Optimum Installation Inclination of Solar Vacuum Tubular Collector in Lhasa

Zou Hang¹, Liu Xin¹, Long Enshen²* and Liu Zhanqiang³

¹China Construction First Group, Beijing, 100071, China
¹Zigong Hi-tech Development Zone, Zigong, Sichuan, 643000, China
²College of Architecture and Environment, Sichuan University, Chengdu, Sichuan, 610065, China
³China Construction First Group, Beijing, 100071, China

*Corresponding author’s e-mail: longes2@scu.edu.cn

Abstract. It is important to accurately design the installation inclination of solar collector for improving the utilization rate. This paper selected Lhasa area as a typical city which was rich in solar energy, setting a mathematical model for energy collection of vacuum tube collector to dynamically analyse the south towards, 0°~90° angle of solar radiation on the surface of the collection on 8760 hours. As the results showed: the ability of the vacuum tube collector to collect solar reflection, scattering and direct radiation varied with the installation inclination a lot. When the inclination angle was 90°, the maximum annual reflection radiation value was collected by the vacuum tube collector; when the inclination angle was 0°, the maximum annual scattering radiation value was collected; when the inclination angle was local latitude, the maximum annual direct radiation value was collected; direct radiation in Lhasa was the main factor, so the maximum installation inclination of solar energy collected during the whole year and heating season was close to the local latitude.

1. Introduction

Fossil energy is increasingly scarce in today's world. Solar energy as an inexhaustible and clean energy has been widely concerned by people. Solar water heater is one of the most mature technology, the most widely used and the best economic benefit in solar energy utilization at present, and its core is solar collector [1]. Solar energy collector is a device that converts solar radiant energy into heat energy and transmits the generated heat energy to heat transfer medium. At present, the most widely used solar collectors include plate collectors and vacuum tube collectors [2], which have obvious differences in structure. The flat plate collector is a continuous plane and the whole surface area can collect solar radiation energy when the sunlight is irradiated [3]. The vacuum tube collector is composed of several vacuum tubes, and there is a gap between the tubes [1]. At present, China's solar water heaters are dominated by vacuum tubes, accounting for 86% [4]. The system efficiency and heat collection performance of vacuum tube collectors are also higher than that of flat plate collectors under the same weather conditions [5].

The performance of solar heat collecting system is reflected in the difference of solar radiation energy collected by the collector [6]. Under the condition of constant solar radiation, the solar radiation energy collected on the inclined plane with different installation angles has great difference [7]. In order to
maximize the solar radiation energy collected, the collector is usually placed at a certain installation angle with the horizontal plane, that is, the optimal installation angle. The receiving surface of is flat. The incident energy of flat plate collector will significantly decrease with the increase of the incident angle of sunlight because of the planar receiving surface. However, the receiving surface of vacuum tube collector is cylindrical, and the incident energy does not significantly decrease when the incident angle of sunlight changes less [8]. Therefore, there are differences between the two in the analysis of the optimal installation angle. In order to better collect solar energy and improve the efficiency of solar heat collecting system, many scholars have studied and analysed the optimal installation angle of vacuum tube collector [9]. However, the structural characteristics and the shielding between tubes are seldom considered when analysing the best installation angle of vacuum tube collector by the energy collection model commonly used [10], which is not completely in line with the actual situation. Therefore, a more reasonable energy acquisition mathematical model is proposed in this paper to accurately quantify the optimal installation inclination angle of vacuum tube collector which can provide reference for practical engineering.

2. Mathematical model and analysis object

2.1. Mathematical model
The vacuum tube collector is always placed at a certain angle of inclination. The solar radiation reaching the surface of the vacuum tube collector should consider the reflected radiation in addition to the direct solar radiation and the scattered solar radiation [11]. The mathematical model of energy collection for vacuum tube collector is:

\[ I = I_B + I_D + I_R \]  

where, \( I \) —total radiation intensity, W/m²; \( I_B \) —direct radiation intensity, W/m²; \( I_D \) —scattered radiation intensity, W/m²; \( I_R \) —reflected radiation intensity, W/m².

2.1.1. Direct radiation intensity \( I_B \)
During a period of time after sunrise and before sunset, the adjacent vacuum tubes will occlude each other when the azimuth of the sun is large and the altitude angle is small, that is, the intertube occlusion (as shown in Figure 1). The expression of direct solar radiation intensity \( I_B \) in vacuum tube collector considering the shielding between tubes [12] is:

\[ I_B = I_{ND} \cos \theta \psi(\xi) \]  

where, \( I_{ND} \) —normal hourly direct radiation value, W/m²; \( \theta \) —the incidence angle of direct solar rays on the collector tube, namely the angle between the projection of sunlight rays on the cross section of the collector tube and sunlight rays; \( \xi \) —the incidence angle of the projection of light rays on the cross section of the tube, namely the angle between the projection of sunlight rays on the cross section of the collector tube and the normal line of the collector; \( \psi(\xi) \) —block coefficient.

![Figure 1. Schematic diagram of occlusion between pipes](image)
In Figure 1 (b), $\xi_0$ is the critical projection incidence angle between pipes:

$$|\xi_0| = \cos^{-1}\left(\frac{D + D_1}{2B}\right)$$  \hspace{1cm} (3)

where, $D$—the outer diameter of the inner tube of a vacuum tube, mm; $D_1$—the outer diameter of the outer tube of a vacuum tube, mm; $B$—center distance between adjacent vacuum tubes, mm.

In Figure 1 (a) and Figure 1 (c), $\xi$ is the projection incidence angle of the ray on the pipe section when the pipe is blocked:

$$\xi = \cos^{-1}\left(\frac{\cos \theta}{\cos \theta_t}\right)$$  \hspace{1cm} (4)

where, $\theta$ —angle of solar incidence.

The incidence angle $\theta_t$ of the direct sunlight on the collector tube depends on the latitude, hour angle, declination and installation inclination:

$$\theta_t = \cos^{-1}\left\{1 - \left[\sin(\beta - \phi) \cos \delta \cosh(\beta - \phi) \sin \delta + \cos(\beta - \phi)\sin \delta\right]^2\right\}^{1/2}$$  \hspace{1cm} (5)

where, $\phi$—latitude; $\delta$—declination; $h$—hour angle.

Declination $\delta$ is:

$$\delta = 23.45 \cdot \sin \left[360(284 + n) / 365\right]$$  \hspace{1cm} (6)

where, $n$—year of date serial number.

Hour angle $h$ is:

$$h = (H_0 \pm \frac{L_u - L_0}{15} + \frac{e}{60} - 12) \cdot 15$$  \hspace{1cm} (7)

where, $H_0$—the 24-hour Beijing time system; $L_u$—longitude; $L_0$—longitude of Sector 8 E; $e$—the daily time difference.

The daily time difference $e$ is:

$$e = 9.87 \cdot \sin 2B - 7.53 \cdot \cos B - 1.5 \cdot \sin B$$  \hspace{1cm} (8)

where, $B$=360 (n-81) / 364.

The angle between the direct sunlight and the surface normal of the collector $\theta$:

$$\theta = \cos^{-1}\left\{\sin \delta \sin(\phi - \beta) + \cos \delta \cosh(\phi - \beta)\right\}$$  \hspace{1cm} (9)

When $|\xi| \leq |\xi_0|$, no shielding between tubes, $\psi(\xi) = 1$.

When $|\xi| > |\xi_0|$, occlusion between pipes:

$$\psi(\xi) = \frac{B}{D} \cos \xi + \frac{1}{2}(1 - \frac{D_1}{D})$$  \hspace{1cm} (10)

where, $\frac{B}{D}$—tube diameter ratio.

2.1.2. Scattered radiation intensity $I_D$

Liu et al. believed that the sky scattering was uniformly distributed. The isotropic vacuum tube collector with an inclination $\beta$ to the horizontal plane could be used to calculate the scattering radiation intensity as follows [13]:

$$I_D = \frac{1}{2} I_{D_H} (1 + \cos \beta)$$  \hspace{1cm} (11)

where, $I_{D_H}$—hourly scattering value of horizontal plane, W/m².
2.1.3. Reflected radiation intensity $I_r$
Under the assumption of isotropic reflection of the ground and buildings, the calculation of reflected radiation intensity from the collector tube with an inclination angle $\beta$ with the horizontal plane is:

$$I_r = \frac{1}{2} \rho I_{shi} (1 - \cos \beta)$$

(12)

where, $I_{shi}$—hourly total radiation value of horizontal plane, W/m$^2$; $\rho$—the reflectivity of the surface of the ground object which is uniformly set as 0.2 in this paper [14].

2.2. Analysis object
Lhasa is located in the central part of the Qinghai-Tibet Plateau with coordinates of 29°36’N, 91°08’E, and an average altitude of 3650 m. Its climate belongs to the plateau temperate semi-arid monsoon climate zone with rich solar energy resources, which belongs to the distribution type of solar energy resources in China [15]. The annual sunshine hours in Lhasa reach 3000 hours, 1800 hours more than Chengdu and 1100 hours more than Shanghai and earning the laudatory title of “Sunshine City”. In addition, rainfall is mostly concentrated in summer and autumn, winter and spring are cold, dry and windy. The annual frost-free period can reach 100~120 days, thus possessing the natural conditions of solar heating [16]. In recent years, vacuum tube collector has been applied rapidly in Lhasa area. The calculation and analysis of the optimal installation angle of vacuum tube collector usually apply the mathematical model of energy collection of flat plate collector, which has some errors. It can be used as a good demonstration in the practice of vacuum tube collectors in other areas if the best installation angle can be determined more accurately.

In this paper, the influence law of installation inclination on solar radiation collected by vacuum tube collector in Lhasa area is studied by using the above mathematical model of energy collection to determine the best installation inclination of vacuum tube collector. The vacuum tube collector is placed due south. The outer diameter of the outer tube is $D_1=58\text{mm}$, the outer diameter of the inner tube is $D=47\text{mm}$, the length of the tube is $L=1800\text{mm}$, and the center distance between the two adjacent tubes is $B=76\text{mm}$.

3. Influence of installation inclination on solar radiation
The installation inclination angle has a great influence on the ability of vacuum tube collector to collect solar radiation intensity. In order to improve the collection efficiency of solar collector to a greater extent, it is necessary to optimize the installation angle of the collector. At present, there are two methods to study the optimal inclination angle of the collector: one is to determine the optimal inclination angle based on the maximum solar radiation received by the collector. The other is to determine the optimal inclination angle by minimizing the annual auxiliary heat demand of the collector [17]. The paper chooses the former as the research method to determine the optimal inclination angle. Therefore, the variation of the intensity of different solar radiation with the installation angle is studied and compared.

Figure 2 shows the variation curve of solar radiation intensity collected by a single vacuum tube in Lhasa area with the installation angle. It can be seen from the figure that the annual direct radiation collected by a single vacuum tube is a single hump type with the change of inclination angle. When the installation inclination angle increases from 0° to 90°, the annual direct radiation intensity increases significantly to a peak of 509.4MJ firstly, and then drops rapidly. When the installation inclination angle is 90°, the direct radiation reaches the minimum value of 187MJ. The annual scattered radiation intensity collected by a single vacuum tube is inversely proportional to the change of inclination angle. With the increase of installation angle, the annual scattered radiation intensity decreases gradually. When the installation inclination angle is 0°, the annual scattered radiation intensity reaches the maximum value of 125.44 MJ, and when the installation inclination angle is 90°, the annual scattered radiation intensity reaches the minimum value of 62.72 MJ. The annual reflected radiation intensity collected by a single vacuum tube is consistent with the change of inclination angle. As the installation inclination angle
increases, the annual reflected radiation intensity gradually rises. When the installation inclination angle is 0°, the annual reflected radiation intensity is 0 MJ, and when the installation inclination angle is 90°, it reaches the maximum value of 61.91 MJ. In addition, it can be seen that the collected annual solar reflected radiation intensity is much smaller than the direct solar radiation intensity and the scattered radiation intensity. Even when the installation inclination angle is 90°, the reflected radiation intensity reaches the maximum, which is far less than the sum of the direct radiation intensity and the scattered radiation intensity. The sum of intensity and scattered radiation intensity. It show that direct radiation and scattered radiation have greater influence on the intensity of solar radiation collected by the collector, and direct radiation is dominant.

![Figure 2. Variation curve of solar radiation collected by a single vacuum tube with installation inclination](image)

**Figure 2.** Variation curve of solar radiation collected by a single vacuum tube with installation inclination

### 4. Optimum mounting Angle
Solar collector system is mainly used to provide domestic hot water and heating. Generally speaking, solar water heating system needs to be considered to operate throughout the year, while solar heating system only considers winter operation. In order to reflect the influence of installation angle on energy collection of vacuum tube collector more objectively and practically, this paper calculates the variation of solar radiation intensity with installation inclination in winter half year (October to next March), summer half year (April to September), heating season (November to next March) and the whole year, so as to select the best installation inclination of vacuum tube collector in Lhasa.

Figure 3 shows the variation curve of the total solar radiation intensity with the installation inclination angle of the Lhasa area collected each month throughout the year. It can be seen that the variation trend of the total solar radiation intensity with the installation inclination angle is single hump type, and the variation trend is consistent. When the installation inclination angle increases from 0° to 90°, the total radiation intensity firstly increases to a certain peak, then decreases, reaching the maximum near the local latitude value, and reaching the minimum at 90°. This phenomenon occurs because the surface of the evacuated tube collector is cylindrical. Although the solar height angle changes constantly in different months of the year, the angle between the collector and the collector section does not change much. Therefore, the best installation inclination varies in a small range from month to month, which is about the local latitude. A further comparison between Figure 3 (a) and (b) shows that the most unfavorable month for collecting total solar radiation occurs in December; the most favorable month for collecting total solar radiation occurs in May.
Figure 3. Variation curves of the total solar radiation intensity with the inclination angle collected in each month

It can be seen from Figure 4 that the total solar radiation intensity collected by a single vacuum tube in Lhasa area throughout the year and the heating season shows a single hump type with the inclination angle. When the installation inclination angle increases from 0° to 90°, the total solar radiation intensity throughout the year and the heating season increases significantly. When the installation inclination angle reaches the highest value, the corresponding installation inclination angle is close to the local latitude. When the installation angle continues to increase, the total solar radiation intensity of the whole year and heating season is significantly reduced, and the total radiation intensity is the smallest when the installation angle is 90°. Through calculation and analysis, it can be concluded that the best
installation angle of Lhasa in the whole year and heating season is 28°. Considering the different latitude and meteorological conditions in Lhasa, the best installation angle of the vacuum tube collector in the whole year and heating season should be 20°~37°.

Figure 4. The relationship between the total solar radiation collected by a single vacuum tube throughout the year and the heating season varies with the installation inclination angle

5. Conclusions
This paper uses the mathematical model of vacuum tube collector energy collection to study the best installation inclination in Lhasa, and the main conclusions are as follows:

(1) When the installation inclination angle is 90°, the vacuum tube collector collects the maximum annual reflected radiation value; when the installation inclination angle is 0°, the vacuum tube collector collects the maximum annual scattered radiation value; when the installation inclination angle is equal to the local latitude, the vacuum tube collector collects the maximum annual direct radiation value.

(2) The best installation angle of vacuum tube collector in Lhasa in summer half year is slightly higher than that in winter half year, but it is close to the local latitude.

(3) As the direct sunlight in Lhasa dominates, the maximum installation inclination angle for collecting solar energy throughout the year and heating season is close to the local latitude, and the best installation inclination angle is 28°. Considering the latitude and meteorological conditions of the entire region are slightly unavailable, the best inclination angle can be selected within the range of 20°~37°.

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