eliminate carbon dioxide emission in Lhasa.
3.1. Optimum surface azimuth angle and tilt angle

Simulation and optimization were carried out to calculate the surface azimuth angle and tilt angle of solar energy collectors in Lhasa by using above optimization model, with research results shown in Figures 3. Figure 3 indicates that, surface azimuth angle of 0° and tilt angle of 55° are the optimum installation parameters of the studied collectors. In addition, the effective heat collecting capacity over entire heating season only changes a bit when the azimuth angle changes from -20° to +20° and tilt angle changes from 40° to 60°, around 10%. Therefore, in the solar heat collection system design, the azimuth angle and tilt angle may be appropriately expanded so as not to be restricted by the building service conditions.

![Fig. 3. Optimum surface azimuth angle and tilt angle of solar collector in Lhasa](image)

3.2. Results comparison

Figure 4 is the optimum azimuth angle and tilt angle of solar collector in Lhasa based on the new optimization model in comparison with the results obtained in accordance with conventional optimization results. As it can be observed in Figure 4, the optimum azimuth angle which is obtained according to the maximum total solar radiation falling on the solar collector is due south; while the optimum azimuth angle obtained according to the effective heat collecting capacity is 5° south by west. The above deviation can be attributed to that, the outdoor atmosphere temperature in the morning is generally lower than that in the afternoon, and less effective heat collecting capacity is obtained at lower outdoor atmosphere temperature under the same radiation intensity, thus leading to about 5° deviation between the optimum results obtained according to effective heat collecting capacity and the optimum results obtained according to maximum total solar radiation falling on the solar collector. Therefore, it is critically important to adopt the new effective heat collection concept in practical applications.

![Fig. 4. Comparison of optimum azimuth angles](image)
4. Conclusion

The optimum installation of solar thermal collector based on effective heat collecting capacity can eliminate the ineffective solar radiation falling on the solar collector, which could determine the optimum azimuth angle and tilt angle of solar collector more accurately, beneficial for improving the solar thermal system efficiency. The case study in Lhasa showed that, there is a 5° deviation between the optimum results obtained according to effective heat collecting capacity and optimum results obtained according to maximum total solar radiation falling on solar collector.

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References


Biography

Pengfei Si graduated with the doctorate degree at Xi’an University of Architecture and Technology in 2015. Research mainly focuses on solar energy utilization, building energy saving and storage.